THE IMPACTS OF LIVESTOCK GRAZING IN THE SONORAN DESERT: A LITERATURE REVIEW AND SYNTHESIS

February 2005

The Nature Conservancy
SAVING THE LAST GREAT PLACES ON EARTH

THE IMPACTS OF LIVESTOCK GRAZING IN THE SONORAN DESERT: A LITERATURE REVIEW AND SYNTHESIS

John A. Hall
Sonoran Desert Program Manager
The Nature Conservancy, Tucson, Arizona

Stephanie Weinstein
Conservation Planner
The Nature Conservancy, Tucson, Arizona

Cheryl L. McIntyre
Graduate Intern
Sonoran Institute, Tucson, Arizona

This report was prepared under Federal Cooperative Agreement No. AAA–02–0005, Task Order AAF–02–0001 by The Nature Conservancy in Arizona for the Bureau of Land Management, Phoenix Field Office

Disclaimer

Recommended Citation

Hall, J.A., S. Weinstein, and C.L. McIntyre. 2005. The Impacts of Livestock Grazing in the Sonoran Desert: A Literature Review and Synthesis. The Nature Conservancy in Arizona, Tucson.

EXECUTIVE SUMMARY

Compared to more productive rangelands, both domestic livestock grazing impacts and grazing management strategies are poorly documented in the scientific literature for the Sonoran Desert. Although the literature, when viewed comprehensively, does document that livestock grazing can cause adverse impacts, it does not provide sufficient information regarding thresholds of grazing intensity that can enable one to distinguish between benign and damaging grazing intensities. The unique ecological characteristics of the Sonoran Desert require specific attention when considering development and implementation of a grazing management strategy. Current approaches to grazing in the Sonoran Desert mostly seem to follow the conceptual thinking underlying grazing management strategies developed and tested for ecosystems typically of higher productivity and of significantly different ecosystem dynamics. As a result, no currently described approach, including continuous grazing and each of the specialized grazing systems, is completely applicable to or appropriate for the Sonoran Desert ecosystem within their current formulations.

Purpose and Scope

An understanding of the ecosystem dynamics of a landscape that is to be subject to livestock grazing and the relationship of these dynamics to different types of grazing management strategies is critical to developing a management approach appropriate to that ecosystem. To better inform decision-making, the Bureau of Land Management's (BLM) Phoenix Field Office requested The Nature Conservancy in Arizona (Conservancy) to conduct a review of the scientific literature regarding the state of knowledge of: (1) the impacts of domestic livestock grazing (primarily cattle) on natural and cultural resources in desert ecosystems, with a focus on the Sonoran Desert; (2) the implications of different grazing management strategies; and (3) Sonoran Desert plant community dynamics. Specifically with respect to impacts, the BLM asked the Conservancy to evaluate the literature relative to how livestock grazing in the Sonoran Desert affects:

- composition, structure, and function of plant communities
- saguaro recruitment and survival
- other individual components of plant communities (such as rare plants)
- soils and biological soil crusts
- wildlife, including non-game species
- cultural sites.

The ecological information is used to provide a context for understanding the impacts of livestock grazing in the Sonoran Desert and for drawing resultant conclusions. In particular, the roles of climate, based in part on an analysis of local weather data, vegetation response, and range ecology theory are highlighted in terms of how they may inform the selection of particular grazing strategies. The information contained in this report is broadly applicable to the Arizona Upland and Lower Colorado River Valley subdivisions of the Sonoran Desert. This report does not evaluate the literature regarding perennial or intermittent, stream-associated riparian habitats that occur within the Sonoran Desert.

Approach

We conducted an extensive literature search using electronic databases and expert input. We focused especially on the peer-reviewed literature and on Sonoran Desert-specific information. We constructed an Access database to manage the information and create data summaries. All compiled impact and management strategy-related literature (260 references) is included in this database, but only a portion of that literature is specifically evaluated in this report. To ensure our review of the literature was comprehensive and objective and met BLM’s information needs, we used three levels of oversight/review of our evaluations and synthesis: an internal Conservancy and Sonoran Institute review team, a BLM review team (to identify any factual errors), and an external committee of non-BLM range management professionals and scientists (our experts).

Findings and Conclusions: Impact Literature

The Sonoran Desert—as an arid and low-productivity, hot desert ecosystem—requires individual attention when considering the nature of soil-, biological soil crust-, and plant community-livestock interactions and their relevance to the development of appropriate grazing management strategies. The literature on grazing impacts in the Sonoran Desert is both limited in its number and scope and sometimes mixed in its observations and conclusions. Unfortunately, the weakest aspect of the livestock impact literature we reviewed was that most of the individual studies were not conceived from the standpoint of assessing grazing management alternatives within the Sonoran Desert. Our assessment of the ecosystem dynamics of the Sonoran Desert in comparison to semiarid or non-desert ecosystems, such as semidesert grasslands, suggests that grazing strategies developed for the latter may have limited applicability to the Sonoran Desert.

The literature on plant community impacts is illustrative of the general coverage of the literature. Most studies assessed the effects of release from historic grazing, few studies compared grazed and ungrazed sites simultaneously (the latter of which typically had experienced historic grazing), and only one study supposedly compared grazed sites with sites that had never been grazed. For all of these studies, detailed knowledge of historic or current stocking densities, timing and duration of grazing if not year-round, and how often grazing occurred generally were lacking. In some cases associated climatic information and site conditions were considered that enabled a more robust interpretation of a study’s findings. Finally, investigations involving Sonoran Desert xeroriparian plant communities and domestic livestock interactions, despite the relative importance of these communities for wildlife and livestock, have not been reported in the literature.

Despite the limitations of the impact studies described above, in combination they do indicate that livestock grazing can adversely impact soils, biological soil crusts, and plant community composition, structure, and function at the sites that were studied. Plant community impacts can manifest as decreased overall vegetation cover and density, reduced cover and density of palatable woody perennials and grasses, reduced species richness of annual plants, and increased species richness, cover, and density of non-native plants. Based on current evidence, we cannot rule out that intact biological soil crusts play an important role in Sonoran Desert ecosystem dynamics. They deserve additional management attention, as they are susceptible to damage from various disturbance sources including livestock grazing. Whether livestock grazing has a positive or negative effect on wildlife depends on the species under consideration—including their preferred forage and foraging habitat, the season of grazing and its intensity, and other site-specific factors. In general, most of the studies we reviewed showed that livestock grazing impacts wildlife indirectly by altering vegetation structure and/or composition. Of the species considered, the evidence for adverse impacts is most prevalent for bighorn sheep.

Specific cause and effect—historic grazing versus current grazing versus cyclical weather patterns—were not always possible to tease out in the various studies. As a result, uncertainty may exist relative to the applicability of findings to specific current grazing practices (which typically were not quantified) and the small breadth of the studies considered in terms of locales and plant communities; however, this uncertainty should not be viewed as evidence that livestock grazing, as currently practiced in the Sonoran Desert, does not have clear, demonstrated significant impacts within the Sonoran Desert ecosystem. The lack of studies and confounding factors that can obscure clear study results can cut both ways depending on the decision-making context. Most importantly, we did not find, based on the available literature, evidence to support what appropriate managed livestock grazing may look like in the Sonoran Desert because apparently such studies have not been conducted.

Findings and Conclusions: Grazing Management Strategy Literature

No particular grazing management strategy can be expected to perform well in all ecosystems, whether the desired management objectives relate to vegetation condition or livestock performance. Approaches that are developed and tested in one ecosystem may not necessarily work in other ecosystems, especially if important environmental variables such as precipitation patterns are not congruent with strategy assumptions. Studies that evaluate grazing management strategies as practiced in the Sonoran Desert are extremely limited and none appear in the primary literature.

Based on our review of the literature on grazing management strategies, we conclude that no currently described approach, including continuous grazing and each of the specialized grazing systems, is completely applicable to or appropriate for the Sonoran Desert ecosystem within their current formulations. Furthermore, in conjunction with our review of stocking rate and drought management considerations, we conclude that continuous grazing in which livestock are maintained within fenced allotments yearlong is not a feasible grazing management strategy on Sonoran Desert public lands.

The conclusion that continuous grazing is not feasible does not imply that seasonal grazing or any particular specialized grazing system, as these approaches are currently described in the literature, is appropriate. A grazing management strategy should be tailored to the specific ecological realities of the Sonoran Desert.

The BLM's use of ephemeral allotments could be an appropriate starting point for a Sonoran Desert-specific livestock grazing management strategy. For most of the Sonoran Desert, as described in this report, only grazing in response to winter rains may be feasible. The eastern margin of the Sonoran Desert, because it receives more reliable summer rains as well as winter rains, also may be amenable to manage for the monsoon pulse of vegetation. In both cases, the ability to set flexible stocking rates and to remove livestock quickly in response to changing conditions will be paramount. Drought conditions—cumulative and during the season of intended use—are the best guide to setting stocking rates in accordance with the three periods of drought: onset, during, and exiting. To enable time for plant reproduction, establishment of new plants, and restoration of vigor of existing plants, a period of deferment would be appropriate when drought conditions do not otherwise preclude grazing. If approached as an experiment, the establishment of appropriate stocking rates commensurate with soil moisture conditions and recovery from drought would enable the eventual setting of research-informed stocking rates that achieve managed grazing objectives. Sensitive resource areas, such as areas susceptible to accelerated soil erosion, are appropriate to protect from livestock grazing and, as a result, would be eliminated from the calculation of stocking rates. Appropriate measures of grazing intensity would provide the necessary benchmark to determine when livestock should be removed from the range, unless removal in response to the onset of seasonal drought occurs first.

ACKNOWLEDGMENTS

Completion of this project would not have been possible without the assistance of numerous individuals that contributed their time and expertise. We especially thank all members of the external review committee (identified in Table 2.4 in the report). All of these individuals freely imparted their knowledge and many of them, 16 in all, took the time to review and provide thoughtful comments to a draft of this report. We also wish to acknowledge members of the internal review committee (identified in Table 2.3) who are not otherwise authors of this report for their time and guidance in shepharding this project towards completion. In addition, we thank the staff at the Bureau of Land Management's Phoenix Field Office for conceiving the need for this literature review and providing a well thought-out set of questions for us to address. The authors, however, assume full responsibility for the interpretations made and conclusions reached in this report. Finally, we owe a huge debt of gratitude to our Conservancy volunteers: Claire Macha, Diana Herz, Stephanie Kopplin, and Jack Stoltz. Claire provided yeoman's services as our librarian. Claire conducted many of the electronic literature searches, otherwise located many of the references we needed, and mentored the other volunteers by providing them the information they needed to find references at the University of Arizona Library and other locations. Diana, Stephanie, and Jack retrieved, duplicated, and delivered references from the University of Arizona Library and other locations. Diana also photocopied, collated, and bound references included in the database and otherwise organized and filed documents. In sum, our volunteers, whether members of the external review committee or Conservancy volunteers, were a vital part of this project.

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

PHOTO CREDIT

Cover photo © Jim Maulsa. The photo shows the Table Top Mountains on the Sonoran Desert National Monument in the background with Arizona Upland vegetation in the foreground.

CHAPTER 1 NEED, PURPOSE, AND SCOPE

Domestic herbivores were introduced to the arid and semiarid Southwest with the arrival of Europeans to the region in the 1500s. Intensive grazing coupled with severe drought in the late 1800s caused widespread range deterioration and led to increased concern for conservation and sustainable use of public lands. Until the Taylor Grazing Act was passed in 1934, livestock grazing was virtually unregulated. Numerous authors have attributed regional landscape and vegetation change to land uses, including livestock grazing, during this period in history (for example, see Bahre 1991, Turner and others 2003).

Today domestic livestock grazing is regulated by federal and state agencies that set stocking rates and monitor forage utilization and rangeland health. In more recent times, federal land managers, such as the Bureau of Land Management (BLM), have been faced with land management decisions related to domestic livestock grazing in which decisions must be made under different contexts and with differing amounts of scientific information available to them to support such decisions. The contexts for decision-making are set by law, regulation, and policy and for any particular land management unit can affect how scientific information and uncertainty are used to make decisions about livestock grazing management.

1.1 NEED FOR THIS LITERATURE REVIEW

Although domestic livestock grazing continues to be a significant use of public rangelands, other land uses such as resource conservation and recreation, have increased dramatically in their importance in part because of shifting public values and demographics. These shifts have resulted in increased pressure on land management agencies to demonstrate that their livestock grazing management practices are compatible with other land uses and values, including the conservation of significant natural and cultural resources.

The BLM manages 183 million acres (11%) of the land in the continental U.S., including 9.2 million acres in the Sonoran Desert of California and Arizona. The BLM has a "multiple-use mandate," which means that the agency is required to manage its lands for sustained natural resource yield while maintaining other values, such as recreational, cultural, and biological resource protection. Livestock grazing is permitted or leased on nearly 12 million acres of BLM-managed lands in Arizona and on approximately 5.5 million acres (96%) of the lands managed by the BLM in the Sonoran Desert in Arizona.[1]

The Sonoran Desert National Monument (SDNM) was established by Presidential Proclamation in January 2001 (see Appendix A) and as such is a unit within BLM's National Landscape Conservation System. The SDNM is managed by the BLM out of its Phoenix Field Office. Although the BLM may still permit multiple land uses on the SDNM (in other words, the monument is not a "strict" nature preserve), the monument designation sets a higher standard of

---

[1] Based on spatial analysis of land management, allotment boundaries, and ecoregional boundaries.

land management and protection that the BLM must meet based on the terms and values articulated in the Proclamation. The BLM is challenged with managing the SDNM in a way that protects the numerous objects for which the monument was designated, which include significant regionally examples of Sonoran Desert biodiversity such as dense stands of saguaro (*Carnegiea gigantea*) and xeroriparian corridors that provide habitat to neotropical migratory birds and other wildlife. As per the Proclamation, livestock grazing will be eliminated in portions of grazing allotments on the SDNM that are located south of Interstate 8 when current permits expire. The Proclamation also requires BLM to assess whether livestock grazing on areas north of Interstate 8 on the SDNM is a land use compatible with protection of the objects described in the Proclamation. The BLM has chosen to conduct this assessment as part of the resource management planning process for the SDNM.

Livestock grazing in the desert Southwest has been controversial for some time. A November 1991 report by the United States (U.S.) General Accounting Office (GAO 1991) provided a review of BLM's grazing programs in the Nation's "hot" deserts: Mojave, Sonoran, and Chihuahuan. The GAO report drew several conclusions and provided the Department of Interior and Congress several options to consider regarding changes to BLM's grazing management practices. Notwithstanding the effects of historic grazing practices, GAO found examples of rangelands that continued to be degraded by extant grazing practices. Moreover, the GAO concluded that grazing revenues did not cover livestock grazing management costs and that BLM's level of spending was insufficient to perform all necessary range management tasks. Whether in response to the GAO report or to other factors that have occurred in the intervening years prior to today, changes undoubtedly have occurred to grazing management practices since 1991, such as the establishment of rangeland health standards. We do not further address the accuracy, then or now, of GAO's specific conclusions and how some of BLM's grazing management practices may have changed as a result since 1991. Instead, of interest here, from a historical context, are the options GAO proposed in draft, Interior's responses, and the final options retained in the report (GAO 1991).

In its draft report (dated August 1991), GAO recommended a number of options, two of which have relevance here: (1) "classify all hot desert allotments as ephemeral, thereby eliminating the operators' preference and giving BLM the opportunity to calculate and authorize grazing levels annually" and (2) "discontinue livestock grazing in hot desert areas. Interior's response—the final 1991 report (GAO 1991) contains Interior's comments to the draft report and GAO's responses—to the first option was predicated on the observation that the Chihuahuan Desert consisted primarily of perennial vegetation and that some of the area considered by the GAO included forests and productive rangeland (presumably this could be referring to semidesert grasslands). Interior contended that on this basis some of the allotments considered in the report, with a focus on those occurring in the Chihuahuan Desert, should not be classified as ephemeral. Interior left standing the appropriateness of the classification recommendation for the Sonoran and Mojave Deserts. The GAO revised this option in the final report, but retained its primary thrust that BLM needed the ability to adjust livestock stocking rates on a seasonal basis. Interior's response to the second option primarily was an objection to a blanket exclusion policy. Instead, it contended that an assessment of whether to continue livestock grazing in hot deserts should be related to whether appropriate levels of grazing intensity could be established area by area rather than a blanket assumption that grazing use in all hot desert areas should be discontinued. Although it agreed with Interior's comment, the GAO did not revise this latter option as it concluded that because BLM did not have the resources to properly manage the intensity of livestock grazing in hot deserts the option of discontinuing livestock grazing should be retained for consideration.

Despite the level of controversy over grazing in the hot deserts of the U.S., as exemplified by the GAO report discussed above (GAO 1991), few comprehensive literature reviews have been conducted of livestock grazing impacts that are relevant to the Sonoran Desert ecosystem. The GAO report arrived at its conclusions and recommendations without a well-documented review of the scientific literature on grazing impacts and ecosystem dynamics. Moreover, the discussion above points out that conclusions about impacts and grazing management recommendations specific to the Sonoran Desert may have become confounded by GAO trying to address all three deserts at once.

Numerous literature reviews have been conducted on the impacts of livestock grazing on plant communities, but each had a large geographic focus, such as for all of the western states or the Southwest (for examples, see Milchunas and Lauenroth 1993, Fleischner 1994, Jones 2000, Jones 2001, Milchunas In Press). Other reviews have looked at the impacts of grazing on a smaller focal area, but either for largely semiarid environments where livestock grazing is typically more productive than in hot deserts, such as in the semidesert grasslands of mostly southeastern Arizona, southern New Mexico, and northern Mexico, or the Chihuahuan Desert (Holechek and others 2004a). Even the more recent textbooks on range management (for example, Holechek and others 2004b) largely overlook the Sonoran Desert in their discussions of rangeland management. Holechek and others (2004b:102) suggested that "because of low forage production and grazing resistance, livestock grazing is not practical in much of the Mojave and Sonoran Deserts." He predicted that the rapidly growing human population characteristic of the Sonoran Desert and growing interest in other types of land uses—presumably the source of grazing resistance—would cause significant future reductions in available rangeland. As of today, however, millions of acres of public and private land in the Sonoran Desert still are used for livestock production.

Given the lack of comprehensive literature reviews relevant to the Sonoran Desert and BLM's assessment needs for the SDNM and across the Sonoran Desert in general, clearly a review of this nature would fill a significant information gap.

1.2 PURPOSE AND SCOPE

The purpose of this report is to address the need identified in section 1.1. Specifically, this report is intended to provide the BLM with information about the state of our knowledge, as indicated by a review of primarily the primary scientific literature, on livestock grazing impacts and grazing management strategies applicable to the Sonoran Desert. Within this context, BLM's Phoenix Field Office posed several specific questions related to livestock grazing impacts in the Sonoran Desert. Specifically, the BLM asked The Nature Conservancy in Arizona (Conservancy) to evaluate the literature relative to how livestock grazing in the Sonoran Desert affects:

- composition, structure, and function of plant communities
- saguaro recruitment and survival
- other individual components of plant communities (such as rare plants)
- soils and biological soil crusts
- wildlife, including non-game species
- cultural sites.

This report also assesses the literature relative to currently practiced grazing management strategies. Moreover, it describes the important characteristics of and the driving ecological processes that shape the plant communities and abiotic features of the Sonoran Desert. This latter information is used to provide a context for understanding the impacts of livestock grazing in the Sonoran Desert and for drawing resultant conclusions. In particular, the roles of climate, based in part on an analysis of local weather data, vegetation response, and range ecology theory are highlighted in terms of how they may inform the selection of particular grazing strategies. All of the above information is synthesized and used to construct sets of general conclusions. Section 2.3 provides a more detailed description as to how this report is organized.

The information contained in this report is broadly applicable to the Arizona Upland and Lower Colorado River Valley subdivisions of the Sonoran Desert (see section 2.1.1). This report does not evaluate the literature regarding perennial or intermittent stream-associated riparian habitats that occur within the Sonoran Desert. We note here at the outset that inconsistent use of terminology can at times obscure the relevance of certain pieces of literature or specific findings. Terms such as arid and semiarid, deserts, semidesert and desert grasslands, and the boundaries of particular geographic regions such as the Sonoran Desert have not been defined or used consistently in the literature. This undoubtedly has led to confusion about the applicability of certain findings. In the appropriate sections of this report, we have attempted to define our use of the preceding terms and boundaries so that the applicability of our findings and conclusions are clear. We also have relied on appropriate references (for example, SRM 1989) to define our use of grazing management terminology.

We expect that this review will be of interest not only to BLM, but also to other land management agencies, natural resource managers, academic researchers, and conservation practitioners concerned with livestock management in the Sonoran Desert. It is our goal that this literature review contributes to the general knowledge of Sonoran Desert ecosystem dynamics, livestock grazing impacts on Sonoran Desert ecosystems, and grazing management strategies appropriate to the Sonoran Desert.

CHAPTER 2 APPROACH

In this chapter we present 3 main topics: (1) the methods used to search for, compile, and evaluate appropriate literature on livestock grazing impacts and management strategies, including a description of the oversight and review process; (2) an overview of the literature compiled and evaluated; and (3) a description of how the remainder of the report is organized.

2.1 METHODS

In the sections that follow we first describe the scope of our literature search and search methods. We then describe how we constructed an Access database to track each citation record and information derived from the literature. A subsequent section addresses other sources of information that we considered. We conclude with a description of our oversight and review process.

2.1.1 Scope of Search

We focused our literature review on studies that evaluated the effects of livestock grazing and its management within the Sonoran Desert. We also included studies conducted in other geographic regions that have ecological similarities to the Sonoran Desert when the study contributed some broader insights into an understanding of impacts or management approaches. These studies generally were used to compensate for the lack of studies specific to the Sonoran Desert. Moreover, we included studies conducted outside the Sonoran Desert that assessed the effect of livestock grazing on species whose range included the Sonoran Desert.

For the purpose of this review, our boundary definition of the Sonoran Desert conforms to the ecoregional boundary delineated by Marshall and others (2000), which is based largely on Brown and Lowe (1980) (Figure 2.1).[2] Based on Marshall and others' (2000) delineation, the Sonoran Desert encompasses four subdivisions: the Arizona Upland, Lower Colorado River Valley, Plains of Sonoran, and Central Gulf Coast. Only the first two subdivisions occur in the United States (U.S.) and our literature review and findings are mostly applicable to these two subdivisions. The boundaries of other ecoregions mentioned in this report, such as the Mojave Desert and Apache Highlands (the semidesert grasslands and Sky Island Mountains in southeastern Arizona and surroundings), also are shown in Figure 2.1. Ecoregional boundaries are conservation planning boundaries and as such may not conform to other geographic depictions meant to serve other purposes. For example, although the Mojave, Sonoran, and Chihuahuan Desert boundaries in Figure 2.1 largely conform to other spatial depictions of these three deserts (at least in the U.S.), the Great Basin Desert is subdivided among a number of ecoregions (for example, the Columbia Plateau, Great Basin, and Colorado Plateau ecoregions).

---

[2] An ecoregion is a large area of land and water—on the scale of tens of millions of acres—that shares similar climate, topography, and biological communities.

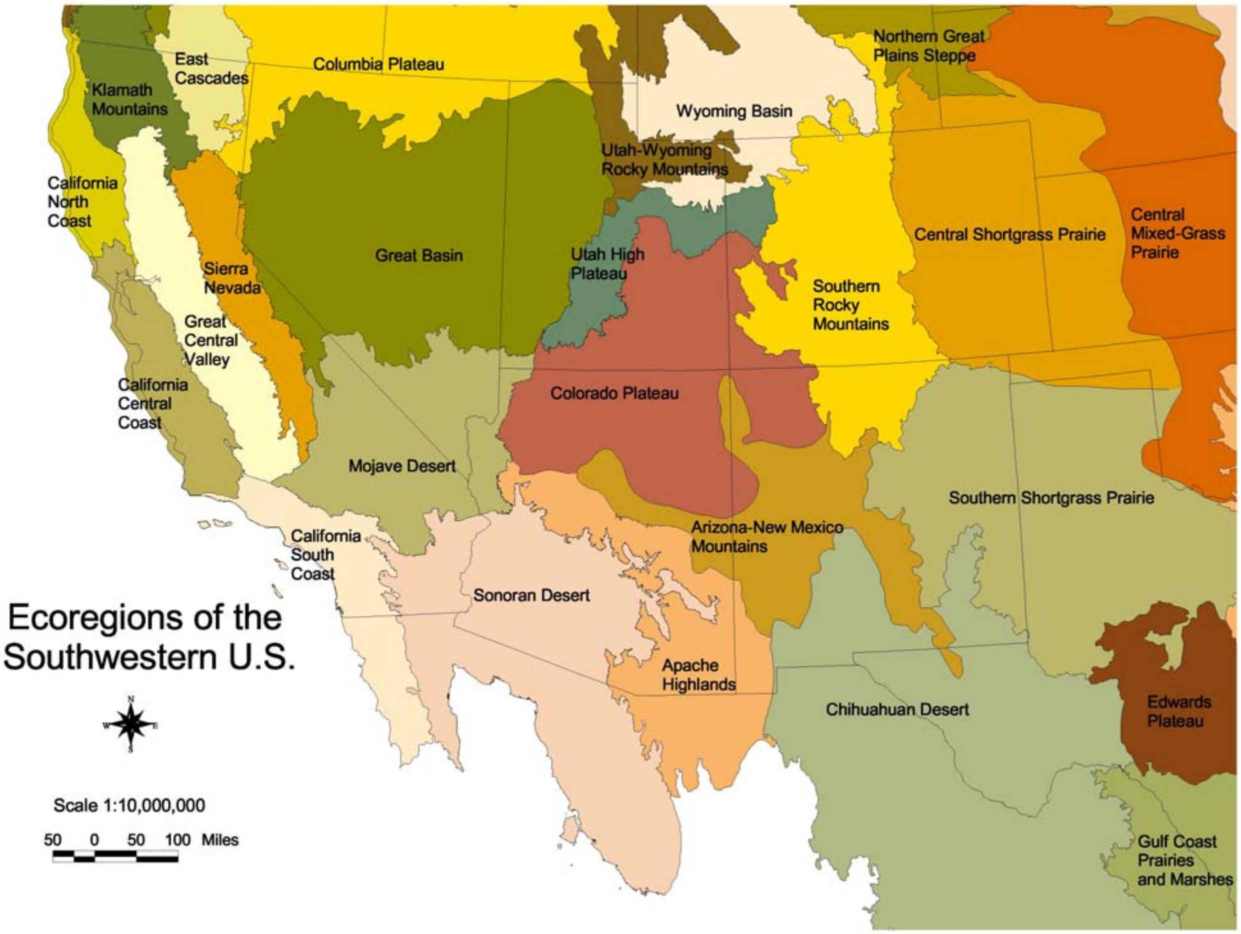


FIGURE 2.1 Ecoregional Boundaries of the Southwestern United States

To limit the scope of our analysis and focus on the most relevant topics of concern to the Bureau of Land Management (BLM), for individual species impacts we narrowed our evaluation of the effects of livestock grazing (primarily cattle grazing) to those species that are present on or in the vicinity of the Sonoran Desert National Monument (SDNM). In addition, we did not review any literature on the impact of livestock grazing on perennial or intermittent stream-associated riparian habitats. The literature is fairly extensive regarding livestock grazing in these habitats and would have expanded the scope of this review quite substantively if included.

2.1.2 Search Methods and Literature Acquisition

We searched for studies on livestock grazing using a multitude of sources. We searched 15 scientific indices that we accessed from on-line sources subscribed to by The Nature Conservancy (Conservancy) or the University of Arizona. In addition to scientific indices, we searched for relevant papers from the Conservancy's library in Tucson (currently with over 5,200 holdings) and on other search engines, including the Journal of Range Management (http://saint-denis.library.arizona.edu:4000/cgi-bin/JRMLogon.cgi) and the University of Arizona's library holdings database (http://80-sabio.library.arizona.edu.ezproxy.library.arizona.edu/search/).

We also identified relevant papers by accessing recent bibliographies and databases, including a database on livestock grazing literature that was compiled by the Center for Biological Diversity (available for download at: http://www.sw-center.org/swcbd/Programs/grazing/grazingbib.html) and a comprehensive bibliography on biological soil crusts (http://www.soilcrust.org/refer.htm). Initial searches were conducted between April 10 and June 15, 2004. A subsequent search regarding the Sonoran pronghorn (*Antilocapra americana sonoriensis*) was conducted in response to reviewer comments to the draft report. The list of indices and other sources that were searched can be found in Table 2.1.

TABLE 2.1 Sources Used in Literature Searches

Source	Date Range
Academic Search Premier	1980 – May 2004
Agricola	1984 – May 2004
Agricultural Research Service TEKTRAN	Varies
Agris	1991 – March 2004
Arid Lands Library	Varies
Article First	1990 - May 2004
BioOne	Varies by journal title
Biosis Previews	1969 – June 2004
Blackwell Synergy	Varies by journal title
CAB Abstracts	1972 – April 2004
Desert Plants	1979 - 2001
Dissertation Abstracts	1861 – May 2004
EBSCOhost	1975 – June 2004
ESA Conferences	2001, 2002
ESA Journals	From first issues
GeoBase	1980 – May 2004
GeoRef	1785 – June 2004
Injenta	1900 – June 2004
Jornada Experimental Range	Varies
Journal of Range Management	Varies
NTIS	1983 – May 2004
SpringerLINK	Varies by journal title
SWIN NBII	Varies
University of Arizona Desert Laboratory	Varies
University of Arizona Library	Varies
Web of Science	1945 – May 2004
Wildlife & Ecology Studies Worldwide	1935 – May 2004

Keywords that were used for searching these indices were usually tried in various combinations (such as “Sonoran Desert” and “grazing”; or “bighorn” and “Arizona” and “grazing”). The list of keywords used in searches can be found in Table 2.2. Note that not every keyword or combination of keywords was used to search each index or search engine listed in Table 2.1. Once we had a list of titles pulled from the indices using keywords, we assessed whether the paper seemed relevant to the purpose of the review based on the paper’s title and abstract.

We also determined additional literature needs by reviewing the literature cited sections of the literature we initially reviewed. At times this led to identifying additional relevant literature. We included books, book chapters, journal articles, conference proceedings, technical reports, and theses and dissertations in our review, but we placed the highest priority on evaluating peer-reviewed literature (journal articles). We acquired copies of the literature from on-line journals (subscribed to by the Conservancy or University of Arizona), from the University of Arizona library holdings, and from interlibrary loans. We made two archival copies of each relevant piece of literature, one for the BLM and one for Conservancy, unless this involved copyrighted books or pieces of literature too large to copy.

2.1.3 Database Construction and Data Entry

Citation information for each piece of literature selected for inclusion in our analysis of livestock grazing impacts and management strategies was first entered into a bibliographic database (ProCite version 5.0 software). Abstracts were acquired (when available) in one of the following ways: (1) by downloading them from on-line sources directly into ProCite, (2) by digitally scanning photocopies using optical character recognition software, or (3) by typing the abstracts into ProCite. We used ProCite because it is the software used by the Conservancy for maintaining library holdings and because of its capability of accepting citation information and abstracts directly from online sources, which greatly minimizes the time and labor required for data entry. The ProCite database was constructed only for the Conservancy’s use and will not be distributed to the BLM.

We then designed a database in Access 2000 to store the citation information and notes on each piece of literature. The database was constructed for both the BLM and Conservancy’s use. We produced a form for data entry and retrieval with three pages (“tabs”) for each piece of literature or reference (see Appendix B). The first page contains basic information about the reference: its citation, abstract, whether it was peer-reviewed or not (“grey literature”), whether it was an empirical study or review, and the geographic location addressed. This page also indicates whether the reference was cited in the report and its overall level of review within the database (see below). The second page includes detailed annotations on the reference, including its main questions or hypotheses, the methods it used, and its main findings and limitations. The third page identifies which questions/topics of interest to the BLM that the reference addresses and a brief summary of the main findings relating to each of the questions/topics.

We produced a data dictionary with information on each field (visible in the Design View of the Grazing Literature Table). Numerous queries were constructed to be able to summarize various attributes of the literature, such as the number of references that addressed a particular topic in each ecoregion. We identified and acquired many more references than what we were able to

TABLE 2.2 Keywords Used in Searches[1]

Category	Specific Keyword
General Topics	Arizona
	Colorado Desert
	Desert
	Exclosure
	Fencing
	Grassland
	Grazing
	Livestock
	Rangeland water
	Semi-desert grassland
	Sonoran Desert
	Xeroriparian
Plants	Acuna cactus (*Echinomastus erectrocentrus* var. *acunensis*)
	Erodium
	Invasives
	Janusia (*Janusia gracilis*)
	Saguaro (*Carnegiea gigantea*)
	Schismus
	Tobosa (*Pleuraphis mutica* or *Hilaria mutica*)
	Tumamoc globeberry (*Tumamoca macdougallii*)
	Vegetation
Soils and Biological Soil Crusts	Biotic soil
	Cryptobiotic
	Cryptogamic
	Microbiotic soil
	Soil
	Soil crust
Wildlife	Ants
	Bighorn sheep (*Ovis canadensis*)
	Cactus ferruginous pygmy-owl (*Glaucidium brasilianum cactorum*)
	Desert bighorn sheep (*Ovis canadensis mexicana*)
	Desert tortoise (*Gopherus agassizii*)
	Lesser long-nosed bat (*Leptonycteris curasoae yerbabuenae*)
	Lizard
	Mule deer (*Odocoileus hemionus*)
	Pronghorn (*Antilocapra americana*)
	Reptile
	Rodent
	Sonoran pronghorn (*Antilocapra americana sonoriensis*)

[1] See text for details.

completely annotate in the database during the course of this project. As a result, many of the records in the Access database are lacking detailed notes, particularly on page 2 of the Grazing Literature Form. In addition, many of the references that we compiled and placed in the database were not evaluated as part of the report and cited in Chapter 12. Many of these were references that dealt with livestock grazing impacts and management strategies outside the Sonoran Desert. Still other references dealt with the impacts of off-road vehicles. Reviewers of the draft report recommended most of this literature to us. We have included those references not cited in the report in the database to provide the BLM a broader access to the literature that addresses livestock grazing and non-grazing impacts.

For quick reference, page 1 of the database indicates the level of review and annotation contained in the database for each piece of literature compiled. Three levels of review are considered. Level 1 includes: basic citation information, abstract (if available), and an indication of which questions/topics (using radial buttons) the reference addressed (both main and other topics). Level 2 includes Level 1 information plus a brief summary of the main findings relating to each of the questions/topics addressed. Level 3 includes the information from Levels 1 and 2 plus the information on page 2 related to the reference's main questions or hypotheses, the methods it used, and its main findings and limitations. All references in the database are annotated to at least Level 1.

2.1.4 Other Sources of Information

To evaluate the impact of livestock grazing on the Sonoran Desert ecosystem, it is necessary to have some understanding of ecosystem dynamics in the absence of grazing pressures, the ecosystem's evolutionary relationship to grazing by large herbivores, and the interaction of grazing with other anthropogenic disturbances and natural ecological processes. In a parallel, but smaller, effort relative to that described in section 2.1.2, we searched for and compiled scientific literature that addressed general characteristics of Sonoran Desert plant communities, climatic patterns, and other key biotic and abiotic factors influencing vegetation dynamics and biological soil crusts. We also downloaded climate data from weather stations at several localities throughout the Sonoran Desert from the Western Regional Climate Center (http://www.wrcc.dri.edu/). Although we refer to numerous studies on Sonoran Desert vegetation dynamics and other relevant background material in this report, the majority of them are not included in the Access database unless they also specifically addressed livestock grazing. We consulted approximately 150 pieces of literature to develop the appropriate ecological context in which to view the impacts of livestock grazing in the Sonoran Desert and to assess appropriate management strategies. We did not supply BLM archival copies of this latter type of literature.

2.1.5 Oversight and Review Process

Livestock grazing is a politically charged issue. To ensure that we were accessing the most appropriate and best available information, and to ensure we included numerous expert reviewers on the topic that could represent diverse viewpoints and disciplines, we formed several review committees to provide guidance and oversee our work. A committee of Conservancy and Sonoran Institute scientists and managers from their respective Tucson offices (the "internal review committee") provided comments on the database design and report structure, suggested key people to contact for information and to act as potential external reviewers, and reviewed draft information for presentation quality and reasonableness of conclusions drawn from the literature (see Table 2.3). The BLM also formed its own internal review committee to serve a similar function but with its primary focus on content accuracy in the draft report. The BLM also communicated with its statewide Resource Advisory Council (RAC) on the purpose and status of the project. Finally, we established an "external review committee" of scientists, range management professionals, agency staff, and other experienced individuals.

TABLE 2.3 Internal Review Committee Members

First Name	Last Name	Title and Affiliation
Nina	Chambers	Associate Director, Sonoran Desert Program, Sonoran Institute
Tom	Collazo	Director of Conservation, The Nature Conservancy
John	Hall	Sonoran Desert Program Manager, The Nature Conservancy
Rob	Marshall	Director of Science, The Nature Conservancy
Cheryl	McIntyre	Graduate Intern, Sonoran Institute
Peter	Warren	Grasslands Conservation Program Manager, The Nature Conservancy
Stephanie	Weinstein	Conservation Planner, The Nature Conservancy

The external review committee members provided us with guidance on: (1) important literature to include in our assessment, (2) information on Sonoran Desert vegetation dynamics, and (3) information relative to the potential to develop state-and-transition models appropriate to Sonoran Desert ecological systems. The external review committee members also agreed to review a draft of the report and to provide us with written comments. We have addressed these comments to the extent possible in the final version of this report. Numerous other people that we contacted as potential, external review committee members also provided us with suggestions and advice on the project, but for various reasons these individuals were unable to commit to review the draft report. The list of external reviewers (16 in total) and others that provided us with information is presented in Table 2.4.

2.2 OVERVIEW OF LITERATURE EVALUATED

We compiled a total of 260 references on livestock grazing impacts or management strategies. Table 2.5 shows the number of references compiled broken down by their geographic focus (ecoregion), the main topic (question) the reference addressed, and if the reference was from the primary literature (peer-reviewed journals) or grey literature (technical report, book, conference proceeding, thesis, and so on). Note that only one main topic was selected per reference, so the total number of references on some topics will be underestimated. For example, if a study evaluated primarily changes in bird communities in response to livestock grazing but also recorded associated differences in vegetation structure, we likely recorded the study as "Wildlife Impacts" and therefore the number of references addressing "Vegetation/Community Impacts"

TABLE 2.4 External Review Committee Members and/or Individuals Contacted for Information

First Name	Last Name	Affiliation	Reviewed Draft Report?
Roy	Averill-Murray	Formerly Arizona Game and Fish Department; now U.S. Fish and Wildlife Service	Yes
Jayne	Belnap	U.S. Geological Survey	Yes
Brandon	Bestelmeyer	Jornada Experimental Range	Yes
Jane	Bock	University of Colorado, Audubon Research Ranch	No
Matt	Brooks	U.S. Geological Survey	Yes
Tony	Burgess	Professional botanist (formerly at Biosphere 2)	Yes
Russ	Engel	Arizona Game and Fish Department	Yes
Todd	Esque	U.S. Geological Survey	No
Tom	Fleischner	Prescott College	No
Jerry	Holechek	New Mexico State University	No
Allison	Jones	The Wild Utah Project	Yes
Paul	Krausman	University of Arizona	Yes
Joe	McAuliffe	Desert Botanical Garden	Yes
Daniel	Milchunas	Colorado State University	Yes
Marcia	Narog	U.S. Forest Service	No
Phil	Ogden	University of Arizona (Emeritus)	Yes
Dan	Robinett	Natural Resources Conservation Service	Yes
Sue	Rutman	Organ Pipe Cactus National Monument	Yes
George	Ruyle	University of Arizona	Yes
Nathan	Sayre	University of Arizona	No
Cecil	Schwalbe	University of Arizona	No
Ray	Turner	Desert Laboratory, Tumamoc Hill	Yes
Bob	Unnasch	The Nature Conservancy	Yes

would be underrepresented. The majority (188) of the 260 references were from the primary literature. Forty-two references focused on livestock grazing in the Sonoran Desert and an additional 46 references were associated with multiple ecoregions, but they included information on either the Sonoran or the Mojave Desert (Table 2.5). Complete citations for each of the 260 references are included in Appendix C.

We reviewed and cited in this report only a subset of the 260 references compiled. We focused on Sonoran and Mojave Desert literature, literature on species whose range extends into the Sonoran Desert even though the study was conducted in another region (for example, studies on mule deer in the Apache Highlands Ecoregion), and on literature that addressed a topic for which we had little or no information from studies in the Sonoran or Mojave Desert. Because there is no sharp ecological division between the Mojave and Sonoran Deserts and they share many biotic and abiotic features, we prioritized studies conducted in the Mojave Desert over other

TABLE 2.5 Count of All References Compiled by Main Topic, Source Type, and Ecoregion

Main Topic[1]	**Source type[2]**	**Sonoran Desert**	**Mojave Desert**	**Multiple (w/ SD or MD)[3]**	**Apache Highlands**	**AZ-NM Mountains**	**Colorado Plateau**	**Chihuahuan Desert**	**Great Basin**	**Multiple (w/o SD or MD)[3]**	**N/A[4]**	**Other[5]**	**Total[6]**
Cultural Site Impacts	Grey	0	0	0	0	0	0	0	0	0	0	0	0
	Primary	0	0	0	0	0	0	0	0	0	0	0	0
Grazing Strategies	Grey	1	0	2	0	0	0	1	0	1	2	0	7
	Primary	2	1	5	4	1	1	1	0	2	16	5	38
Non-grazing Impacts	Grey	0	2	2	0	0	0	1	0	0	0	0	5
	Primary	0	7	0	0	0	0	1	0	0	0	1	9
Other (Plant) Species Impacts	Grey	0	0	0	0	0	0	1	0	0	0	0	1
	Primary	3	0	1	0	0	2	1	0	0	1	2	10
Saguaro Impacts	Grey	4	0	1	0	0	0	0	0	0	0	0	5
	Primary	4	0	0	0	0	0	0	0	0	0	0	4
Soil and Biological Soil Crust Impacts	Grey	2	0	3	0	0	0	0	0	2	1	1	9
	Primary	1	2	3	1	0	4	1	3	2	0	2	19
Vegetation/Community Impacts	Grey	7	3	3	2	0	1	2	0	1	2	2	23
	Primary	11	2	7	12	3	1	6	1	2	12	8	65
Wildlife Species Impacts	Grey	6	0	11	1	0	0	1	0	1	0	2	22
	Primary	1	3	8	10	0	0	2	3	4	0	12	43
Total	**Grey**	**20**	**5**	**22**	**3**	**0**	**1**	**6**	**0**	**5**	**5**	**5**	**72**
	Primary	**22**	**15**	**24**	**27**	**4**	**8**	**12**	**7**	**10**	**29**	**30**	**188**
	Total	**42**	**20**	**46**	**30**	**4**	**9**	**18**	**7**	**15**	**34**	**35**	**260**

[1] One main topic selected per reference.

[2] Source type: Where is the reference published? Primary=peer-reviewed journal; Grey=from a source in which there is not the same rigorous peer review process for publication, such as books, technical reports, theses and dissertations, or conference proceedings. Some of these sources, such as books and conference proceedings, may be subject to some peer review, but we included them as grey literature because the level of peer review is unknown.

[3] The reference addresses multiple ecoregions. SD= Sonoran Desert, MD= Mojave Desert

[4] N/A= Not applicable. Includes conceptual papers or general references that are not focused on any one particular geographic area.

[5] Other ecoregion not included in this list.

ecosystems because results also may be relevant to the Sonoran Desert. Throughout the text we have tried to be clear as to when a study was conducted within the Sonoran Desert and when it was not so that any inferences we make about the applicability of a particular piece of literature are transparent.

Table 2.6 shows the number of references that we reviewed and cited in the report, broken down by ecoregion, main topic, and source type (primary or grey literature). Table 2.7 is similar to Table 2.6 except that instead of breaking down the references as primary or grey literature, it shows the number that are empirical (in which data were gathered by the authors on a particular topic) or review papers (that summarize the main findings of others' work on a particular topic). Although review papers do not include any new data on a subject, they are useful in an analysis such as the one we are conducting here because they expose the reader to broader patterns of results and a breadth of information from numerous sources that might not be available otherwise. We reviewed a total of 62 review papers (Table 2.7). We also summarized the total number of times a topic was addressed in the literature, including instances where multiple topics were addressed in a single reference (Table 2.8). For example, if a study evaluated changes in both plant communities and soil properties in response to livestock grazing, each of these topics would be tallied. As a result, the total count of each topic in Table 2.8 is greater than the total number of references reviewed.

Each of the references that we reviewed has its own strengths and weaknesses. Some studies were well-designed experiments with rigorous methods and thorough interpretations of results and alternative hypotheses. Other studies did not convincingly rule out alternative hypotheses to explain their results, did not address confounding variables, or had faulty experimental design. The grazing literature database includes annotation on the questions posed, methods, main findings, and any limitations or important caveats associated with a number of (but not all) the empirical studies evaluated in this review. We discuss as appropriate, however, the general characteristics or limitations of each of the impact or management strategy references that we cite in this report. We accomplish this in each of the appropriate subsequent chapters that address one of the question/topic areas (Chapters 4 to 10).

2.3 ORGANIZATION OF THE REPORT

Chapter 1 discussed the need, purpose, and scope of this report. Here in Chapter 2, we outlined our approach towards conducting the literature review. In the following chapter, Chapter 3, we set the ecological context for a management unit of interest to BLM, relative to grazing administration decisions, by describing the abiotic and community-level biotic conditions that exist on the SDNM and surroundings. We include brief descriptions of the plant communities and habitats that have been mapped on the SDNM, and we also include analyses of climatic data (primarily precipitation) from weather stations in the vicinity of the SDNM and in other parts of the Sonoran Desert.

Chapters 4 through 8 each synthesize the literature on how livestock grazing impacts a component of the Sonoran Desert ecosystem, including: plant community composition, structure, and function (Chapter 4); saguaro recruitment and survival (Chapter 5); other plant species (Chapter 6); soils and biological soil crusts (Chapter 7); and wildlife (Chapter 8). To

TABLE 2.6 Count of References Reviewed and Cited in this Report by Main Topic, Source Type, and Ecoregion (subset of all the references compiled)[1]

Main Topic	**Source type**	**Sonoran Desert**	**Mojave Desert**	**Multiple (w/ SD or MD)**	**Apache Highlands**	**AZ-NM Mountains**	**Colorado Plateau**	**Chihuahuan Desert**	**Great Basin**	**Multiple (w/o SD or MD)**	**N/A**	**Other**	**Total**
Cultural Site Impacts	Grey	0	0	0	0	0	0	0	0	0	0	0	0
	Primary	0	0	0	0	0	0	0	0	0	0	0	0
Grazing Strategies	Grey	1	0	1	0	0	0	1	0	1	2	0	6
	Primary	1	1	2	1	0	0	0	0	2	11	1	19
Non-grazing Impacts	Grey	0	0	1	0	0	0	0	0	0	0	0	1
	Primary	0	0	0	0	0	0	0	0	0	0	0	0
Other (Plant) Species Impacts	Grey	0	0	0	0	0	0	0	0	0	0	0	0
	Primary	3	0	0	0	0	0	0	0	0	1	2	6
Saguaro Impacts	Grey	3	0	1	0	0	0	0	0	0	0	0	4
	Primary	3	0	0	0	0	0	0	0	0	0	0	3
Soil and Biological Soil Crust Impacts	Grey	2	0	3	0	0	0	0	0	0	0	0	5
	Primary	1	0	3	1	0	2	0	1	0	0	1	9
Vegetation/Community Impacts	Grey	4	1	2	1	0	1	0	0	0	1	0	10
	Primary	10	2	4	3	1	1	0	0	2	11	4	38
Wildlife Species Impacts	Grey	4	0	9	1	0	0	0	0	0	0	1	15
	Primary	1	3	7	7	0	0	2	1	1	0	10	32
Total	**Grey**	**14**	**1**	**17**	**2**	**0**	**1**	**1**	**0**	**1**	**3**	**1**	**41**
	Primary	**19**	**6**	**16**	**12**	**1**	**3**	**2**	**2**	**5**	**23**	**18**	**107**
	Total	**33**	**7**	**33**	**14**	**1**	**4**	**3**	**2**	**6**	**26**	**19**	**148**

[1] See footnotes for Table 2.5 for explanations of column headings.

TABLE 2.7 Count of References Reviewed and Cited in this Report by Main Topic, Literature Type, and Ecoregion (subset of all the references compiled)[1]

Main Topic	Lit type[2]	Sonoran Desert	Mojave Desert	Multiple (w/ SD or MD)	Apache Highlands	AZ-NM Mountains	Colorado Plateau	Chihuahuan Desert	Great Basin	Multiple (w/o SD or MD)	N/A	Other	Total
Cultural Site Impacts	Empirical	0	0	0	0	0	0	0	0	0	0	0	0
	Review	0	0	0	0	0	0	0	0	0	0	0	0
Grazing Strategies	Empirical	1	1	0	1	0	0	0	0	0	1	0	4
	Review	1	0	3	0	0	0	1	0	3	12	1	21
Non-grazing Impacts	Empirical	0	0	0	0	0	0	0	0	0	0	0	0
	Review	0	0	1	0	0	0	0	0	0	0	0	1
Other (Plant) Species Impacts	Empirical	3	0	0	0	0	0	0	0	0	0	1	4
	Review	0	0	0	0	0	0	0	0	0	1	1	2
Saguaro Impacts	Empirical	6	0	1	0	0	0	0	0	0	0	0	7
	Review	0	0	0	0	0	0	0	0	0	0	0	0
Soil and Biological Soil Crust Impacts	Empirical	3	0	2	1	0	2	0	1	0	0	1	10
	Review	0	0	4	0	0	0	0	0	0	0	0	4
Vegetation/Community Impacts	Empirical	14	3	1	3	1	1	0	0	1	1	4	29
	Review	0	0	5	1	0	1	0	0	1	11	0	19
Wildlife Species Impacts	Empirical	4	3	3	7	0	0	2	1	1	0	11	32
	Review	1	0	13	1	0	0	0	0	0	0	0	15
Total	**Empirical**	**31**	**7**	**7**	**12**	**1**	**3**	**2**	**2**	**2**	**2**	**17**	**86**
	Review	**2**	**0**	**26**	**2**	**0**	**1**	**1**	**0**	**4**	**24**	**2**	**62**
	Total	**33**	**7**	**33**	**14**	**1**	**4**	**3**	**2**	**6**	**26**	**19**	**148**

[1] See footnotes for Table 2.5 for explanations of column headings.

[2] Lit Type: Empirical: the study conducted original research and data collection; Review: the reference is primarily a review of others' work.

TABLE 2.8 Count of All Topics Addressed in Reviewed and Cited References by Literature Type and Ecoregion (subset of all the references compiled)[1]

Topic Addressed	Lit type	Sonoran Desert	Mojave Desert	Multiple (w/ SD or MD)	Apache Highlands	AZ-NM Mountains	Colorado Plateau	Chihuahuan Desert	Great Basin	Multiple (w/o SD or MD)	N/A	Other	Total
Cultural Site Impacts	Empirical	0	0	0	0	0	0	0	0	0	0	0	0
	Review	0	0	0	0	0	0	0	0	0	0	0	0
Grazing Strategies	Empirical	4	1	0	1	0	0	1	0	0	0	2	9
	Review	1	0	4	0	0	0	1	0	3	12	1	22
Non-grazing Impacts	Empirical	3	2	0	1	0	1	0	0	0	0	1	8
	Review	0	0	1	4	0	0	0	0	0	0	0	5
Other (Plant) Species Impacts	Empirical	5	0	0	0	0	0	0	0	0	0	1	6
	Review	0	0		1	0	0	0	0	0	1	1	3
Saguaro Impacts	Empirical	6	0	2	0	0	0	0	0	0	0	0	8
	Review	0	0	0	0	0	0	0	0	0	0	0	0
Soil and Biological Soil Crust Impacts	Empirical	5	2	2	1	0	2	0	1	1	0	1	15
	Review	0	0	8	1	0	1	1	0	2	1	1	15
Vegetation/Community Impacts	Empirical	16	5	3	7	1	3	0	0	2	2	4	43
	Review	1	0	7	1	0	1	1	0	2	12	0	25
Wildlife Species Impacts	Empirical	5	4	3	8	0	1	2	1	1	0	11	36
	Review	2	0	15	1		1	1	0	0	1	0	21
Total[2]	**Empirical**	**44**	**14**	**10**	**18**	**1**	**7**	**3**	**2**	**4**	**2**	**20**	**125**
	Review	**4**	**0**	**35**	**8**	**0**	**3**	**4**	**0**	**7**	**27**	**3**	**91**
	Total	**48**	**14**	**45**	**26**	**1**	**10**	**7**	**2**	**11**	**29**	**23**	**216**

[1] See footnotes for Tables 2.5 and 2.8 for explanations of column headings.

[2] Totals are greater than the number of references reviewed because some references address multiple topics.

.

properly interpret the literature and understand how livestock grazing may impact each of these ecosystem components, we first need to have an idea of the ecological dynamics associated with each component in the absence of grazing. For example, if we are to understand if livestock grazing impacts saguaro recruitment, we need to understand the factors that influence saguaro recruitment in the absence of livestock grazing or other anthropogenic activities. As a result, we start each of Chapters 4 through 8 with descriptions of the dynamics of the ecosystem component in the absence of grazing and the mechanisms through which livestock grazing may have a direct or indirect impact on that component. Following these initial sections, we review the impacts of livestock grazing as discussed in the literature. We conclude each chapter by summarizing and synthesizing the key points into an overall set of conclusions. We also describe any limitations to the state of our knowledge on each topic.

Chapter 9 address livestock grazing impacts to cultural sites; however, the literature is extremely limited in regard to this topic. Chapter 10 provides an overview of grazing management strategies and their applicability to the Sonoran Desert. This chapter also includes a discussion of range ecology theory and the debate over equilibrium-non-equilibrium dynamics and their associated management model applications. The synthesis of the preceding topics is used to derive conclusions about what may constitute an appropriate grazing management strategy for the Sonoran Desert in the last section of Chapter 10. In Chapter 11 we present a synopsis of the general conclusions we derived from the literature review. Chapter 12 includes complete citation information for all literature that was cited in the report.

We also include several appendices as part of this report. The Proclamation that established the Sonoran Desert National Monument is included in Appendix A. Appendix B is a copy of the Access template for data entry and annotation on the references we compiled related to livestock grazing impacts and management strategies. Appendix C includes the citations for all grazing impact and management strategy references compiled, including those that were not cited in the report. Appendix D provides examples of findings made relative to the main and other questions addressed by a particular reference, as annotated in the database for a representative cross-section of references cited in the report. Appendix E includes all of the comments we received from external reviewers to the draft report, with annotations on how we resolved each of their comments.

CHAPTER 3 THE SONORAN DESERT NATIONAL MONUMENT IN AN ECOLOGICAL CONTEXT

In this chapter we briefly describe the abiotic and community-level biotic conditions that characterize the Sonoran Desert National Monument. In addition, we provide an overview of the objects identified in the Presidential Proclamation that established the Sonoran Desert National Monument (SDNM). Finally, we highlight data on regional and local precipitation and temperature patterns, based on the long-term records of weather stations located along a west to east gradient. Our emphasis is on detailing the inherent variation in precipitation quantity and timing and how that changes across the gradient. The preceding information will be useful in providing an appropriate ecological context for interpreting the literature on livestock grazing impacts and its applicability for informing grazing administration decisions on the SDNM.

3.1 GENERAL DESCRIPTION AND PHYSIOGRAPHY

The SDNM is located about 60 miles southwest of Phoenix. The outer boundaries of the monument encompass 496,337 acres, of which 486,149 acres represent land or interests in land owned or controlled by the United States. The remaining acres are a mix of Arizona State Trust Land and private lands. Figure 3.1 identifies the land administration associated with the SDNM and immediately surrounding areas, as well as the currently existing grazing allotments. Allotments associated with the SDNM are based on the ownership or control of water. None are based on the ownership or control of land.

Elevations on the SDNM range from about 800 feet to over 4,300 feet. The landscape is dominated by three distinct mountain ranges—the Sand Tank Mountains in the southwestern corner of the monument, the Table Top Mountains to the east of the Sand Tanks, and the Maricopa Mountains extending in a northeasterly direction within the northern portion of the monument—and some scattered complexes of smaller hills. The Sand Tank Mountains are shared with the adjoining Barry M. Goldwater Range to the southwest of the SDNM. Its highest peak, Javelina Mountain, tops out at 4,085 feet. Prior to November of 2001, a 77,957-acre portion of the SDNM (the former Area A) was withdrawn from the public domain as a part of the range. This area has not experienced permitted livestock grazing since the early 1940s. Table Top Mountain is the tallest and most massive mountain on the SDNM, with an expansive mesa-like summit that reaches 4,373 feet at its highest point. Mountain summits within the Maricopa Mountains range from roughly 2,700 to 2,900 feet.

The preceding mountain ranges are biologically linked by intervening valleys. Between the Sand Tank and Table Top Mountains lie the Vekol Valley and Wash, the latter of which courses northerly at a low gradient through the southern portion of the SDNM before heading northeasterly after it exits the monument. The valley and wash originate on the adjoining Tohono O'odham Nation. To the northeast of the Maricopa Mountains lies the Rainbow Valley, which runs northwesterly and links the preceding mountains to the Sierra Estrella. The Sierra Estrella lies outside the SDNM to the northeast. To the west and southwest of the SDNM lie

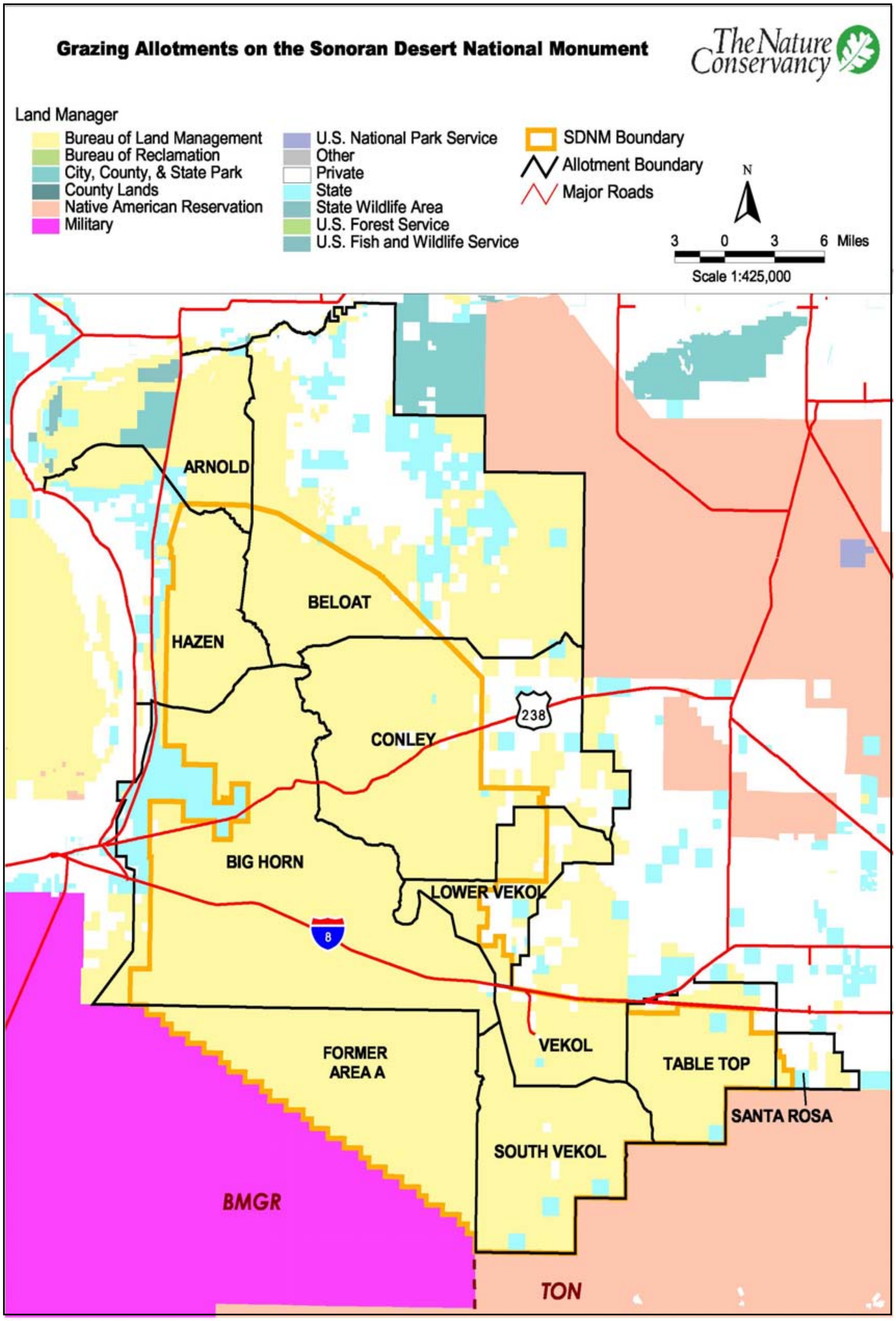


FIGURE 3.1 Land Management and Livestock Grazing Allotments on the Sonoran Desert National Monument and Vicinity

the Gila Bend Plain and Sauceda Valley, respectively. The lowest elevations on the SDNM are located within the Gila Bend Plain. The Sauceda Valley lies between the Sand Tank and Sauceda Mountains.

3.2 GEOLOGY AND SOILS

In the following descriptions dominant rock or sediment type and age are based on the Geologic Map of Arizona (Richard and others 2000). The Maricopa Mountains, especially the North Maricopa Mountains, are primarily granitic rocks. The South Maricopa Mountains also include areas of volcanic, sedimentary, and metasedimentary rocks. The geology of the Sand Tank Mountains is complex and includes large areas of volcanic and metamorphic rocks, along with areas of granitic and sedimentary rocks of different ages. The Table Top Mountains consist mostly of granitic and metasedimentary rocks, but also include several inclusions of volcanic rocks.

The valley floors, Gila Bend Plain, and some bajada (piedmont slope) surfaces are composed of surficial deposits of Holocene and Pleistocene age, with Rainbow Valley containing large areas of primarily Holocene-age surfaces. The bajada surface along the western flank of the Table Top Mountains is of strictly Pleistocene age. The bajada surfaces between the Sand Tank and South Maricopa Mountains and along the eastern flank of the Sand Tank Mountains are older surficial deposits from as early as the Upper Pliocene. Playas and sand dunes are not present on the SDNM.

Soil survey information for the SDNM is incomplete. The formerly withdrawn portion of the SDNM (previously known as Area A) encompassing most of the Sand Tank Mountains lacks a soil survey. The rest of the SDNM is covered by three different state soil survey areas. Our descriptions here of SDNM soils are generalized to their association with Natural Resources Conservation Service ecological sites. Viewed in this way, the mapped areas of the SDNM contain 15 dominant ecological site classes (Morrison and others 2003). Typically the classes are defined in association with a precipitation zone; however, the roll up into 15 classes does not enable distinguishing the precipitation zones. Most of the SDNM is classified as either in the 2 to 7 inch (Lower Sonoran Desert) or 7 to 10 inch (Middle Sonoran Desert) precipitation zone. Portions of the Sand Tank and Table Top Mountains are in the 10 to 13 inch (Upper Sonoran Desert) precipitation zone. We identify the predominant classes in order of the mapped acreage they cover on the SDNM.

The two most extensive ecological site classes are first the Limy Fan and then the Limy Upland, Deep, which combined cover almost half the mapped area of the SDNM and are associated with the surficial deposits of the valley floors and Gila Bend Plain. Next is the Granitic Hills, which covers most of the rocky slopes and summits of the mountain ranges. The bajadas surrounding the Table Top and North Maricopa Mountains are mostly in the Limy Upland class, whereas the upper portion of the Vekol Valley and the bajadas to the north and east of the South Maricopa Mountains can be classified as Sandy Loam, Upland. The Sandy Bottom class is associated with washes throughout the SDNM. The Basalt Hills class is scattered around the Table Top Mountains, a portion of the South Maricopa Mountains, and portions of the mapped northern extent of the Sand Tank Mountains. The Shallow Upland class is associated mostly with bajadas surrounding Table Top and the North Maricopa Mountains. The Schist Hills class occurs within the center of the South Maricopa Mountains and the eastern mapped margin of the Sand Tank Mountains. The last ecological site class that covers any area of significance is the Limy Slopes class, which is associated with bajadas on the southern end of the South Maricopa Mountains and the northern portion of the Sand Tank Mountains. The remaining five ecological site classes cover much smaller areas; in combination they cover only slightly more than half the area of the Limy Slopes class.

Two soil surveys merge just west of the Table Top Mountains. Here the Limy Upland, Deep and Limy Upland ecological site classes occur as a discontinuity across the survey boundary, yet the pattern of the mapped classes implies this discontinuity is artificial. This indicates that soil surveys performed at different times and with potentially different methods may reach different classification conclusions for closely related soil types.

3.3 NATURAL COMMUNITIES

At the scale at which biotic subdivisions are delineated, the SDNM is located mostly within the Arizona Upland Subdivision. Some areas of the SDNM, associated with Rainbow Valley, Gila Bend Plain, and a portion of Vekol Valley, are located within the Lower Colorado River Valley Subdivision. As a result, the SDNM contains plant communities characteristic of both main Sonoran Desert subdivisions occurring in Arizona.

Pacific Biodiversity Institute (PBI) recently mapped and described the natural communities of the SDNM (Morrison and others 2003; Figure 3.2). Natural communities are a combination of traditionally defined plant communities and habitats based in part or primarily on abiotic features. Habitats defined primarily on the basis of abiotic features that occur on the SDNM are rock outcrops and tinajas (bedrock depressions that seasonally hold water), both of which occur primarily within the Arizona Upland Subdivision. All of the remaining natural communities identified by PBI are defined based to a greater or lesser degree on a combination of biotic and abiotic features.

The other Arizona Upland Subdivision-associated communities include Paloverde-Mixed Cacti-Mixed Scrub on Bajadas, Paloverde-Mixed Cacti-Mixed Cacti on Rocky Slopes, Mountain Upland, Desert Grassland, Mountain and Valley Xeroriparian Scrub, and Desert Spring. The first two communities are the matrix[3] communities associated with this subdivision. The Mountain Upland is a large patch community limited to the highest elevations (and mostly northern aspects) of the Sand Tank and Table Top Mountains. It is a botanically diverse community and includes and is defined by a number of species otherwise uncommon in the Sonoran Desert that can tolerate regular freezing temperatures such as crucifixion thorn (*Canotia holocantha*) and Arizona rosewood (*Vaquelinia californica sonorensis*). The Desert Grassland is large patch community, identifiable by its dominant grass component, tobosa grass (*Pleuraphis*

---

[3] Matrix communities form extensive and contiguous cover 5,000 to over 1.2 million acres in size (2,000 to 500,000 ha), whereas large patch communities, in which cover may be interrupted, range from about 125 to 5,000 acres (50 to 2,000 ha) in size and small patch communities form small, discrete areas of cover 2.5 to 125 acres (1 to 50 ha) in size.

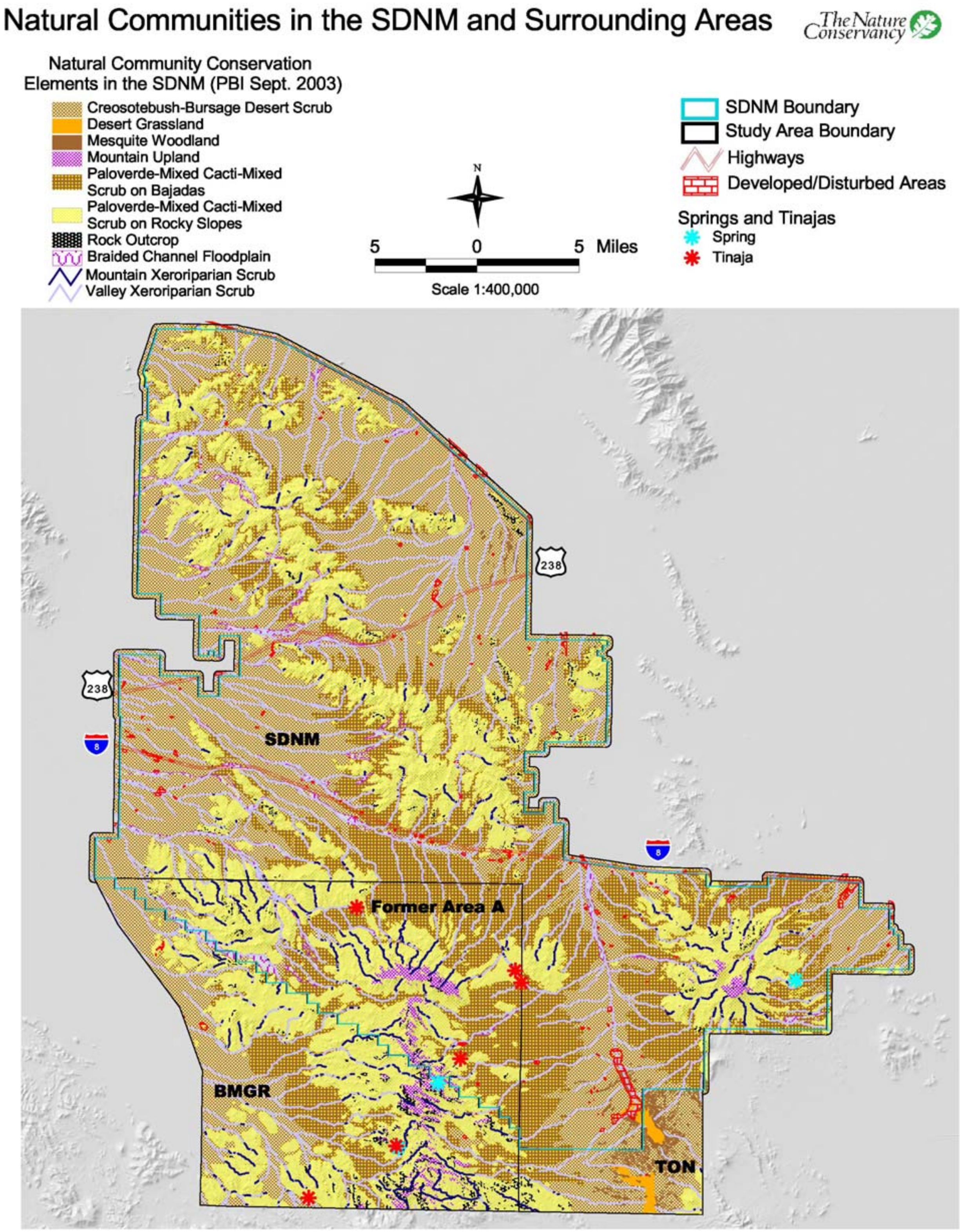


FIGURE 3.2 Natural Communities of the Sonoran Desert National Monument and Adjacent Areas

mutica). This community type is limited in its occurrence on the SDNM to the upper Vekol Valley basin floor. It is not technically a community associated with the Arizona Upland Subdivision but is included here based on its geographic overlap. Mountain Xeroriparian Scrub is a linear community that occurs around and encompasses the seasonal wash beds on the steeper mountain slopes of the SDNM, in which the wash channel is confined to a bedrock substrate. In contrast, Valley Xeroriparian Scrub occurs around and encompasses the seasonal wash beds on the lower bajadas (and basin floor; see below), in which the wash channel is not confined to a bedrock substrate. The Desert Spring community is limited in occurrence on the SDNM. Livestock cattle grazing on the SDNM is mostly confined to the Paloverde-Mixed Cacti-Mixed Scrub on Bajadas, Desert Grassland, and Valley Xeroriparian Scrub communities within the Arizona Upland Subdivision, with some historical exceptions.

Natural communities associated with the Lower Colorado River Valley Subdivision on the SDNM include Creosotebush-Bursage Desert Scrub, Mesquite Woodland, Valley Xeroriparian Scrub, and Braided Channel Floodplain. Creosotebush-Bursage Desert Scrub is the matrix community for this subdivision and occupies the lower bajada and basin floor. As mentioned in the preceding paragraph, the Valley Xeroriparian Scrub community also occurs on the lower bajada and basin floor within this subdivision and dissects the Creosotebush-Bursage Desert Scrub community. On broad floodplain areas within the mountain valleys and along major washes on the bajadas, the Valley Xeroriparian Scrub community intergrades with the Braided Channel Floodplain community. The Braided Channel Floodplain is a large patch community characterized by multiple, cross-braiding channels. Mesquite woodland is a small patch, or at times linear, community that occurs on the basin floor. On the SDNM, mesquite stands are closely associated with water impoundments, xeroriparian communities, and areas that have experienced substantial grazing pressure or periodic flooding. As mapped by PBI, the preceding communities may extend into the Arizona Upland Subdivision, but with the exception of the Valley Xeroriparian Scrub community the overlap is largely an artifact of the mapping accuracy for the subdivision boundary. All of these communities are accessible to livestock grazing on the SDNM.

3.4 SONORAN DESERT NATIONAL MONUMENT: OBJECTS AND ADMINISTRATION

The Antiquities Act (16 U.S.C. 431, Section 2) authorizes the President "to declare by public proclamation historic landmarks, historic and prehistoric structures, and other **objects** of historic or scientific interest that are situated upon the lands owned or controlled by the Government of the United States to be national monuments…." The term "object" is used generically to refer to the preceding unique attributes of an area that make it worthy of designation as a national monument. The proclamation that establishes a particular national monument specifically identifies the objects intended to be protected by monument designation.

The Presidential Proclamation that established the SDNM on January 17, 2001 (Appendix A) identifies numerous biological features, as well as significant archaeological and historical sites, as objects worthy of protection. Several plant communities, similar in description to the natural communities described above, are identified. Unique woodland associations of the higher peaks (Mountain Upland community), complex examples of paloverde-mixed cacti communities, including "abundant saguaro cactus forests," tinajas, desert grassland, creosotebush-bursage, and washes are all identified as objects. A number of individual species, plant as well as animal, also are identified separately as objects in the proclamation.

The SDNM proclamation also identifies administrative restrictions that are established to ensure protection of the identified objects. Specifically included are prohibitions and compatibility standards associated with livestock grazing on the SDNM. South of Interstate 8, which runs west to east and bisects the monument into north and south portions, the proclamation requires that permits on federal lands not be renewed at the end of their current term. Moreover, for federal lands north of the interstate, the proclamation provided that “grazing…shall be allowed to continue only to the extent that the Bureau of Land Management determines that grazing is compatible with the paramount purpose of protecting the objects in this [SDNM] proclamation.” As a result, the SDNM proclamation establishes a compatibility standard that assigns the burden of proof on the compatibility of livestock grazing with object protection.

At present the grazing allotments north of Interstate 8 are administered as perennial-ephemeral allotments, except for the Arnold allotment (Figure 3.1) which is ephemeral only (B. Lambeth, personal communication for the information in this paragraph). The perennial aspect of the allotment permit allows a set year-round stocking density. The ephemeral aspect of the allotment permit allows for application for additional livestock in response to ephemeral forage production. These rates are approved in 30-day increments. Generally, only winter rains provide enough reliable forage to permit ephemeral grazing on the SDNM. It is likely that historic grazing on the SDNM did not reach the stocking rates that may have been realized elsewhere within the Sonoran Desert. Grazing did not occur on the area now occupied by the SDNM until wells were developed in the early 1900s in the Rainbow and Vekol Valley areas. Most of the grazing in the Maricopa Mountains did not occur until after enactment of the Taylor Grazing Act in 1934, which resulted in fenced allotments, set stocking rates, and development of more livestock waters. Over the last 10 years the total numbers of livestock that have actually grazed on the SDNM, including accounting for ephemeral use, have been below the total livestock authorized under the perennial permits.

3.5 STATE-WIDE, REGIONAL, AND LOCAL PRECIPITATION AND TEMPERATURE PATTERNS

Climate is the predominant ecological process that drives vegetation and animal responses in the Sonoran Desert. The most important components are precipitation and temperature. In this section we present relevant historical data on state-wide, regional, and local (within the vicinity of the SDNM) precipitation and temperature. Data originate from weather stations located in southern Arizona and Blythe, California. Figure 3.3 depicts the locations of the primary weather stations used in our data analysis, as well as the boundaries of the Sonoran Desert in Arizona and the SDNM. Table 3.1 provides location and elevation data for each station, as well as the years in which the station was in service. For certain analyses we incorporate data from additional stations not shown in the figure or table.

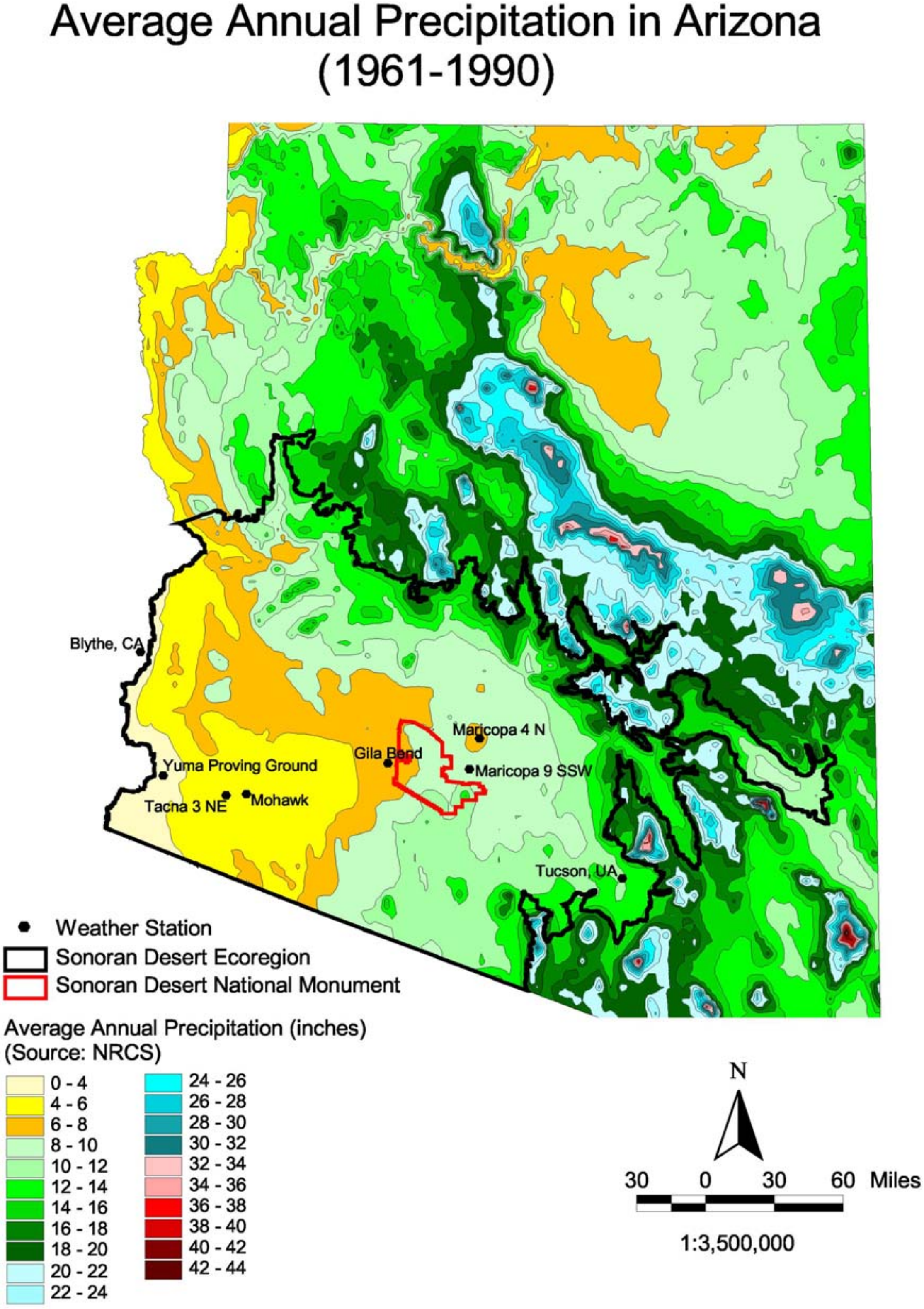


FIGURE 3.3 Average Annual Precipitation in Arizona (1961 to 1990) and Localities of Some Weather Stations in the Sonoran Desert. (Precipitation data source: PRISM, NRCS)

TABLE 3.1 Locations, Elevations, and Years Data were Collected for Eight Sonoran Desert Weather Stations along a West to East Gradient

Weather Station	Latitude	Longitude	Elevation (feet)	Years
Blythe, California	33.6131N	114.5972W	269	1931 to 2004
Yuma Proving Ground	32.8356N	114.3942W	314	1958 to 2004
Tacna 3 NE	32.7217N	113.9183W	301	1969 to 2004
Mohawk	32.7333N	113.7667W	567	1900 to 1951
Gila Bend	32.9481N	112.7131W	728	1892 to 2004
Maricopa 9 SSW	32.9167N	112.1W	1,384	1898 to 1958
Maricopa 4 N	33.1139N	112.0303W	1,141	1960 to 2004
Tucson, University of Arizona	32.2297N	110.9539W	2,398	1894 to 2004

3.5.1 State-Wide Precipitation Patterns

Figure 3.3 also depicts state-wide patterns of precipitation in terms of average annual precipitation based on data compiled from 1961 to 1990. The underlying precipitation data were collected using all available and appropriate weather stations, including local, state, regional, and federal networks. To spatially extrapolate and depict the data across the state, the Natural Resources Conservation Service used a model developed by Oregon State University, the Parameter-elevation Regressions on Independent Slopes Model, or PRISM. This model is a hybrid statistical-geographic approach to mapping climate variables that uses point measurements of data (in this case precipitation data from the weather stations) and a digital elevation model to generate estimates of annual, monthly, and event-based climatic events (see http://www.ncgc.nrcs.usda.gov/branch/gdb/products/climate/ for additional detail).

The precipitation pattern mapped in Figure 3.3 illustrates the overall west to east gradient in total precipitation that characterizes the central portion of the Sonoran Desert in Arizona. This pattern is broken in spots by precipitation averages associated with some of the taller mountain ranges on the northern and eastern margins of the desert. Along the Sonoran Desert's northern and eastern boundaries in Arizona, except for extensions along prominent river valleys, precipitation averages approach and then exceed 16 inches per year as the higher elevations of southeastern Arizona and the Mogollon Rim are reached. Based on this rather coarse information, the SDNM encompasses a rainfall gradient from six to 16 inches average annual precipitation. The 10- to 16-inch gradient encompasses portions of the Sand Tank and Table Top Mountains.

3.5.2 Regional and Local Precipitation Patterns

This section will highlight the variability in precipitation that is an inherent environmental attribute of the Sonoran Desert. Variation in precipitation can be along a geographic gradient and at any particular location, in quantity and timing across different time scales. As a result, we first assess variation at a regional scale by evaluating precipitation data from eight weather stations located along a west to east gradient from Blythe, California to Tucson, Arizona (see Figure 3.3 and Table 3.1 for location data associated with each weather station). We then consider specific patterns of variation at three weather stations located in the immediate vicinity of the SDNM.

Regional Precipitation Patterns

Figure 3.4 and Table 3.2 provide summary data for the eight weather stations consisting of annual means, minimums and maximums, and standard deviations, as well as the absolute and relative average seasonal contribution of precipitation at each station for winter (for a given year of record the prior November and December plus January through March of the year of record), summer monsoon (July and August), tropical rains (September and October), and other (spring-summer drought: April through June). Data from individual years or seasons were not included in the calculations if any individual month within the year or season had greater than five days of data missing. The data illustrate the general trend that total precipitation increases from west to east with the average annual amount of rain in Tucson triple that of Blythe. With the exception of Tucson, each station receives on average roughly half of its annual rainfall amount in the winter. The relative seasonal contributions of the summer monsoon season and tropical storms are more variable.

Also depicted in Table 3.2 are values for the coefficient of variation (CV) associated with variability of annual and seasonal amounts of precipitation. In Figure 3.5 we plotted values of CV against mean precipitation for 18 weather stations: the original eight stations plus five additional stations located in the Sonoran Desert plus five weather stations located in the Apache Highlands Ecoregion. We added the Apache Highlands stations, which ranged from 12.6 to 22.0 inches on average of rain annually, to add higher rainfall locations outside the Sonoran Desert to our analysis. Station elevation ranged from 3,277 to 5,200 feet but did not correlate with total annual precipitation. We plotted values for mean annual, winter, summer monsoon, and summer monsoon plus tropical rain and then computed regression lines (power function) to show the general trend in values of CV with the precipitation gradient. The basic conclusion to draw from these regressions, no matter the type of plot, is that as annual or seasonal precipitation decreases along a rainfall gradient, its variability (as indicated by values of CV) increases. In simpler terms: the less rain an area receives on an annual or seasonal basis, the more unpredictable and variable that rainfall will be over time. The preceding insight has significant implications for trying to devise livestock grazing strategies that are based on rigid formulas rather than on flexibility.

The dashed line on each plot is an estimate of where on average (ignoring the higher elevations) the SDNM fits along the regression line. For the mean annual precipitation plot the dashed line crosses at eight inches, which is halfway between the six to 10 inch lower elevation precipitation gradient across the monument. Recall that this is a coarse estimate for the SDNM as it is based on the state-wide precipitation data. For the other plots the dashed line represents the average of the mean seasonal rainfall at the Gila Bend, Maricopa 4 N, and Maricopa 9 SSW weather stations. As a result, these latter plots tend to put the SDNM slightly more towards the lower end of the west to east precipitation gradient within the Sonoran Desert.

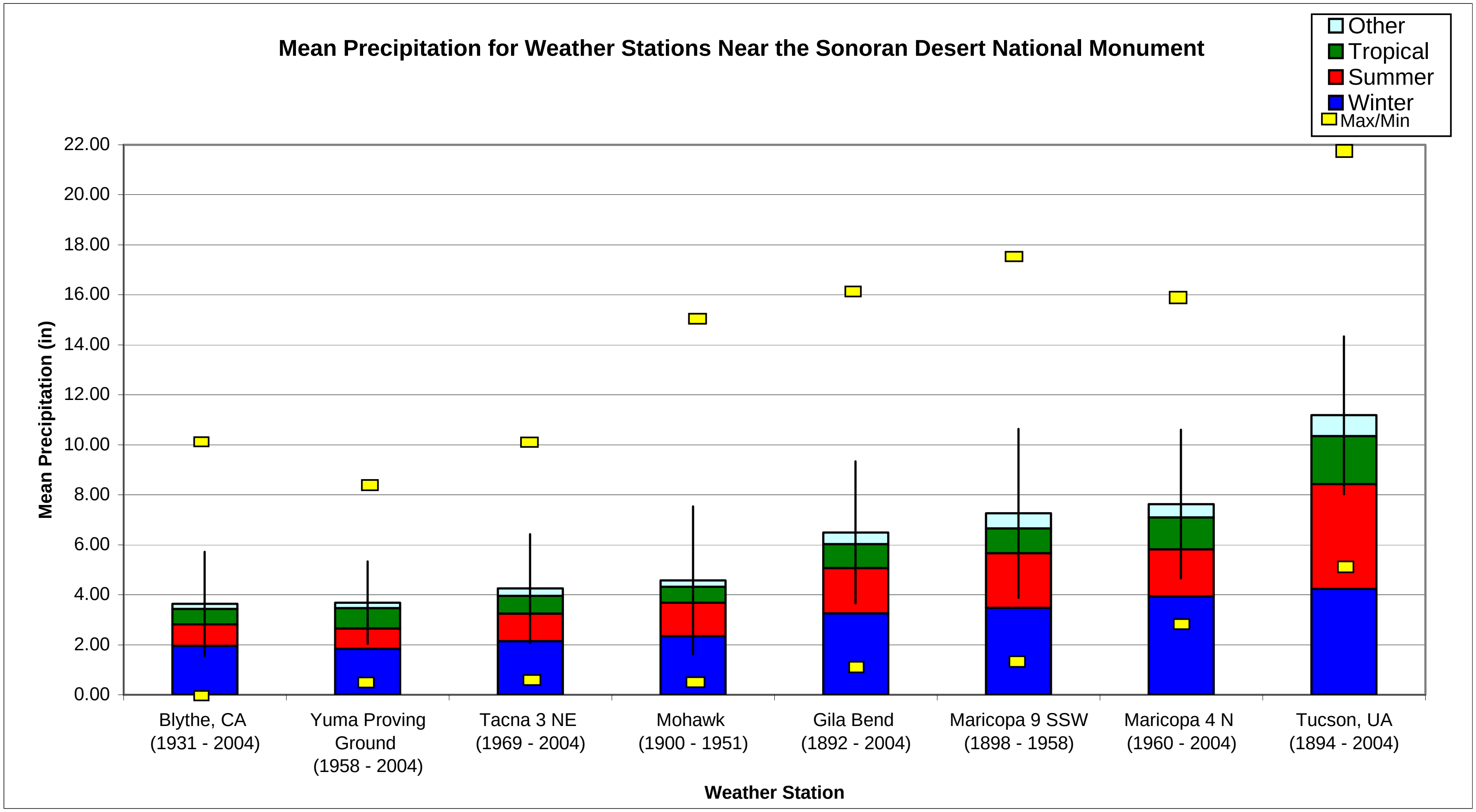
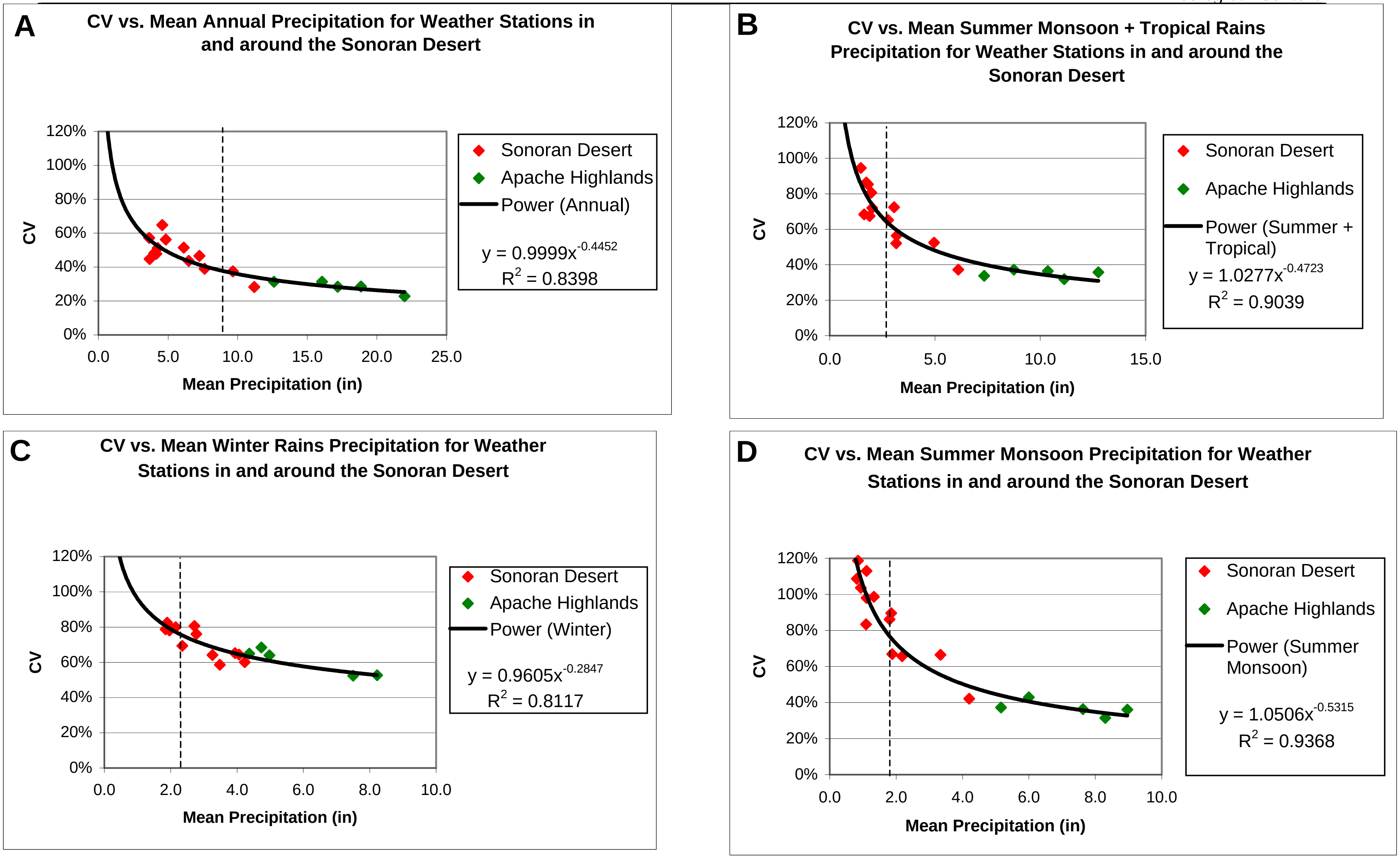


FIGURE 3.4 Mean Annual and Seasonal Precipitation at Eight Weather Stations within the Sonoran Desert Located Along a West to East Gradient. Winter equals the prior year November to December plus the current year January to March. Summer monsoon equals July to August and tropical equals September to October. The vertical lines show one standard deviation above and below the sum of the seasonal means.

TABLE 3.2 Mean Annual and Seasonal Precipitation Data (in Inches Unless Otherwise Indicated) from Eight Sonoran Desert Weather Stations along a West to East Gradient[1]

			Weather Station							
			west →							east
			Blythe, CA (1931 - 2004)	Yuma Proving Ground (1958 - 2004)	Tacna 3 NE (1969 - 2004)	Mohawk (1900 - 1951)	Gila Bend (1892 - 2004)	Maricopa 9 SSW (1898 - 1958)	Maricopa 4 N (1960 - 2004)	Tucson, UA (1894 - 2004)
	Annual (sum of seasonal precipitation)	Mean	3.64	3.69	4.25	4.58	6.50	7.26	7.63	11.19
		StDev	2.08	1.65	2.18	2.96	2.84	3.38	2.98	3.16
		CV	57.3%	44.8%	51.2%	64.7%	43.7%	46.5%	39.0%	28.2%
		Median	3.21	3.54	3.85	4.37	6.09	7.51	6.95	10.72
		Max	10.22	8.51	10.22	14.91	16.12	17.73	15.78	21.66
		Min	0.19	0.64	0.79	0.55	1.30	1.56	3.19	5.18
Season	Winter Rains (prior year Nov, Dec + current year Jan - Mar)	Mean	1.96	1.84	2.15	2.35	3.26	3.48	3.94	4.23
		StDev	1.53	1.45	1.72	1.63	2.09	2.04	2.56	2.55
		CV	78.0%	78.7%	80.0%	69.4%	64.1%	58.6%	65.1%	60.1%
		Median	1.32	1.62	1.54	2.12	2.92	2.72	2.97	2.55
		Max	6.72	6.13	6.63	7.79	9.17	8.89	9.59	11.95
		Min	0.01	0.10	0.20	0.10	0.26	0.60	0.23	0.84
		% of Annual	54.0%	50.0%	50.6%	51.4%	50.2%	47.9%	51.6%	37.9%
	Summer Monsoon (July - Aug)	Mean	0.85	0.82	1.10	1.33	1.80	2.18	1.88	4.20
		StDev	1.01	0.89	1.25	1.31	1.55	1.43	1.26	1.77
		CV	118.7%	108.7%	113.1%	98.7%	86.1%	65.7%	66.9%	42.1%
		Median	0.59	0.50	0.68	0.72	1.57	2.15	1.62	1.77
		Max	6.00	3.33	6.39	4.43	8.37	5.04	5.60	10.24
		Min	0.00	0.00	0.00	0.00	0.00	0.20	0.20	0.80
		% of Annual	23.4%	22.2%	26.0%	29.0%	27.7%	30.0%	24.7%	37.6%
	Tropical Rains (Sep - Oct)	Mean	0.62	0.82	0.70	0.64	0.97	1.00	1.28	1.91
		StDev	0.99	0.97	0.76	1.11	0.93	0.90	0.95	1.53
		CV	158.5%	118.3%	108.3%	172.5%	96.2%	90.3%	74.6%	80.1%
		Median	0.20	0.43	0.43	0.29	0.72	0.58	1.15	1.53
		Max	5.72	3.78	3.17	5.31	3.57	2.83	4.48	9.40
		Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		% of Annual	17.1%	22.2%	16.6%	14.0%	14.9%	13.8%	16.8%	17.1%
	Other (Apr - Jun)	Mean	0.20	0.21	0.29	0.26	0.46	0.60	0.53	0.84
		StDev	0.39	0.40	0.37	0.43	0.62	0.69	0.62	0.74
		CV	195.8%	190.8%	127.6%	167.4%	135.4%	115.4%	116.8%	87.6%
		Median	0.02	0.03	0.10	0.12	0.26	0.46	0.28	0.74
		Max	1.93	1.91	1.29	2.14	3.02	3.12	2.72	3.79
		Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		% of Annual	5.5%	5.7%	6.9%	5.6%	7.1%	8.2%	7.0%	7.5%

[1] Individual year excluded from calculations if any month in that year had more than five days missing data.
Individual season excluded from calculations if any month in that season had more than five days missing data.



A CV vs. Mean Annual Precipitation for Weather Stations in and around the Sonoran Desert

B CV vs. Mean Summer Monsoon + Tropical Rains Precipitation for Weather Stations in and around the Sonoran Desert

C CV vs. Mean Winter Rains Precipitation for Weather Stations in and around the Sonoran Desert

D CV vs. Mean Summer Monsoon Precipitation for Weather Stations in and around the Sonoran Desert

FIGURE 3.5 Variability in the Coefficient of Variation versus a Precipitation Gradient for 18 Weather Stations in the Sonoran Desert and Apache Highlands: A. Mean Annual Precipitation; B. Mean Summer Monsoon Plus Tropical Rains Precipitation; C. Mean Winter Rains Precipitation; D. Mean Summer Monsoon Precipitation. Dashed lines estimate precipitation on the Sonoran Desert National Monument. See text for additional details.

Local Precipitation Patterns

To describe additional patterns of variation in rainfall at the local scale, we graphed inter-annual variation in: (1) annual precipitation, (2) percent contribution to total precipitation by season, (3) winter precipitation, and (4) summer monsoon plus tropical rains precipitation. We did this for the Gila Bend weather station (Figures 3.6, 3.7, 3.8, and 3.9, respectively) and for the combination of the Maricopa 9 SSW and Maricopa 4 N weather stations (Figures 3.10, 3.11, 3.12, and 3.13, respectively). We combined the two Maricopa weather stations data to facilitate comparisons with the Gila Bend data. The Maricopa 9 SSW station was moved after 1958 to its current location at 4 N. Based on its location in Figure 3.3, Maricopa 4 N would appear to be in a slight rain shadow northeast of the Sierra Estrella; however, at least its mean precipitation values do not seem to be too different from the previous location at Maricopa 9 SSW (Table 3.2). Note that years without lines do not represent zero precipitation; instead they represent data not depicted for that year if any individual month within the year or season had greater than five days of data missing. Each figure (except Figures 3.7 and 3.11) includes lines that demarcate the mean plus standard deviation and median annual precipitation, respectively.

The figures graphically illustrate the large amount of variation in rainfall, on both an annual and seasonal basis, at particular locales in proximity to the SDNM. In regard to annual precipitation (Figures 3.6 and 3.10), the number of years precipitation is less than the mean is greater than half the time (56% and 53% for Gila Bend and the combined Maricopa weather stations, respectively).[4] High rainfall years bias the mean annual precipitation total to some degree. The percentage is higher for the Maricopa weather stations if the data for winter rain variation is considered (Figure 3.12; 60%). The percentages for the summer monsoon plus tropical rains were the same as the annual percentages. In addition, a significant number of years are well below the mean, whether on an annual basis or by season. For example, using one half the mean amount of precipitation as an arbitrary screening value, the Gila Bend and combined Maricopa stations received precipitation below this value: 10% and 8% of the time, respectively, on an annual basis; 24% and 21% of the time, respectively, during the winter; and 19% and 18% of the time, respectively, during the summer monsoon plus tropical rains. The seeming discrepancy in these values—especially between the annual percentages and the seasonal percentages—may be explained in part by the variation in percent contribution to total precipitation by season (Figures 3.7 and 3.11). A less than average rainfall in one season may be offset by a higher than average rainfall in another season during the same year of record.

The preceding information on precipitation variability has significant implications for the compatibility of, and the ability to be successful in, grazing livestock in the Sonoran Desert. Given this variability, the tendency that more often than not years and seasons are below average, and the need for recovery following periods of drought, any grazing management strategy that aims to manage in regard to average conditions risks overestimating the capacity of the range to support livestock. The overestimate can be either in terms of adequate forage or in achieving compatibility with maintaining other resource values, such as the objects on the SDNM. The implications of precipitation variability are addressed in detail in Chapter 4.

---

[4] We realize that using the mean as a reference point for comparison purposes may have statistical limitations (see section 4.1.2). Our purpose here, however, is simply to provide the reader a flavor of the variation in the precipitation data that discussion about the mean enables.

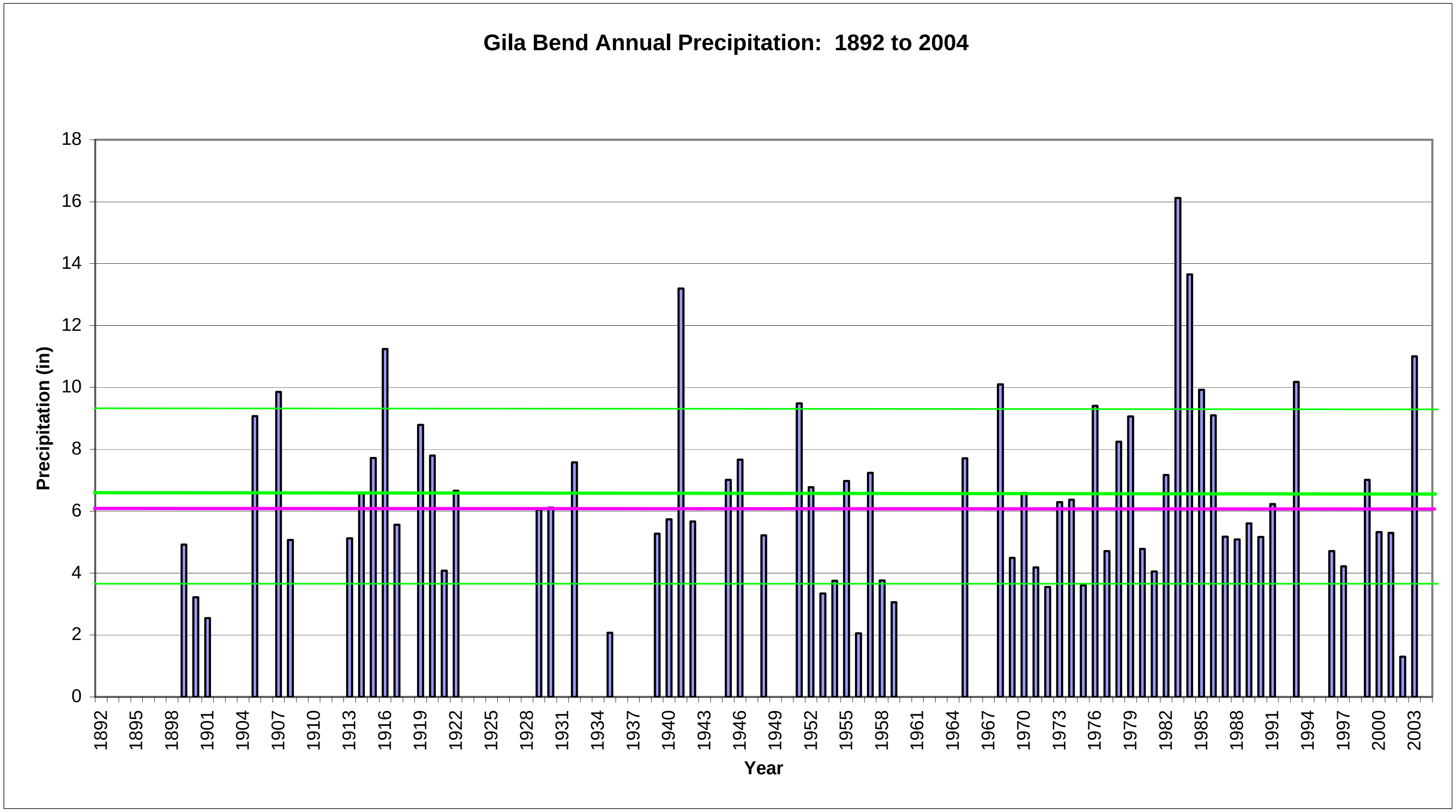


FIGURE 3.6 Total Annual Precipitation at the Gila Bend Weather Station: 1892 to 2004. A year equals the prior November to December plus the current January to October. Data for a year are not included if any month in that year has more than five days missing data. Green lines represent the mean annual precipitation plus and minus one standard deviation (6.50 +/- 2.84 inches). Purple line represents the median annual precipitation (6.09 inches).

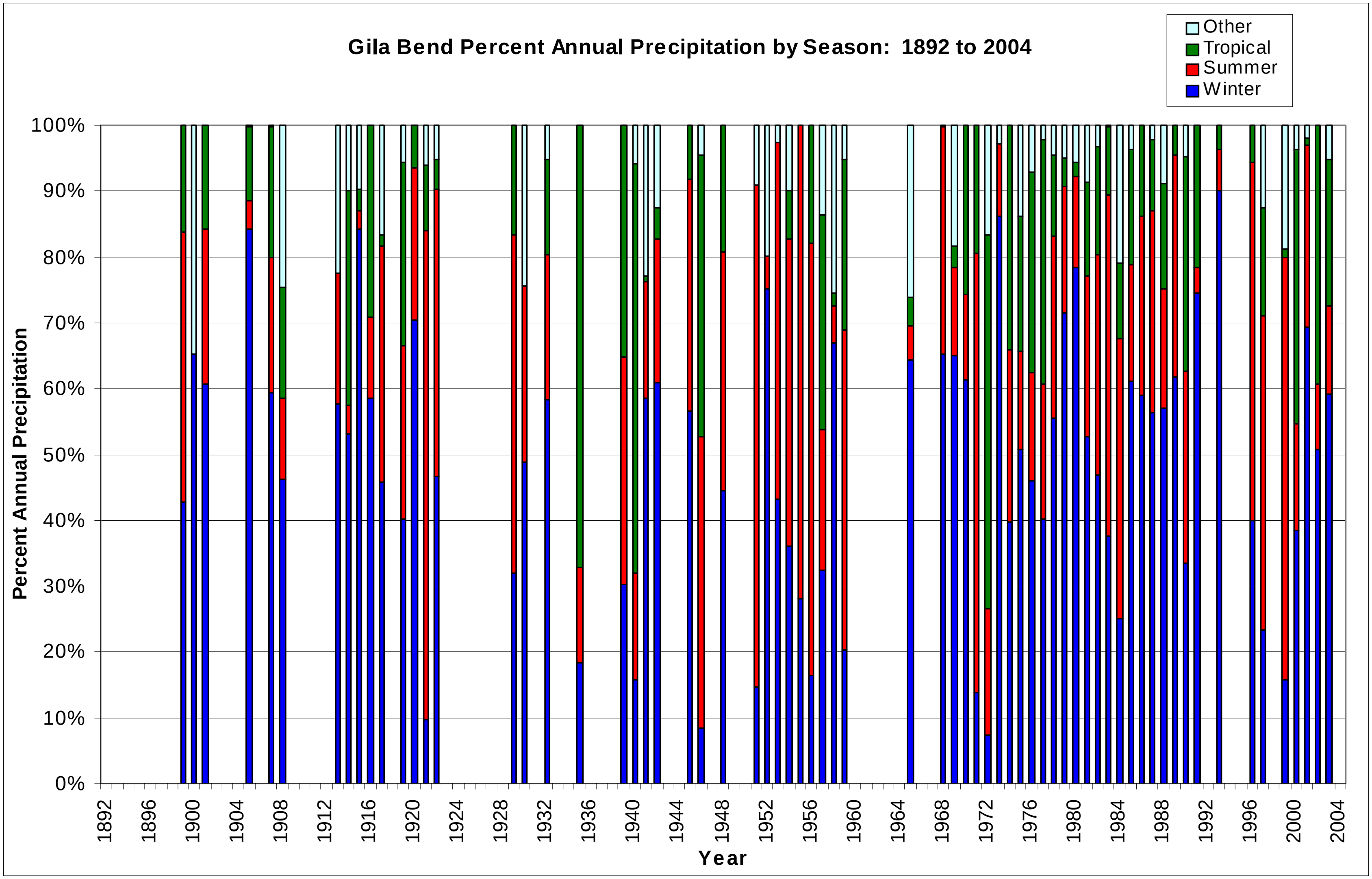


FIGURE 3.7 Seasonal Rainfall as a Percentage of Annual Rainfall at the Gila Bend Weather Station: 1892 to 2004. Winter equals the prior year November to December plus the current year January to March. Summer monsoon equals July to August and tropical equals September to October. Data for a year are not included if any month in that year has more than five days missing data.

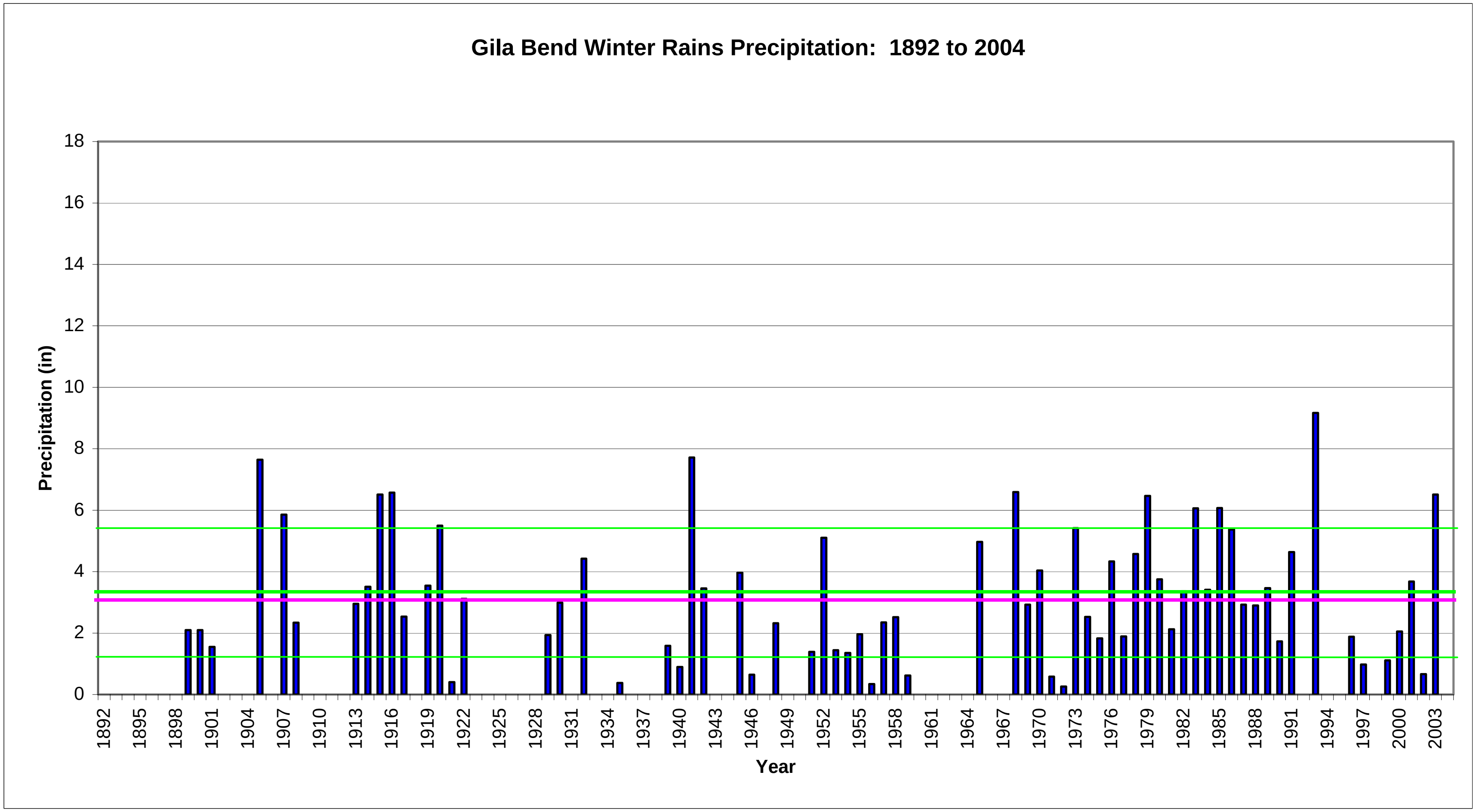


FIGURE 3.8 Annual winter rains precipitation at the Gila Bend Weather Station: 1892 to 2004. Winter equals the prior year November to December plus the current year January to March. Data for a year are not included if any month in that winter has more than five days missing data. Green lines represent the mean winter precipitation plus and minus one standard deviation (3.26 +/- 2.09 inches). Purple line represents the median winter precipitation (2.92 inches).

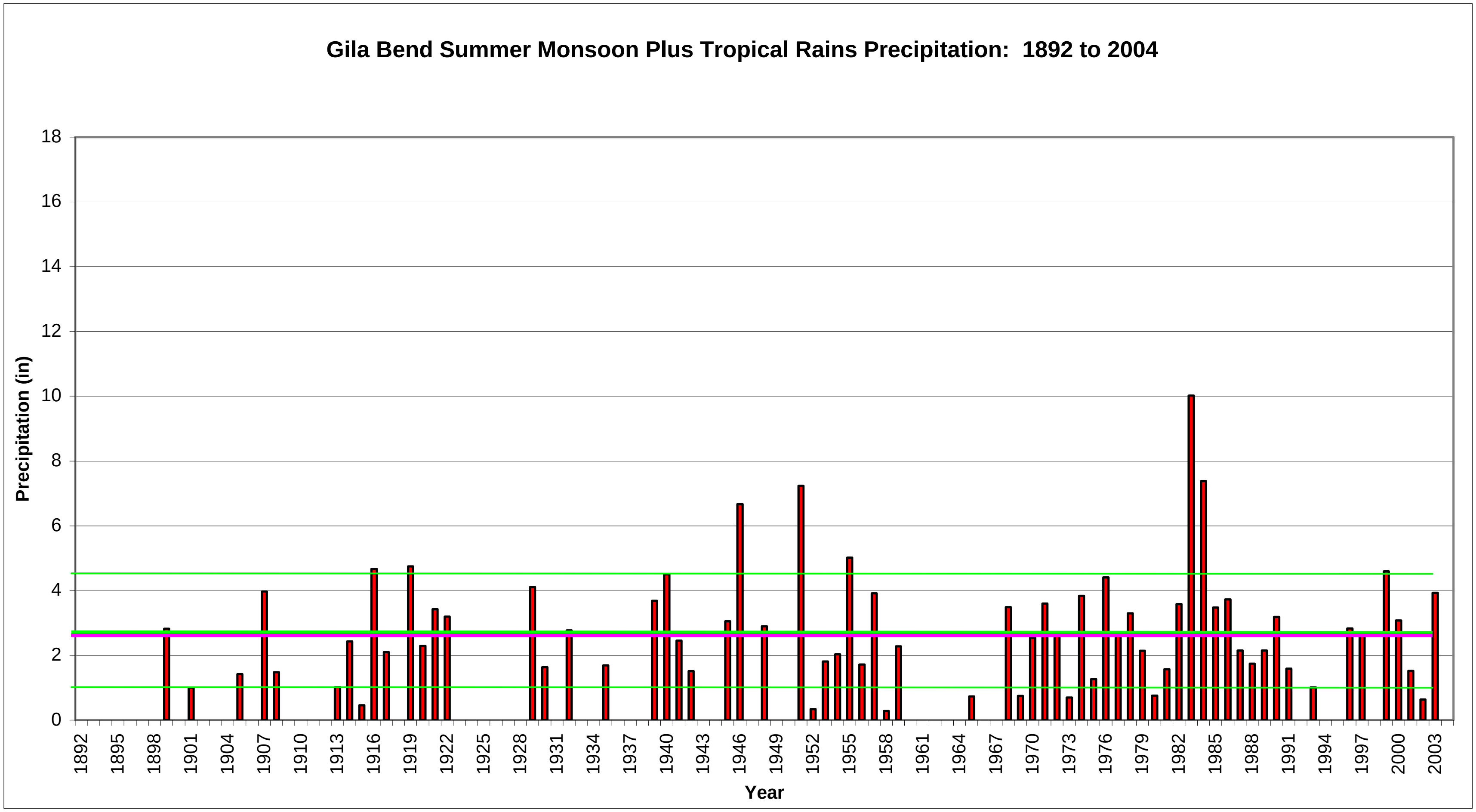


FIGURE 3.9 Annual Summer Monsoon Plus Tropical Rains Precipitation at the Gila Bend Weather Station: 1892 to 2004. Summer monsoon equals July to August and tropical equals September to October. Data for a year are not included if any month in the period July to October has more than five days missing data. Green lines represent the mean July to October precipitation plus and minus one standard deviation (2.77 +/- 1.81 inches). Purple line represents the median July to October precipitation (2.63 inches).

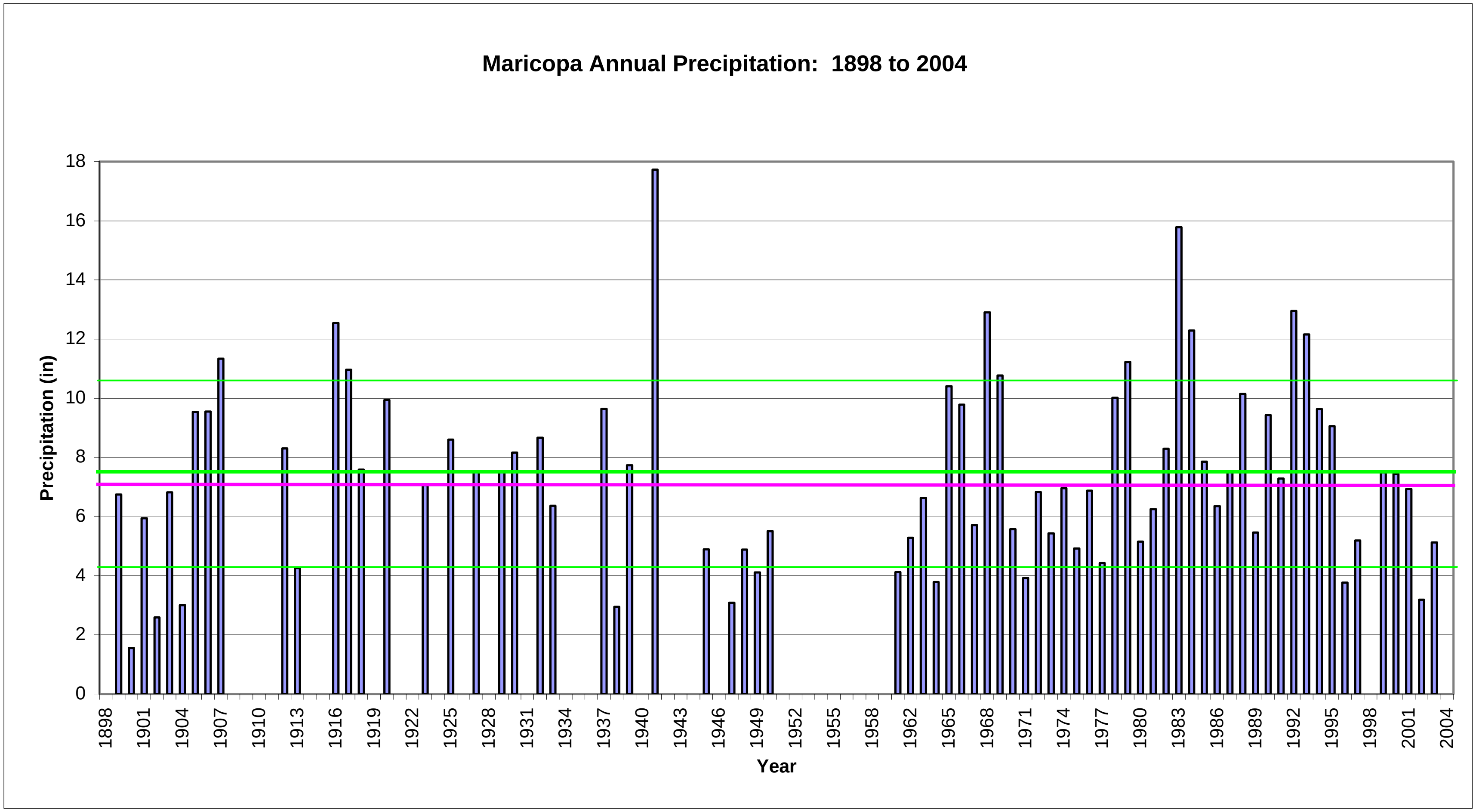


FIGURE 3.10 Total Annual Precipitation at the Combined Maricopa Weather Stations: 1898 to 2004. Data for 1898 to 1958 are from Maricopa 9 SSW, whereas the data for 1960 to 2004 are from Maricopa 4 N. A year equals the prior November to December plus the current January to October. Data for a year are not included if any month in that year has more than five days missing data. Green lines represent the mean annual precipitation plus and minus one standard deviation (7.47 +/- 3.14 inches). Purple line represents the median annual precipitation (7.06 inches).

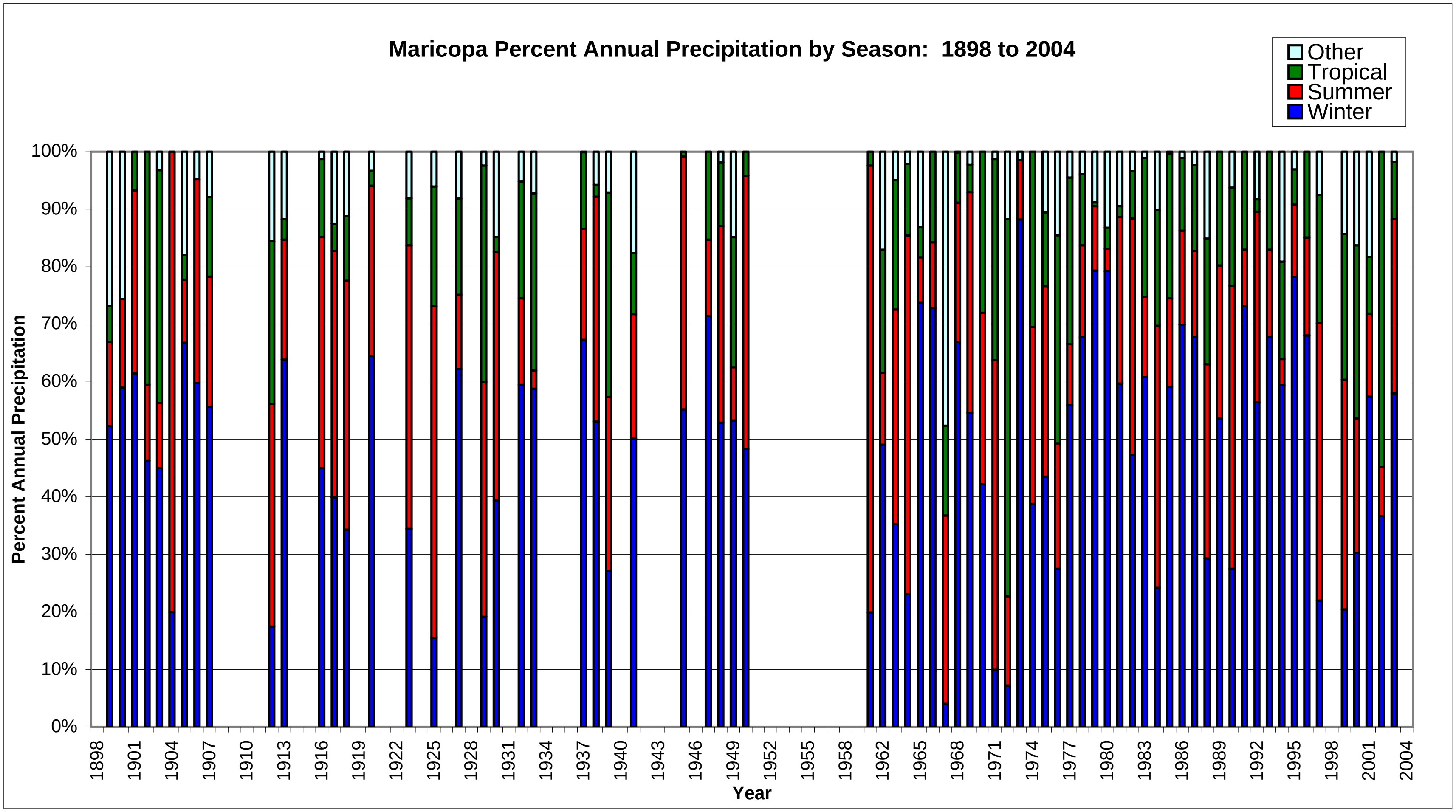


FIGURE 3.11 Seasonal Rainfall as a Percentage of Annual Rainfall at the Combined Maricopa Weather Stations: 1898 to 2004. Data for 1898 to 1958 are from Maricopa 9 SSW, whereas the data for 1960 to 2004 are from Maricopa 4 N. Winter equals the prior year November to December plus the current year January to March. Summer monsoon equals July to August and tropical equals September to October. Data for a year are not included if any month in that year has more than five days missing data.

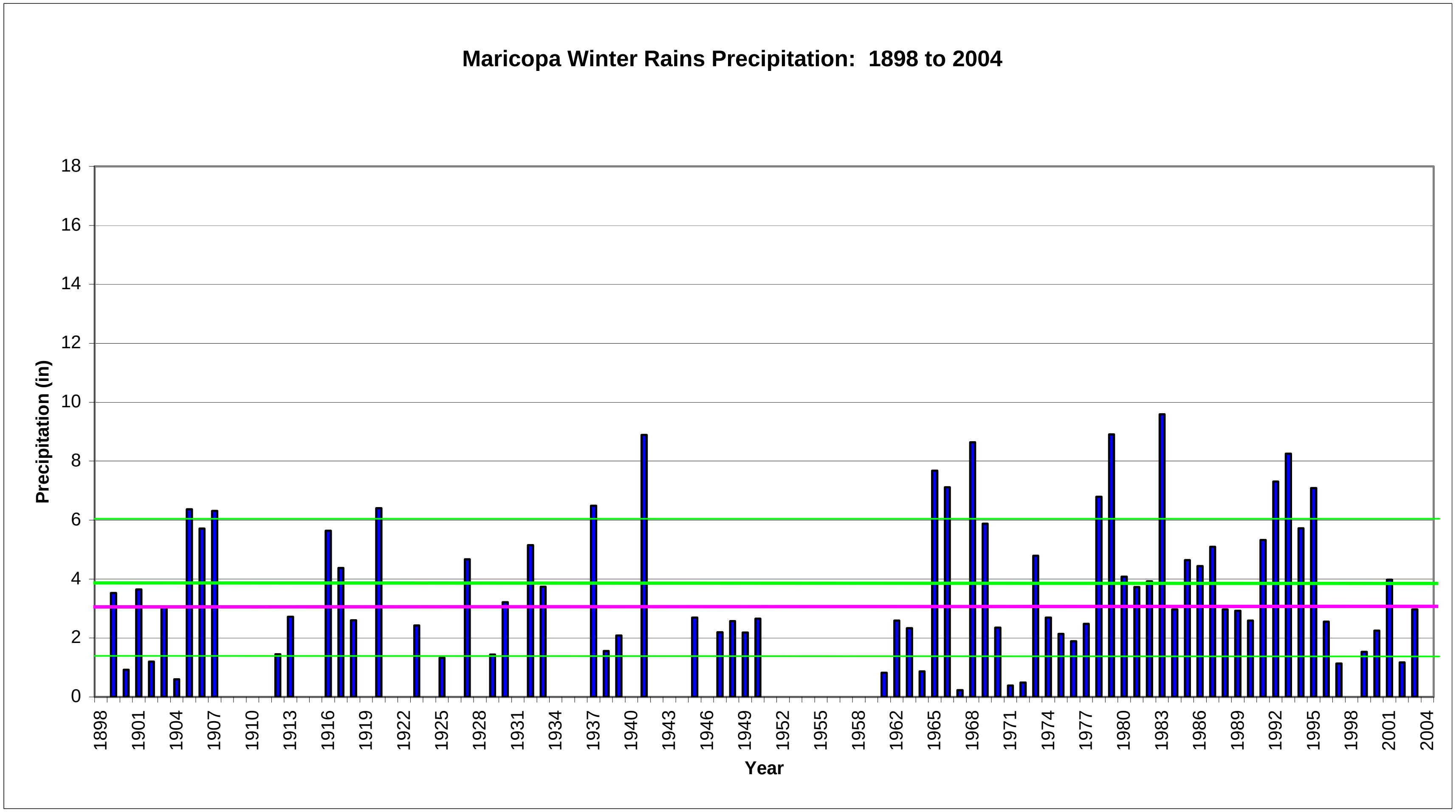


FIGURE 3.12 Annual Winter Rains Precipitation at the Combined Maricopa Weather Stations: 1898 to 2004. Data for 1898 to 1958 are from Maricopa 9 SSW, whereas the data for 1960 to 2004 are from Maricopa 4 N. Winter equals the prior year November to December plus the current year January to March. Data for a year are not included if any month in that winter has more than five days missing data. Green lines represent the mean winter precipitation plus and minus one standard deviation (3.74 +/- 2.35 inches). Purple line represents the median winter precipitation (2.97 inches).

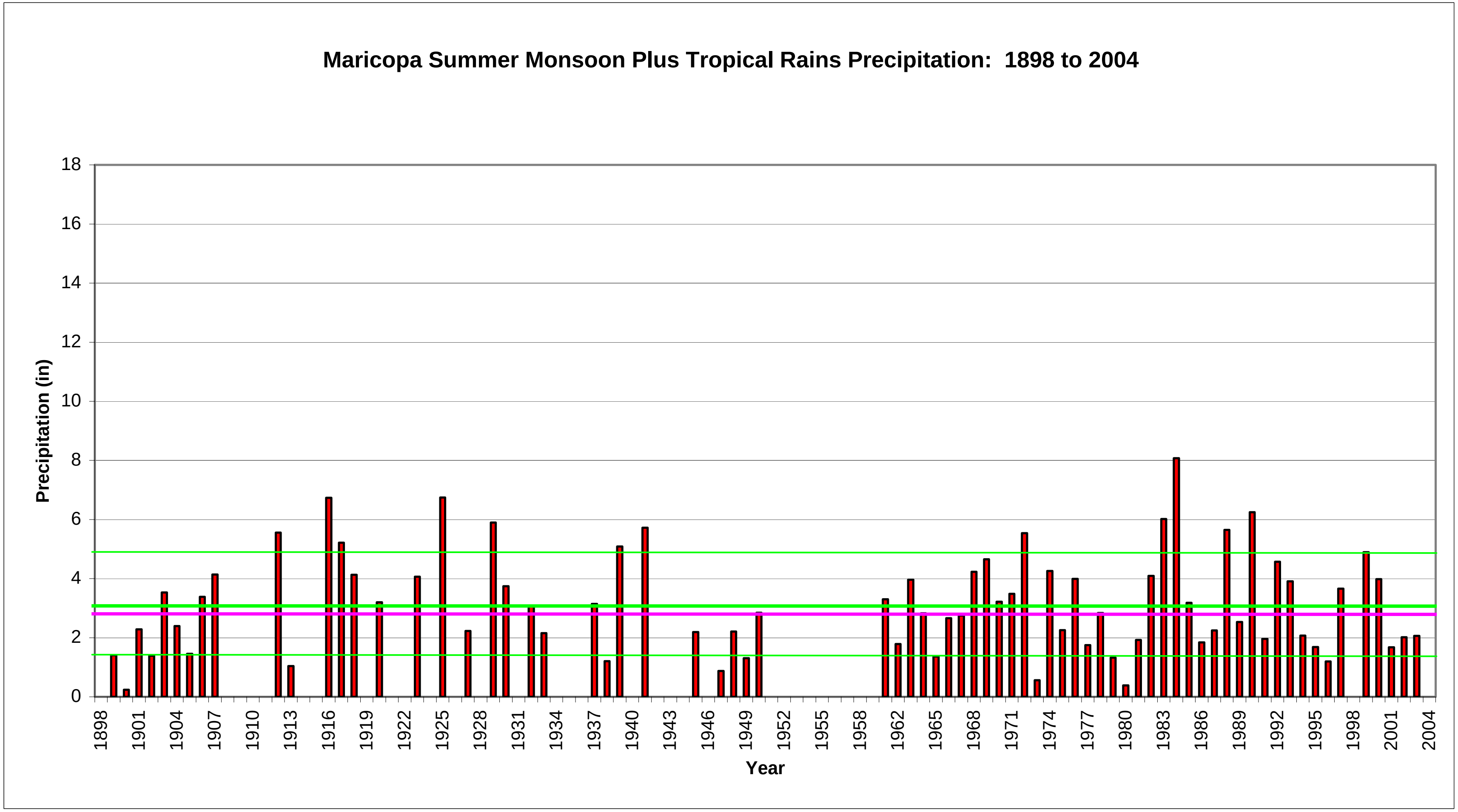


FIGURE 3.13 Annual Summer Monsoon Plus Tropical Rains Precipitation at the Combined Maricopa Weather Stations: 1898 to 2004. Data for 1898 to 1958 are from Maricopa 9 SSW, whereas the data for 1960 to 2004 are from Maricopa 4 N. Summer monsoon equals July to August and tropical equals September to October. Data for a year are not included if any month in the period July to October has more than five days missing data. Green lines represent the mean July to October precipitation plus and minus one standard deviation (3.17 +/- 1.70 inches). Purple line represents the median July to October precipitation (2.85 inches)

3.5.3 Local Temperature Patterns

Temperature can be a limiting factor that controls the occurrence and distribution of numerous plant species within the Sonoran Desert. Moreover, some species may tolerate below freezing temperatures, but not if the interaction of temperature and length of exposure exceeds certain threshold values. A catastrophic freeze is one that has the potential to kill or injure many species of plants, particularly species that have tropical affinities and reach their northern range limits within the Sonoran Desert. As a result, already established vegetation may be subject to catastrophic mortality if rare periods of below freezing temperatures occur over a sufficient period of time. Cold temperatures also may stress plants and could act synergistically with other stressors. Bowers (1981) and Turner and others (1995) identify a number of the Sonoran Desert plants susceptible to the effects of below freezing temperatures.

Almost the entirety of the Sonoran Desert is subject to below freezing temperatures during some years for a portion of the day (Turner and others 2003; see also section 4.1.3). Figure 3.14 depicts data for average number of days with temperatures below freezing for three weather stations in the vicinity of the SDNM (see Table 3.1 for weather station location and years of data collection). Note that this is not an indication of "catastrophic freeze" because the data do not indicate the duration of freezing temperatures, only the mean monthly number of days that freezing temperatures were reached during the period in which weather data were collected for each station. Still the data provide an idea of the probability of freeze at a site. In addition, microhabitat conditions at these particular weather stations—for example, perhaps one or more is in a location that receives cold-air drainage from surrounding slopes—may or may not reflect the typical conditions of the lower elevations of the SDNM as a whole.

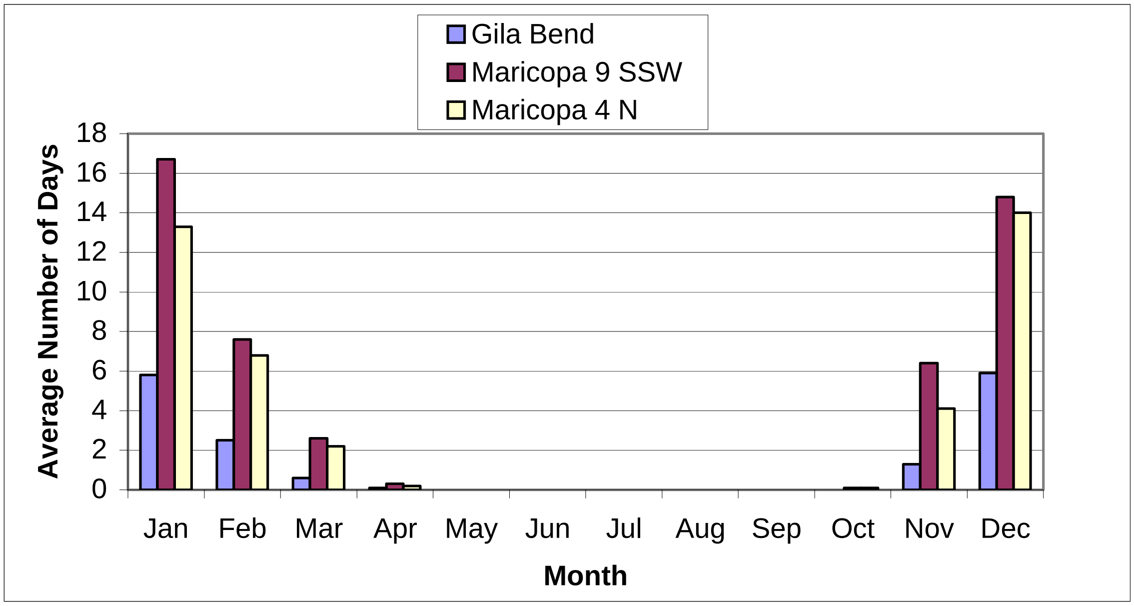


FIGURE 3.14 Average Number of Days per Month with Minimum Temperatures Below Freezing at Sites Near the Sonoran Desert National Monument. See Figure 3.3 and Table 3.1 for weather station location data.

The intersection of livestock grazing with the potential to exacerbate the consequences of catastrophic freezes has to do with the potential for grazing to alter microhabitat conditions. The effects of below freezing air temperatures can be mitigated by microhabitat conditions related to vegetation structure and plant litter accumulation that can maintain the effective environmental temperature (the temperature actually experienced by the plant) higher than the air temperature. To the extent that livestock grazing can alter these microhabitat conditions, then the adverse impacts of below freezing temperatures will be greater (see section 4.1.3 for additional discussion of the topic).

We do not address in this report to any detail the potential impacts of high temperatures, except to note that precipitation and temperature have a relationship of management concern. Precipitation that falls during the summer also is subject to increased evapotranspiration demand. As a result, for the same amount of precipitation less water will be available to plant use if ambient temperatures are higher. To the extent that climate change will result in higher average temperatures and more extreme high temperatures, and assuming no corresponding changes in precipitation amount and pattern, the temperature change alone may result in seasonal and annual reductions in plant available moisture. The effects of drought may be exacerbated under these conditions. Moreover, for grazing systems that rely on summer rainfall, higher temperatures could have a significant negative effect on plant productivity (though this could be potentially counterbalanced by shifts in photosynthetic efficiencies).

CHAPTER 4 PLANT COMMUNITY COMPOSITION, STRUCTURE, AND FUNCTION

The purpose of this chapter is to (1) provide an overview of the ecological processes that influence plant community dynamics in the Sonoran Desert and (2) summarize the literature on livestock grazing impacts to Sonoran Desert plant community composition, structure, and function. The overview of ecological processes and community dynamics is not be meant to be exhaustive, but instead focuses on those aspects in which the intersection with livestock grazing is of consequence.

4.1 ECOLOGICAL PROCESSES AND PLANT COMMUNITY DYNAMICS

Noy-Meir (1973) qualitatively defined deserts as “water-controlled ecosystems with infrequent, discrete, and largely unpredictable water inputs.” The Sonoran Desert is the warmest of North America’s four deserts (Sonoran, Mojave, Chihuahuan, and Great Basin; Turner and others 2003:figure 1.1) by virtue of its lower elevations (MacMahon and Wagner 1985). Relative to the three hot deserts (Sonoran, Mojave, Chihuahuan), the Sonoran Desert’s rainfall pattern is considered transitional—summer and winter rainfall both contribute notably to annual precipitation, whereas the patterns of the Mojave and Chihuahuan Deserts are dominated by winter and summer rainfall, respectively (MacMahon and Wagner 1985, Turner and others 2003). Whereas the lack of appreciable summer rainfall seems to determine the western boundary of the Sonoran Desert, the approximate eastern and northern boundaries encompass an area to the west and south, exclusive of high elevation mountain tops, in which mid-day temperatures never stay below freezing (Turner and others 2003; see section 4.1.3).

The Sonoran Desert is rich in biodiversity and harbors a high proportion of endemic plants and reptiles (Marshall and others 2000), due in part to its warm climate, bimodal pattern of rainfall, and multiple origins of its flora. The most recent expansion of the Sonoran Desert, following the last glacial period of the late Pleistocene, occurred only about 9,000 years ago with the modern plant and animal communities developing 4,500 years later (Van Devender 2000). McLaughlin (1986), in his floristic analysis of the southwestern United States that included the U.S. portion of the Sonoran Desert, suggested that overall the majority of the species contained within the flora of the Southwest are relatively rare (that is, they tend not to occur in many local floras). Based on this finding and a clear association of floristic elements (assemblages) with “rather narrowly circumscribed Holocene environments,” he suggested that many southwestern species “have migrated little and are of rather recent, probably post-glacial origin” (McLaughlin 1986).

In contrast to the other North American Deserts, which are dominated by low shrubs, the Sonoran Desert is distinguished by its arboreal species and succulents (Brown 1994a). Sonoran Desert plants have both tropical and temperate affinities. In general, many of the species that respond primarily to summer precipitation are those that originated in tropical thornscrub communities further south in Mexico, and those adapted to cool winter rains originated in more temperate regions to the north. About 50% of the species recorded in local Sonoran Desert floras are annuals and 60 to 80% of these are winter annuals (Venable and Pake 1999).

The plant communities of the Sonoran Desert differ between subdivisions, and in general they are characterized not only by their species richness but also by their structural diversity. For example, within the Arizona Upland subdivision, understory plants typically include a patchy cover of perennial grasses, annual grasses and forbs, and small perennial shrubs and cacti. Midstory layers include numerous species of short-statured leguminous trees, shrubs, and cacti. Columnar cacti, such as the saguaro (*Carnegiea gigantea*), form the visually dominant canopy layer. Vines, a reminder of the Sonoran Desert's tropical origins, form interconnections between structural layers and individual plants. In contrast, within the Lower Colorado River subdivision trees, tall shrubs, and succulent life forms are often confined to drainages, whereas otherwise the vegetation is typically both open and simple (Brown 1994a).

To understand how livestock grazing may or may not be responsible for changes in plant community composition, structure, or function, we must first understand the inherent characteristics of and the key ecological processes that influence Sonoran Desert plant communities in the absence of an anthropogenic disturbance such as domestic livestock grazing.

4.1.1 Productivity, Biomass, and Litter

Deserts are typically characterized as regions of low productivity (Hadley and Szarek 1981). Noy-Meir (1973) summarized primary productivity data from various arid and semiarid regions. Based on his use of annual precipitation ranges to define these two regions, they overlap in the six to 10 inch (15 to 25 cm) precipitation range in which this range for arid regions represents areas with high evaporation rates during the growing season (which effectively reduces the amount of water available to plants). Semiarid regions can receive as much as 20 inches (50 cm); again, the upper end of the range includes areas in which high evaporation rates occur during the growing season.[5] Annual aboveground net primary production (ANPP) ranges from around 270 to 1,785 pounds dry weight per acre (lbs/acre; 30 to 200 $g{\cdot}m^{-2}$ [incorrectly reported as 30 to 300 $g{\cdot}m^{-2}$ by Hadley and Szarek 1981]) in arid regions, whereas in semiarid regions the range is 890 to 5,355 lbs/acre (100 to 600 $g{\cdot}m^{-2}$) (Noy-Meir 1973). Hadley and Szarek (1981) reviewed additional studies, which encompassed seasonal and year-to-year variation in precipitation, that generally conformed to the ranges provided by Noy-Meir. Noy-Meir (1973) estimated that total production (sum of aboveground and belowground production) may range from 890 to 3,570 lbs/acre (100 to 400 $g{\cdot}m^{-2}$) in arid regions and 2,230 to 8,925 lbs/acre (250 to 1,000 $g{\cdot}m^{-2}$) in semiarid regions.

Productivity of Sonoran Desert Plant Communities

Two studies have attempted to measure plant community ANPP within the Arizona portion of the Sonoran Desert. Szarek (1979) reported an ANPP of 490 lbs/acre (55 $g{\cdot}m^{-2}$) for representative (dominant) perennial species associated with a bajada site 31 miles (50 km) northwest of Tucson at an elevation of 2,300 feet (700 m). Summer-active ephemeral production was estimated at 100 lbs/acre (11.2 $g{\cdot}m^{-2}$). The site was qualitatively described as lush for a

---

[5] Noy-Meir (1973) also defined an extreme [hyper] arid region in which annual precipitation was less than 2.4 to 4 inches (6 to 10 cm; which also represents the lower limit for arid regions) and vegetation was restricted to favorable sites only versus a diffuse distribution across the landscape characteristic of arid regions.

Sonoran Desert area and encompassed five major soil types. The ANPP values in combination likely underestimate to some degree total community ANPP, as not all plant community components were sampled.

Whittaker and Niering (1975), as part of a broader study evaluating plant community biomass, production, and diversity along an elevational gradient of the southern slope of the Santa Catalina Mountains near Tucson, measured whole community ANPP and estimated total net primary production of three desert community types and a semidesert grassland community (Table 4.1). In lieu of collecting root data, these authors used estimates of root-shoot estimates from the literature to calculate belowground production. Herb (grasses and forbs) productivity included both spring and summer growth. The values for the desertscrub communities fall within the ranges specified by Noy-Meir (1973) for arid regions. Based on the community descriptions provided by Whittaker and Niering (1975) the Spinose-Suffrutescent Desert Scrub community likely corresponds to the Paloverde-Mixed Cacti-Mixed Scrub on Rocky Slopes community that we described in Chapter 3 for the Sonoran Desert National Monument (SDNM). Similarly, the Paloverde-Bursage Desert Scrub community likely corresponds to the Paloverde-Mixed Cacti-Mixed Scrub on Bajada community and the Creosotebush Desert Scrub community likely corresponds to the Creosotebush-Bursage Desert Scrub community on the SDNM. Compositional and life-form productivity differences likely exist between one or more of the communities in these two locations, in part due to the increased importance of winter rains to annual precipitation totals and lower overall precipitation amounts going from east to west in the Sonoran Desert of Arizona (see Table 3.2). Soils on the southern slope of the Catalina Mountains are granite-gneiss or alluvium derived from such parent material. Whittaker and Niering (1975) suggested that their desert samples represented the mesophytic margin of southwestern desert environments and that much lower productivity occurred in more arid areas.

TABLE 4.1 Summary of Production and Biomass Measurements for Three Sonoran Desert Plant Communities and a Semidesert Grassland Community[1]

Characteristic	**Desert Grassland**[2]	**Spinose-Suffrutescent Desert Scrub**	**Paloverde-Bursage Desert Scrub**	**Creosotebush Desert Scrub**
Elevation (ft)/Aspect	4,000/SSW	3,350/SSE	2850/SSE	2490/W
Annual Net Productivity (lbs/acre [$g \cdot m^{-2}$])				
Aboveground	1,240 [139]	1,150 [129]	935 [105]	820 [92]
Total	2,500 [280]	1,875 [210]	1,515 [170]	1,250 [140]
Biomass (lbs/acre [kg/ha])				
Aboveground	2,350 [2,630]	11,690 [13,100]	3,500 [3,920]	3,830 [4,290]
Total	5,350 [6000]	18,740 [21,000]	5,350 [6000]	5,350 [6000]
Biomass Accumulation Ratio[4]	1.9	10.2	3.7	4.7

[1] Data from Whittaker and Niering (1975). See text for additional details.
[2] Equals semidesert grassland of Brown (1994a). See text for additional details.
[3] Spinose = trees and arborescent shrubs with spines or similar projections; suffrutescent = plants possessing a woody stem or base.
[4] Aboveground Biomass/ANPP.

Productivity values within the Sonoran Desert differ with respect to regional and local scales, environmental gradients, and seasonal and interannual precipitation patterns. Primary productivity increases in the Sonoran Desert from west to east in concert with the precipitation gradient (see Chapter 3). In general, productivity is much lower within the Lower Colorado River Valley and Central Gulf Coast subdivisions than in other Sonoran Desert subdivisions found farther east or at higher elevations (Búrquez and others 1999). Much spatial and temporal heterogeneity in production occurs, however, based on temporal and water catchment variation in rainfall and local-scale habitat differences that reflect different soil and nutrient conditions (Búrquez and others 1999; nutrient cycling, especially nitrogen, is addressed in Chapter 7). The study of Whittaker and Niering (1975; Table 4.1) illustrates the changes in plant community composition and associated productivity that accompany a moisture gradient (which is only crudely represented by changes in elevation). Data reported by Búrquez and others (1999, citing Martínez-Yrízar and others 1993) illustrate that dramatic changes in productivity can occur at locale scales unrelated to elevational changes. In upland desertscrub habitat near Hermosillo, Sonora, annual litter production (used as a surrogate here for primary production) equaled 805 lbs/ acre (90 $g{\cdot}m^{-2}$), whereas in the adjacent, densely vegetated xeroriparian habitat litter production totaled 3,300 lbs/ acre (370 $g{\cdot}m^{-2}$).

Interannual differences in precipitation, when responses are measured at the same location, cause the most dramatic changes in productivity, especially for certain plant groups. For the Sonoran Desert, as is the case in the Mojave Desert as well, the largest year-to-year variation in aboveground production occurs for annual species, whereas perennial grasses show the greatest variation in production in the northern Chihuahuan Desert (Hadley and Szarek 1981). Moreover, despite their brief life cycles, Sonoran Desert annual plants can make significant contributions to plant community productivity in wet years. For example, Patten (1978) detected a ten-fold increase in the ANPP of winter annuals, from 84 to 850 lbs/acre (9.4 to 95.2 $g{\cdot}m^{-2}$), mostly because of a five-fold increase in winter precipitation between years at a site near Cave Creek, Arizona. Moisture sufficient for initiating germination also was delayed almost two months during the dry year compared to the wet year.

In addition, studies by Halvorson and Patten (1975) and Patten (1978) demonstrate that the contribution of winter annuals to community production differs by microhabitat and its intersection with wet and dry years. Also at a Cave Creek study site, Halvorson and Patten (1975) found that growth rates throughout the growing season and final biomass production for annuals growing under the canopy of relatively low density shrubs were double those annuals growing just outside the canopies. Along an elevation gradient at the study site, productivity decreased with elevation commensurate with an increase in shrub density. As a result, more shrubs do not necessarily translate into more winter annual productivity. Patten (1978) further explored the microhabitat relationships between winter annuals, most of which have C_3 mechanisms for fixing carbon in which shade from intense sun may be beneficial, and trees, shrubs, and open spaces. During both wet and dry years production in the interspaces between shrubs and trees was about 30% of the total, though open spaces covered almost half of the study area. Different species contributed to production within each microhabitat of open space and shade (with differences even dictated by shrub type). Wet-year production within the open spaces was more than triple the total winter annual production in the dry year. Production efficiency (conversion of solar energy to the caloric content of the plants) over the course of a growing season was as much as 30 times greater for winter annuals growing in the shade versus open spaces.

Productivity and Biomass in Semidesert Grasslands: Comparative Data

Comparisons to semidesert grassland productivity (and biomass) is of interest here; however, the Desert Grassland community of Whittaker and Niering (1975) is not necessarily comparable in its productivity and biomass characteristics to the Desert Grassland community that is present on the SDNM and adjoining areas of the Tohono O'odham Nation (Figure 3.2) because of differences in precipitation amounts, timing of precipitation events, and soils. For example, summer monsoon rain amounts at Whittaker and Niering's (1975) grassland site are about double the amount received at the SDNM Desert Grassland site (see Table 3.2 for roughly comparable local precipitation data). On the SDNM and adjoining portions of the Tohono O'odham Nation, the Desert Grasslands are dominated by tobosa grass (*Pleuraphis mutica*) on heavy clay soils that receive significant hydrologic flow accumulation from the surrounding uplands (Morrison and others 2003). Although Brown (1994a) includes these grasslands under the general category of semidesert grassland, we suggest this may tend to obscure their ecological distinctiveness from other higher elevation and rainfall semidesert grasslands. Throughout the remainder of this discussion, we refer to "grassland" areas outside the boundary of the Sonoran Desert as semidesert grassland in keeping with the terminology of Brown (1994a) and to distinguish them from the Desert Grassland community found on the SDNM and adjoining areas of the Tohono O'odham Nation.

Productivity values for semidesert grassland from Whitttaker and Niering's (1975) study are provided in Table 4.1. McClaran (1995) summarized other productivity studies that estimated a range of 2,230 to 3,120 lbs/acre (250 to 350 $g{\cdot}m^{-2}$) for total net annual productivity in semidesert grasslands. Whittaker and Niering's (1975) value places their site toward the low end of the range, which supports their supposition that this site was near the arid limit for grasslands. McClaran's (1995) range of values overlaps both the upper end of the arid range and the lower end of the semiarid range of Noy-Meir's (1973) productivity values.

Of seeming interest as well is the relative similarity in aboveground productivity between semidesert grassland and Spinose-Suffrutescent Desert Scrub (Whittaker and Niering's 1975; Table 4.1); however, the allocations of productivity among life form categories is quite different. For the semidesert grassland community, herbs constitute 43% of the aboveground productivity, whereas for Spinose-Suffrutescent Desert Scrub this category contributes about 9% (Whittaker and Niering 1975). Moreover, belowground productivity contributes a higher relative amount of the total productivity for the semidesert grassland community than the three desert communities (Table 4.1). This same pattern is also true for standing biomass (Table 4.1). The other distinction between these communities highlighted by the information in Table 4.1 is that ANPP is large with respect to aboveground biomass (low biomass accumulation ratio) for the semidesert grassland community, whereas ANPP is relatively much less compared to standing biomass for the desert communities. This is especially true for the Spinose-Suffrutescent Desert Scrub community that is characterized by relatively large amounts of non-photosynthetic woody material. The data suggest that compared to desert communities, semidesert grasslands, even when total biomass is similar, have more of their standing biomass underground and have high relative ANPP values when compared to their aboveground biomass.

Available data does not support a high belowground/aboveground biomass (root/shoot) ratio as characteristic of desert vegetation generally. Such a pattern may be more closely related to certain life forms or to temperature rather than aridity (Noy-Meir 1973, Hadley and Szarek 1981). Winter-active annuals have root/shoot ratios less than 0.5. In hot deserts the ratio for perennials differs between species with most species less than one, whereas in cool deserts the dominant perennial species have ratios significantly greater than one (ratio data summarized in Hadley and Szarek 1981).

Theoretical Considerations Associated with Desert Productivity

Various researchers have attempted to develop theoretical relationships between ANPP (or total net productivity) and water use/availability[6] in desert/arid environments (Noy-Meir 1973, Whittaker and Niering 1975, Webb and others 1978). Whittaker and Niering (1975) hypothesized that plant communities of arid (and presumably semiarid environments that would include semidesert grasslands) are surface-limiting (versus more humid environments in which the communities are surface-abundant): transpiration surfaces are minimized, but the production efficiencies of these surfaces are enhanced by their exposure to relatively full sunlight. Moreover, based on their empirical data they suggested that for a given amount of precipitation, surface-limiting communities that are typically exposed to higher temperatures than surface-abundant communities will exhibit comparatively lower net productivity (as a result of increased respiration and evaporative stress). The implications of these observations are that plant communities of arid environments—despite higher production efficiencies per unit leaf area, when compared to surface-abundant communities: (1) are more limited in their ability to increase productivity per unit increase in available moisture and (2) have lower net productivity for the same amount of total precipitation received in an area (Whittaker and Niering 1975).

Similarly, Webb and others (1978) divided ecosystems into water-limited (deserts and grasslands) and water-abundant (forests) (perhaps roughly equivalent to the surface-limiting and surface-abundant categories of Whittaker and Niering [1975], respectively). Their desert sites included the same Sonoran Desert site studied by Szarek (1979; see above). For water-limited ecosystems, they determined that ANPP has a linear relationship with actual evapotranspiration (AET) above a minimum amount of water needed annually to sustain the ecosystem. For water-abundant ecosystems ANPP does not show a relationship to AET. This latter finding is in agreement with Whittaker and Niering (1975) who suggest that for cooler, wetter environments evapotranspiration remains relatively constant and that precipitation itself is the variable to which productivity may be related. Above a certain precipitation amount, productivity may plateau as other factors become limiting (Whittaker and Niering 1975). Webb and others (1978) further investigated the transition between water-limited and water-abundant ecosystems. They analyzed the relationship between ANPP and AET for grassland sites along an AET gradient and

---

[6] Water use/availability is typically measured in terms of precipitation or actual evapotransporation (AET). Evapotranspiration amounts can be derived by subtracting other losses, such as stream runoff, from precipitation. For arid/desert environments, AET is typically assumed to be equal to precipitation (Whittaker and Niering 1975, Webb and others 1978).

suggested that the rate of increase in ANPP is a decreasing function of water use (relationship is an exponential curve that flattens out at higher values of AET). As a result, grasslands at the low end of the AET gradient behave more like deserts and grasslands at the high end of the AET gradient behave more like forests.

Although deserts and semidesert grasslands (versus grasslands at the higher end of the AET gradient) both demonstrate linear relationships between ANPP and AET, Webb and others (1978) determined that the forms of the relationships are significantly different between hot deserts and semidesert grasslands-cool deserts (their shortgrass prairie-cold deserts). First, though they share as water-limited ecosystems a minimum water requirement,[7] the empirically derived values for hot deserts are quite lower than those for semidesert grasslands-cool deserts. They derived values of 1.5 inches (38 mm) for hot deserts, which is within the range suggested by Noy-Meir (1973) for arid (hot desert) ecosystems of between 1 to 3 inches (25 to 75 mm), and 6.7 inches (170 mm) for semidesert grasslands-cool deserts. Second, Webb and others (1978) calculated different productivity increases per increment of water above the minimum requirement for hot deserts and semidesert grasslands-cool deserts. For hot deserts ANPP increases 86.4 lbs/acre per inch of water (0.38 $g \cdot m^{-2}$ per mm of water), whereas for semidesert grasslands-cool deserts ANPP increases 247.1 lbs/acre per inch of water (1.09 $g \cdot m^{-2}$ per mm of water). These values generally agree with similar increment estimates provided by Whittaker and Niering (1975), but are slightly lower than those estimated by Noy-Meir (1973). The conclusion, regardless of specific differences in quantitative values, is that the vegetation of hot deserts responds less (rate of productivity increase) to additional water than does semidesert grassland-cool desert vegetation (Webb and others 1978).

Webb and others (1978) identified two possible explanations for why productivity relationships to available water differ between hot deserts and semidesert grasslands-cool deserts. First, desert perennials may have evolved a more conservative strategy with respect to their response to precipitation. Because annual precipitation is more variable as aridity increases (see information in section 3.5 as an example of this pattern), rapid growth in response to years of relatively greater precipitation would result in a standing biomass that would be severely stressed in succeeding years of low precipitation. Second, evaporative potential is higher in hot deserts compared to semidesert grasslands-cool deserts. Precipitation may rapidly evaporate back to the atmosphere before vegetation can use it. This latter explanation supports the rationale behind the precipitation range overlap between Noy-Meir's (1973) arid and semiarid ecosystems. Despite receiving similar amounts of rainfall, vegetation in an arid ecosystem effectively loses access to a larger portion of this water than in a semiarid ecosystem because of higher evaporative losses during the growing season. Webb and others (1978) added that although hot desert productivity per unit of water above minimum requirements is inefficient relative to other ecosystems, hot desert perennials are still clearly better adapted to [initiate] producing with less water than the perennials of semidesert grasslands-cool deserts.

Finally, Webb and others (1978) also found that for semidesert grasslands-cool deserts primary productivity in any one year was partly related to primary productivity (related to water

---

[7] Presumably equivalent to the zero-yield intercept concept of Noy-Meir (1973) that accounts for water losses through evaporation and runoff or as defined by Webb and others [1975]: annual water necessary to sustain zero net primary production.

availability and use) during the previous year, whereas in hot deserts the only significant correlation between ANPP and water use was with the current year's precipitation when both annual and perennial vegetation were considered. When only perennial vegetation was assessed, the data tended to support an influence of the previous year's precipitation but not conclusively. Annual vegetation ANPP was itself poorly correlated with annual precipitation. As a result, Webb and others (1978) hypothesized that the seasonal timing of precipitation is more critical for the growth of annuals than the total annual precipitation. If true, this would make the relationship between incremental increases in water and corresponding increases in ANPP "coarse" for hot deserts (Szarek 1979).

Plant Litter

Litter is an important component of nutrient cycling and energy flow in terrestrial ecosystems and can modify the microclimate and chemical characteristics of soil (West 1979). West (1979) defines litter as the accumulation of all dead remains of plants before it is converted into humus; however, he indicates that in practice the term usually is applied only to the horizontal accumulation of organic matter on the soil surface and not to dead material which has yet to fall. For deserts, biological soil crust inputs to litter have rarely been considered, but they may be important relative to nutrient cycling, especially nitrogen (see Chapter 7 for further discussion). The spatial distribution of litter on desert substrates is patchy. Most litter accumulates in wind-protected areas around the bases of shrubs or within shallow depressions in the soil surface as a result of the overland flow water also augmenting accumulation (West 1979). Búrquez and others (1999), citing unpublished data, reported litter accumulations of 185 lbs/acre (21 $g \cdot m^{-2}$) in open areas versus 1,875 lbs/acre (210 $g \cdot m^{-2}$) beneath trees and shrubs near Hermosillo, Sonora (Plains of Sonora subdivision). In hot deserts litter production may be irregular, especially when leaf-shedding correlates with the precipitation pattern. The temporal and spatial patterning of litter in deserts may have considerable importance in influencing seedling establishment, nutrient cycling, and invertebrate activity (West 1979).

4.1.2 Precipitation Patterns, Drought, Plant Responses, and Pulse Dynamics

In Chapter 3 we provided an analysis of regional and local (proximity to the Sonoran Desert National Monument) precipitation patterns based on weather station data. Here, we describe some general features of the Sonoran Desert precipitation pattern, as identified in the literature, and some associated plant responses. We then provide a brief treatment of the concept of drought and then conclude this section with a discussion of the concept of pulse dynamics and its relevance to understanding Sonoran Desert ecosystem responses to precipitation events.

Sonoran Desert Regional-Scale Precipitation Patterns

The Sonoran Desert's precipitation pattern typically has been characterized as an unreliable and uneven bimodal (biseasonal) pattern of rainfall, separated by periods of spring and fall drought (Brown 1994a). Normally frontal storms whose moisture emanates from the North Pacific Ocean bring gentle rains in the winter, and hot convective currents and moisture carried primarily from the Gulf of Mexico result in violent thunderstorms in the summer. A third period of rainfall irregularly occurs in the late summer and early fall, when dissipating tropical cyclones bring moisture in from the southwestern coast of Mexico (Turner and others 2003). Within the boundaries of the Sonoran Desert, a number of gradients in the precipitation pattern exist beyond the effects of changes in elevation. As demonstrated in section 3.5.2 a significant west to east rainfall gradient exists across the Sonoran Desert, in which total annual rainfall increases toward the east. The low end of the gradient (not addressed in section 3.5.2) begins west of the Colorado River in Baja California (about 1.2 inches [30 mm] mean annual precipitation; Turner and others 2003). Two seasonal gradients are also of note: west to east summer rainfall becomes increasingly dominant, whereas the proportional contribution of summer rainfall to total precipitation also tends to increase from north to south (Turner and others 2003).

Comrie and Glenn (1998) identified precipitation regions of the U.S.-Mexico border area based on seasonality and variability of monthly precipitation, rather than precipitation totals, at 309 weather stations during the period 1961 to 1990. By not relying on absolute precipitation totals, their approach excludes the effect of elevation on precipitation. They identified nine regions with characteristic precipitation regimes, two of which are of interest here. The desert region encompasses areas surrounding the Mojave Desert and lower Colorado River Valley, including southeastern California and Nevada, western Arizona, northwestern Sonoran, and Baja California Norte. To the east its boundary skirts around the sky island region of southeastern Arizona and the Sierra Madre Occidental in northwestern Mexico. North of Tucson its boundary heads mostly due North. The desert region is arid year-round (less than 12 inches [30 cm] of rain on average annually) with marginally more rain in winter. As a result, a prominent monsoon precipitation peak (relative to winter rain) is notably absent. Climate controls in this region are likely a mix of the neighboring monsoon (see below) and Mediterranean (to the west) regions, though the relatively flat precipitation distribution with little seasonal signal from low precipitation amounts weakens any apparent correspondence.

To the east of the desert region is the monsoon region. This is a large geographic region encompassing most of the remaining extent of Arizona outside the desert region, all of New Mexico, southwestern Texas, and a large swath extending south into Mexico east of the coastal margin of the Gulf of California. The region is characterized by a strong mid- to late-summer precipitation maximum with considerably less precipitation the remainder of the year. Because of the large areal extent and latitude range encompassed by the monsoon region, Comrie and Glenn (1998) further subdivided this region into four subregions. The subregion of interest here borders the desert region and extends into western New Mexico west of the Continental Divide and most of northern Mexico east of the desert region except for the extreme northeastern corner. In southern Arizona its western boundary with the desert region bulges slightly in the vicinity of the Ajo Mountains. This particular subregion is characterized as having a long dry period in the early summer, monsoon rainfall principally in July and August, and a small winter precipitation signal.

As discussed above and also in section 3.5.2, precipitation gradients exist across the Sonoran Desert. The existence of such gradients would caution making too broad a generalization about precipitation patterns remaining consistent within the regions defined by Comrie and Glenn (1998). Still, these regions have heuristic value in identifying the dominant rainfall patterns of an area and the affinity of particular locales to different precipitation regions. As a result, the vast extent of the Sonoran Desert apparently shares a rainfall pattern that also is characteristic of the Mojave Desert. Because those portions of the Sonoran Desert in Arizona northeast of Tucson in the San Pedro and Gila River watersheds, the immediate Tucson vicinity, and south of a line extending approximately from Tucson to Ajo are located in the monsoon region, they share a rainfall pattern that at the subregion level is characteristic of the semidesert grassland areas of eastern Arizona, western New Mexico, and northern Mexico.

Variation in Precipitation Patterns

As was demonstrated in section 3.5.3, mean annual rainfall statistics greatly mask the variation inherent in precipitation patterns in the Sonoran Desert. For example, in 1956 a mere 0.25 inches (6 mm) of rain fell in Yuma but in 1905 rainfall totaled over 11 inches (280 mm) (Turner and others 2003). Variation in precipitation has spatial, temporal, and intensity components that may interact in a number of different ways. Spatial variability relates to the west to east and north to south gradients described previously (notwithstanding the overarching nature of the precipitation regions described above), elevational changes in precipitation, and the spotty nature of the summer monsoon convective storms. Differences in runoff and water accumulation patterns, as well as local edaphic conditions that affect soil moisture conditions, also will affect the overall spatial variability in effective precipitation (that is, the water available to support biological soil crust and vascular plant establishment and growth) independent of the inherent variability of precipitation that may fall in an area. Temporal variability can be described based on decadal or greater patterns, annual totals, seasonal totals and patterns, intra-seasonal precipitation patterns, and other time subdivisons. Variation in precipitation intensity relates to the size distribution (amount of precipitation falling per unit time or pulse size) of individual rainfall events. All components of variation in precipitation patterns may affect, to a greater or lesser degree, the establishment and survival of species within the Sonoran Desert.

The analysis of precipitation data in section 3.5.2 already illustrated some features of rainfall variability in the Sonoran Desert. Some authors have suggested that summer rainfall in the Sonoran Desert is more predictable (less variable) than winter rainfall (MacMahon and Wagner 1985, Turner and others 2003); however, based on the information in Table 3.2 the pattern of variability shifts with geographic location. For the Tucson weather station, which is located within the monsoon precipitation region of Comrie and Glenn (1998), the coefficient of variation (CV) is smaller for summer monsoon precipitation than it is for winter precipitation. For all other stations the summer monsoon CVs are greater, with the difference in CV values between summer monsoon and winter rains getting progressively larger moving from east to west. As a result, the general pattern seems to be that for locales within the monsoon precipitation region summer rainfall is less variable than winter rainfall and for locales within the desert precipitation region winter rainfall is less variable than summer rainfall. Superimposed on this pattern within the desert precipitation region of the Sonoran Desert is the tendency for winter rainfall CVs to increase from east to west commensurate with the overall reduction in total and seasonal precipitation along this gradient (Table 3.2 and Figure 3.5). An analysis of the north to south pattern of annual precipitation totals and shifts in which season has the more variable precipitation also may be of interest (data not analyzed here).

Intra-seasonal patterns of precipitation have been little studied until recently, but could have significant ecological effects. These patterns have a temporal dimension—number of and time in between rainfall events, as well as an intensity dimension. For example, Cable and Huxman (2004) examined the distribution of rainfall events (without regard to season) of pulse sizes corresponding to 0.08 inch (2 mm) bins for precipitation data collected in the vicinity of Tucson, Arizona during the years 1996 to 1999. They concluded that rainfall events near Tucson are dominated by small pulse sizes. Such rainfall tends to benefit only biological soil crust organisms (Noy-Meir 1973). Reynolds and others (2004) examined a longer data set for Tucson (1915 to 2000) and found that Tucson averaged 70 rain days per year. On 37 of these days (53%), precipitation did not exceed 0.04 inches (1 mm) and was regarded as a trace event. If Mojave Desert data from the same study are used to predict an east to west pattern for the Sonoran Desert, the tendency would be to observe a decreasing amount of rain days, with a proportional (but not absolute) increase in the number of days with rain less than 0.04 inches (1 mm). Of interest here is the finding by Huxman and others (2004) that for all three deserts, total summer (July through September) precipitation was strongly and mostly linearly correlated with the total number of precipitation events greater than 0.2 inches (5 mm) but was independent of the number of events less than 0.2 inches (5 mm). Variation in summer rainfall depended solely on the distribution of “large” rainfall events, with the number of small events remaining fairly constant commensurate with what was characteristic for each desert. Finally, a sequence of rainfall events rather than a single rainfall event often may be necessary to produce a biologically significant pulse of soil moisture recharge (Reynolds and others 2004). Reynolds and others (2004) found that summer storms in Tucson—defined as sequences of precipitation occurring on successive days, separated by gaps of rain-free days—are strongly clustered with most storms having gaps of less than 10 days (with a majority of those less than five days). The linkage is not as tight for winter rainfall (Reynolds and others 2004), which is not unexpected given the greater variability in winter precipitation described previously for the Tucson area.

Decadal and greater periods of variation in precipitation are gaining increased interest given the recent prolonged drought affecting most of the Southwest. Precipitation patterns in the western U.S. are influenced by macro- and mesoscale drivers, such as the Pacific Decadal Oscillation, El Niño Southern Oscillation events, and North American Monsoon, whose effects are modified at the regional scale by topography and orography (Loik and others 2004). The preceding drivers impose pulsed patterns (cycles of wet and dry periods) on long-term precipitation trends—both seasonal and annual—at the regional scale (clusters of state climate divisions; see Loik and others [2004] for details) on the order of multiple years to several decades. Although coarse for any particular region, the temporal trends imposed by the major drivers are to some degree discernible and predictable. Ultimately, the drivers also influence the temporal distribution of daily precipitation at landscape scales. Temporal distribution at this scale considers the size-class distribution of daily precipitation events and the size-class distribution of the amount of time that has elapsed since the last precipitation event (Loik and others 2004; see the preceding paragraph for example data). For the western U.S. as a whole, Loik and others (2004) found that the hottest and driest locations have precipitation regimes dominated by small precipitation events and intra-seasonal drought regimes dominated by long dry periods.

Continuation and deepening of the present drought could have profound implications for plant and animal species viability within the Sonoran Desert. In addition, superimposed on any long-term natural variation in climate patterns, the possible consequences of long term anthropogenic-induced changes in climate are not only changes in the mean value of annual precipitation but also potential shifts in the current patterns of variability. Shifts in such patterns—for example, the distribution of light versus heavy rains or the seasonal distribution of rain—may affect vegetation and landform patterns. For example, Cooke and Reeves (1976) hypothesized that a statistically significant reduction in the frequency of light rains (which reduced grass cover) and a non-significant trend toward an increase in the frequency of heavy summer rains during the latter part of the 19th century significantly influenced arroyo formation in southern Arizona. In a second example, Neilson (1986) attributed vegetation changes in the northern Chihuahuan Desert since the last glacial maximum to shifting patterns of seasonal rainfall, in which warm season C_4 grass species were favored when winters were dry and cool season C_3 shrub species were favored when winters were wet. Although the previous examples are seemingly a result of natural variation in an aspect of climate, the impacts of anthropogenic-induced climate change, including changes in precipitation patterns, are potentially more dramatic and longer lasting (Schwinning and others 2004).

Drought

Despite many attempts at defining and quantifying the condition of drought, a standardized conceptual meaning that meets all purposes remains elusive. Moreover, the public perception of drought, which guides public and decision-maker responses, often seems to reflect a view that drought is an abnormal event. Once perceived average or above average precipitation patterns return, the consequences of drought (and its return) are forgotten. In reality, “drought is an inevitable part of normal climate fluctuation and should be considered as a recurring, albeit unpredictable, environmental feature which must be included in planning” (Thurow and Taylor 1999:413; the authors likely used “planning” in the broadest public policy sense; however, the focus of their paper was on the role of drought in range management). Given the findings discussed throughout this document regarding precipitation patterns in arid environments, the likelihood of recurrent drought (no matter how defined) is even more likely an inevitable event within the Sonoran Desert.

From the perspective of range management and the potential synergistic effects of livestock grazing and drought on plant and animal communities, the periods of entering drought (onset), during drought, and coming out of (exiting) drought are all important aspects for managers to consider. The beginning and end of a drought may be hard to recognize, effects may accumulate slowly as a dry period begins, and effects may linger even after “normal” rainfall patterns have resumed (Thurow and Taylor 1999). The challenge then is to establish appropriate definitions and metrics that identify these periods, to understand the interactions that occur between livestock grazing and native biota and ecological processes during each period, and to craft appropriate livestock management actions that respond to the ecological constraints of each period. The uncertainty associated with identifying drought often has resulted in a lagged management response (such as reducing stocking rates) that has had negative land management consequences (Thurow and Taylor 1999).

So what are those definitions of drought that have been used and may be applicable to a range management context? A brief review of the literature indicates that our conceptualization of drought has become more complex. Holechek and others (2004b:176) referred to drought qualitatively as “a period of low precipitation in relation to a longer-term average,” but also acknowledged drought has been difficult to define quantitatively. The Society for Range Management in its 1974 glossary of terms used in range management defined drought as: “prolonged dry weather, generally when precipitation is less than 3/4 of the average annual amount” (SRM 1974). Cooke and Reeves (1976:76) added a specific temporal component to what they termed an arbitrary definition of a “dry period” and defined such periods as composed of at least three successive years in which annual precipitation is below the mean (how much below the mean wasn’t defined). Based on this definition and its application to southern Arizona precipitation patterns, they made three observations of interest: (1) periods of dry years (or wet years; the definition also applied to wet periods above the mean) are fairly common, (2) spatial occurrence of drought is not consistent from locale to locale over the same timeframe, and (3) drought years are often immediately followed by one or more relatively wet years. Cooke and Reeves (1976) concluded that the consequences of the preceding patterns were that vegetation cover is depleted during a drought and takes more than a year to recover, such that surfaces may be particularly conducive to runoff and erosion during the wet year.

The preceding definitions, though to some degree quantitative, are entirely meteorologically based[8] and, because they focus on mean annual precipitation values, potentially non-conservative. In addition, they suffer from two statistical issues (Thurow and Taylor 1999). First, “normal” precipitation is often based by convention on a 30-year record, which will not adequately reflect a long-term climatic record, especially for arid and semiarid environments in which inter-annual variation is large. Second, the median is a more statistically appropriate method for expressing “normal” than the mean. By 1989 the Society for Range Management’s revised glossary (SRM 1989) included a more complex, but less quantitative, definition of drought that consisted of two slightly different, but overlapping conceptualizations. First, drought was defined as a prolonged chronic shortage of water compared to the norm. Such shortages were often associated with high temperature and seasonal winds. Although not stated, the second part of this conceptualization implies that hot temperatures and convective forces, such as wind, that can increase evaporative losses exacerbate water shortages. Second, reduced precipitation amounts are related to reductions in soil moisture to such an extent that plants suffer from the lack of water. This latter conceptualization is equivalent to an agricultural drought perspective (Thurow and Taylor 1999).

Thurow and Taylor (1999) suggested that the different currently considered perspectives about drought—meteorological, agricultural, hydrologic, and socio-economic—and their accompanying definitions made it difficult for people with diverse interests to agree about what constituted a drought and its beginning and end. For example, a meteorological drought does not have a direct relationship to agricultural drought because other factors, such as temperature, wind, soil properties—and their effect on infiltration rate and soil moisture storage capacity—and the timing of precipitation relative to plant phenology, are not accounted for by meteorological drought definitions. The unfortunate paradox is that the frequency and consequences of drought defined from an agricultural perspective can be independent of any change in the frequency or intensity of meteorological drought (Thurow and Taylor 1999). In

---

[8] Our goal is not to be exhaustive in defining the various approaches to measuring drought, meterologically or otherwise. Drought indices, such as the Standardized Precipitation Index and Palmer Drought Severity Index, are widely used. Each, however, has its limitations in the context of range management. For more information on various drought indices, the reader is referred to the useful website: http://www.drought.unl.edu/whatis/indices.htm.

addition, Thurow and Taylor (1999) suggest that many perceived agricultural droughts are really forage shortages resulting from inappropriate stocking policies. Absent this recognition, they further suggest that inappropriate stocking rates on rangelands during the various periods of drought or on sites that are in poor condition to begin with are likely to manifest agricultural drought more frequently and more severely than sites that are in good condition or are appropriately stocked.

In summary, drought is a complex phenomenon; however, within an arid ecosystem such as the Sonoran Desert its occurrence should be expected and appropriately accounted for in livestock grazing management plans. Various perspectives on drought exist, none of which, along with their current accompanying definitions and metrics, may in isolation or in combination fully account for an ecological perspective on drought in the Sonoran Desert. Such a perspective needs to address the geographic and time-scale dependent variability in precipitation and temperature patterns characteristic of the Sonoran Desert and how the native plant and animal species respond to such variability. Moreover, any definitions of, metrics for, and livestock management responses to drought in the Sonoran Desert need to account for the three periods of drought: onset, during, and exiting.

Some Examples of Sonoran Desert Plant Responses

Perennial plants in the Sonoran Desert are adapted to withstand months without precipitation and low soil moisture and to respond quickly when water becomes available. In some cases the ability to store water also enables a disconnect between a precipitation event and a plant response. Conversely, annual plant recruitment and subsequent production is closely linked to rainfall events, but is highly variable as it is dependent on both precipitation timing and amount. Rainfall predictability and shift between winter and summer annual dominance is also dependent on location within the Sonoran Desert, which as we have seen previously affects the predominant seasonal rainfall pattern. For example, at the eastern margin of the Sonoran Desert in some years with regularly spaced and high amounts of summer monsoonal rains (for example, Tucson summers of 1984 and 1990), production of native summer ephemerals such as six-weeks needle grama (*Bouteloua aristidoides*) and six-weeks grama (*B. barbata*) may be relatively high, especially on sandy soils on basin floors (J. McAuliffe, personal communication). Infrequent but extreme occurrences of drought and wet conditions may shape vegetation patterns for subsequent decades or longer.

Many Sonoran Desert species have their greatest germination and establishment events in response to rare precipitation pulses that may be tied to tropical hurricanes in September and October. This seems to be true for creosotebush (*Larrea tridentata*), triangle-leaf bursage (*Ambrosia deltoidea*), and jojoba (*Simmondsia chinensis*). Seedlings of these species were observed in great numbers all over the Tucson Basin after the hurricane of 1983 (J. McAuliffe, personal communication). Data on triangle-leaf bursage collected by Bowers (2002) supports McAuliffe's observations. Eight pulses in triangle-leaf bursage seedling establishment occurred from 1988 to 1998, in response to an average of 1.6 +/- 0.5 inches of rainfall (40.7 +/- 12.9 mm). This is substantially more than what is required for germination of other species in the same habitat, such as brittlebush (*Encelia farinosa*), which requires 0.7 inches (19.0 mm). Rains leading to germination were delivered over several days. Triangle-leaf bursage is one of the most abundant shrubs in the Sonoran Desert and is important as a nurse plant for the establishment and survival of numerous other species.

The amount and timing of rainfall determines perennial seedling germination and emergence, and the probability of seedling survival in the first year improves with greater total annual rainfall (Bowers and others 2004). In a study of perennial seedlings at Tumamoc Hill in Tucson, Bowers and others (2004) found that 0.7 to 1.4 inches (17.5 to 35.6 mm) of precipitation was required for germination and emergence of 15 species of perennial seedlings. Two germination seasons occur, early spring (February to March) and summer (July to October), with more of the preceding species emerging in August and October than in any other month. Summer rainfall is important for establishment and production of Sonoran Desert plants with subtropical affinities, including both C_3 and C_4 summer annuals (Mulroy and Rundel 1977). Precipitation events during the summer monsoons are of high intensity, which may exceed soil infiltration rates. As a result, much of the rainfall can be lost in runoff. Shallow-rooted plants, such as cacti (including saguaro), ocotillo (*Fouqueria splendens*), and paloverde (*Cercidium* spp.) may take advantage of these rains (J. McAuliffe, personal communication). Although the production of many Sonoran Desert perennials occurs after the monsoons, stable isotope work shows that the water that is used for growth is actually stored from winter rains from the previous season or even prior years (J. McAuliffe, personal communication). This is true for creosotebush, mesquite (*Prosopis* sp.), catclaw acacia (*Acacia greggii*), and other deep-rooted species that generally have distributions in temperate regions. These findings have implications for the timing of plant production in response to rainfall.

Turner’s (1990) study of long-term vegetation change at MacDougal Crater in the Pinacate Reserve, Sonora, provides valuable insights into vegetation dynamics at a site that is seemingly fully protected from local anthropogenic disturbances. He found major turnover in species by evaluating matched photos (from 1907, 1960, and 1986), permanent plots (evaluated six times from 1959 to 1982), and a 170 year-old population of saguaro. Turner (1990) documented a 50 to 90% loss of creosotebush and 60% loss of blue paloverde (*Cercidium floridum*) due to drought before 1960 with little subsequent recruitment and a 200-fold increase in mesquite due to two tropical hurricanes in the 1970s, which created ideal germination conditions. He also found that population patterns were asynchronous between saguaro and paloverde. During the period when paloverdes were in greatest decline, saguaros experienced their greatest increase in numbers. Paloverdes provide essential cover to young saguaro, but death rates of paloverdes are higher among those that have adult saguaros beneath their canopy. With declines in paloverdes due to drought, it is expected that saguaro recruitment will be limited in the future. Turner’s (1990) study is unique in that it clearly shows that there can be dramatic turnover in Sonoran Desert vegetation due to the variable nature of climate alone.

Pulse Dynamics in Arid Ecosystems: Relationships between Precipitation Variability, Soil Moisture, and Plant Functional Types

Section 4.1.1 discussed productivity patterns in the Sonoran Desert and the preceding information in this section focused on important attributes of precipitation patterns within the Sonoran Desert and some example plant responses. Here we attempt to identify current thinking on the linkages between plant productivity (and plant responses in general) to variable precipitation events. Understanding such linkages has important implications for setting appropriate livestock stocking rates while meeting other ecosystem needs in arid and semiarid ecosystems. Earlier attempts at describing relationships between precipitation and ecosystem responses, such as plant production, focused on the effects of mean precipitation averaged at annual, seasonal, or monthly time scales (Schwinning and others 2004). For example, Le Houérou and others (1988) analyzed 77 arid land data sets (none from the Sonoran Desert) on annual production and precipitation. They found that on average variability in production is 1.5 times greater than variability in precipitation. This relationship implies that in a "dry" year production drops off proportionally more than the decline in precipitation, with the opposite result in a wet year.

In arid and semiarid ecosystems, however, precipitation (and often water itself) is available as discrete pulses separated by at times long periods in which it is unavailable. As a result, and especially in water-limited and low productivity ecosystems such as deserts, temporal variation in water availability can be as important as annual (or seasonal) total amounts for plant performance and can result in even greater variation in ecological processes such as productivity. Moreover, the response to the temporal dynamics of water availability can differ between species (Chesson and others 2004, Sher and others 2004) and between different components of plant fitness (Lundholm and Larson 2004). About 30 years ago, two different paradigms were put forth that attempted to provide a conceptual framework for explaining and testing precipitation variability relationships in arid (desert) ecosystems.

The first paradigm, Walter's (1971; as described in Ogle and Reynolds 2004) two-layer conceptual model, predicted that woody and herbaceous plants successfully co-exist in savannas because they use water from two different depths in the soil. Seasonal precipitation characteristics determine community composition and whether herbaceous plants (primarily grasses) or woody plants dominate or whether both life forms co-exist. Walter (1971) proposed that co-existence occurred at about 8 inches (200 mm) of summer rainfall. Summer rainfall that greatly exceeded this amount would result in woody plant dominance because supposedly a larger proportion of water would infiltrate to deeper soil layers that only these plants could access. Conversely, at lower total summer rainfall values, grasses would dominate because little water infiltrates to deeper soil layers and grasses are expected to outcompete woody plants for shallow soil water. Ogle and Reynolds (2004) concluded that the two-layer hypothesis had severe limitations that did not account for the plastic rooting habits of woody plants and their phenology and the timing and magnitude of individual rain events. Furthermore, their analysis of precipitation data for 49 grass and shrub communities argued for an opposite conclusion from Walter (1971) in that grasslands were more common in the western U.S. when summer rainfall exceeded about 10 inches (250 mm). We don't further consider the Walter (1971) two-layer conceptual model here, but from a historical perspective recognize that it was an important attempt to conceptualize how different plant life forms—or perhaps more accurately plant functional types—use water and as a result structure plant communities in different environments.[9]

---

[9] Plant functional types, as used by Ogle and Reynolds (2004) and Reynolds and others (2004), are groupings of plants that share common responses to water availability. Groupings considered include: (1) cacti or succulents, (2) summer active C_4 grasses and forbs, (3) winter active C_3 grasses and forbs, (4) perennial C_4 grasses, (5) perennial C_3 forbs, and (6) woody plants subdivided into categories based on their rooting patterns (Ogle and Reynolds 2004).

The second paradigm, the pulse-reserve conceptual model of Westoby-Bridges and co-workers (published and described in Noy-Meir 1973), includes a trigger component (for example, a rain event of sufficient size, which can itself represent a pulse), a pulse response to the trigger (for example, a pulse of production of annuals), and a reserve (for example, seeds, roots, or stems) compartment. Much of the production pulse is lost rapidly by mortality or consumption but some amount is diverted into the reserve as carbon and energy. Losses from the reserve compartment—from respiration, herbivory, or decay—occur slowly during the no-growth period and from the reserve the next growth pulse is initiated. For arid ecosystems, Noy-Meir (1973) recognized that the trigger—rain—occurred not only discontinuously but stochastically; as a result, plants, and in some cases organisms at the higher trophic level, needed to adapt by adopting strategies that enabled a flexible transition between an inactive (resistant) and active (susceptible) state in intermittently favorable environments.

The notion that biologically important rain events (that is, above threshold amounts) occur that stimulate plant growth and reproduction, as addressed by the pulse-reserve conceptual model, remains a useful and robust concept for understanding arid ecosystem function (Ogle and Reynolds 2004). Recent work has attempted to build on the pulse-reserve paradigm by (1) determining explicitly what constitutes a biologically significant precipitation pulse, (2) adding a compartment to the model that translates precipitation pulses into the more meaningful concept of usable soil moisture pulses, (3) and differentiating the "pulse" compartment into a production compartment that accounts for how various plant functional types use soil moisture in terms of growth (Reynolds and others 2004). Ogle and Reynolds (2004) have further modeled plant functional types to address group differences in response time to a rain event, duration of response, precipitation thresholds necessary to elicit a response, and size of response.

The refinements to the pulse-reserve conceptual model outlined above caution against making generalizations regarding the relationship between precipitation and vegetation response, primarily but not exclusively production, in arid ecosystems. In addition to precipitation and plant functional type response variability, soil properties and their resultant effect on the spatial and temporal distributions of soil moisture play a significant role in mediating vegetation responses in water-limited ecosystems. McAuliffe (2003) identified three aspects of soil moisture distribution that influence vegetation response in both arid and semiarid regions: vertical (depth) distribution, localized evenness versus patchiness in horizontal distribution, and temporal persistence. Soil texture in particular, in conjunction with rainfall intensity, controls surface infiltration and the depth to which water percolates. Evaporative loss occurs mostly within the top 12 inches (30 cm) of the soil profile, with the most rapid loss occurring within the upper two or four inches (5 or 10 cm; Noy-Meir 1973). Low intensity rainfall events may wet only the upper layers of the soil, whereas high intensity events penetrate deeper. Coarse-textured (sandy) soils facilitate more rapid and deeper movement of water than do fine-textured (clayey) soils. The fact that for arid regions water generally is not lost via deep drainage even in coarse-

---

The groupings do not appear to be static as Reynolds and others (2004) categorized shrubs into functional types based on whether they were evergreen or deciduous rather than root patterns. As a result, the conceptual approach seems flexible enough to enable development of, given sufficient relevant data on factors such as rooting patterns and water storage capabilities, landscape-specific plant functional types and apparently even may allow biological soil crusts to be included as a functional type (for example, see Cable and Huxman 2004).

textured soils water—that is, all soil moisture is either evaporated or transpired—leads to the inverse texture effect hypothesis of Noy-Meir (1973), in which coarse soils lose less moisture to evaporation and consequently support taller and denser vegetation (that is, higher production) than fine soils (the opposite of what is expected in humid climates).[10]

Horizontal spatial heterogeneity of soil moisture can result from several factors. For example, extremely rocky substrates or soils with shallow, strongly cemented calcic horizons (caliche) that crack and are penetrated by roots can create heterogeneous horizontal distributions of soil moisture (McAuliffe 2003). Surface cover spatial patterns, for example, those resulting from the distribution of plants and biological soil crusts, also can affect the horizontal distribution of water in the soil profile (Loik and others 2004). Temporal persistence of plant-available soil moisture is related to depth of moisture storage (McAuliffe 2003). As discussed in the preceding paragraph, water confined to the upper soil layers is more apt to be lost to evaporation before it can be used by plants and biological soil crusts, especially when temperatures are hot and humidity is low. In arid and semiarid environments, clay-rich argillic horizons can form that inhibit water movement to deeper portions of the soil profile. Such soils, because they reduce the capacity for water storage at depth, amplify seasonal variation in plant-available moisture in contrast to soil conditions that dampen seasonal variation by facilitating storage (McAuliffe 2003). The formation of argillic horizons indicates the importance of surface age in determining the soil moisture properties of desert soils. Argillic horizons may take tens to hundreds of thousands of years to form. As surfaces age they determine the distribution and duration of soil moisture and ultimately the types of plants that dominate on each surface (McAuliffe 1991, 1995).

Two other concepts, not yet explicitly mentioned, deserve mention. First, is the idea that precipitation pulse patterns (that translate into soil moisture pulses) and the responses they engender in the biota and ecological processes can be organized in a hierarchical manner (Schwinning and Sala 2004). For example, small pulses of moisture that last only a short duration and do not penetrate much of the soil profile may trigger only limited ecosystem responses, such as activating soil microbes that live at the soil surface. Higher pulses of precipitation or rainfall clusters that achieve deeper and longer levels of soil moisture trigger greater responses. Different plant functional types would be expected to evolve different response thresholds and physiological/structural response strategies to soil moisture pulses. Pulse thresholds and a hierarchical response framework again caution against expecting a simple scaling relationship between annual or seasonal total precipitation amounts and process rates in arid and semiarid ecosystems, as the size and frequency class distribution of pulse events change with total precipitation amounts (Schwinning and Sala 2004). Second, to this point we have described the impact of a precipitation pulse event as if it occurred under dry soil conditions. The level of antecedent moisture may dampen or amplify the effect of an individual precipitation pulse and is an important aspect of the soil water compartment of the modified pulse-reserve conceptual model (Reynolds and others 2004).

---

[10] The inverse texture effect hypothesis may be mediated somewhat by nutrient turnover dynamics. Austin and others (2004) suggest that nitrogen mineralization increases (which increases plant-available nitrogen) linearly with increased precipitation in coarse-textured soils, whereas in fine-textured soils nitrogen mineralization increases much more rapidly than in coarse-textured soils at low precipitation values and then plateaus (saturates) at higher values.

Reynolds and others (2004) ran an 85-year simulation model in an attempt to elucidate some of the conceptual thinking behind the "modified" pulse-reserve conceptual model. They assessed a variety of plant functional types (along with their characteristic rooting profiles, germination and growth patterns, and biomass); soil moisture availability as a function of precipitation input, soil texture, and antecedent water; and daily precipitation records for three locales, one each within the Chihuahuan, Mohave, and Sonoran (Tucson area) Deserts. For the plant functional types they considered—six groupings that included two shrub groups, winter annuals, summer annuals, perennial forbs, and perennial grasses—they suggested that precipitation variability is best understood as a sequence of rainfall events that produce biologically significant pulses of soil moisture recharge, as opposed to individual rain events. This conclusion, however, may be sensitive to the functional types considered because of the hierarchical nature of biotic and ecological process response to rain events (Schwinning and Sala 2004). The intersection of precipitation patterns and soil texture across the three desert locales produced different soil moisture recharge patterns (Reynolds and others 2004). For example, for loamy sands (12% clay), Mojave rainfall regimes recharged the 15.7 to 23.6 inch- (40 to 60 cm) soil layer in 36% of the years but in only 15% of the years for the 23.6 to 31.5 inch- (60 to 80 cm) soil layer, whereas at the Tucson local the percentages were 83% and 53%, respectively. Across all deserts deep recharge (>31.5 inches [80 cm]) was an uncommon event, except in sand (6% clay). Regardless of soil texture and desert, plant functional types obtained 60% of their annual water from the top 15.7 inches (40 cm) of the soil profile. Generalizations regarding specific growth responses by plant functional types to moisture pulses were not that conclusive (Reynolds and others 2004). The most consistent, strong positive relationships across deserts were for C_3 annuals to winter rain, C_4 annuals to summer rain, and C_3 perennial forbs to winter rain. At the Sonoran Desert site, the greatest plant growth responses occurred following large storms (>2 inches [5 cm]) with dry antecedent soil conditions. Despite this latter finding, for all three deserts precipitation that fell in the winter seemed to provide a more biologically useful seasonal pulse than did summer rain. The summary of findings outlined above belies the overall complexity of Reynolds and others (2004) simulation model outcomes and their interpretation. In addition, some simplifying assumptions made by the authors, such as initiating the simulations with the same total biomass (reserve) and the same distribution of that biomass among plant functional groups for all three desert locales, could have significant consequences for the realism of simulation outcomes for each desert locale.

From the seminal work of Noy-Meir (1973) to the present, out understanding of desert ecosystem dynamics continues to improve. Current work has elucidated some of the complexities involved and at the same time confirmed the importance of understanding the interactions between precipitation variability, soil moisture recharge, and variable plant response in desert ecosystems. Such understanding has importance for land managers when designing ecologically compatible strategies for land use. Work still remains to refine the models, their input data, and the ability to interpret model outcomes in terms of desert and plant-community specific findings. The greatest value of this work at present is its heuristic value in identifying key process variables and plant responses that shape the communities of desert ecosystems and in improving our ability to develop appropriate land management strategies.

4.1.3 Catastrophic Freeze

Within the Sonoran Desert extreme temperatures change markedly with elevation and the degree of continental or coastal influence, with summer high temperatures frequently exceeding 120ºF (49ºC) in northwestern Sonora (Búrquez and others 1999). The occurrence of below freezing temperatures and their duration establish the northern (and elevational) limits of many Sonoran Desert plant species (Turner and others 2003). The mean freeze frequency per year and the severity of freezes differs by site and is largely dependent upon elevation, aspect, and topography. The occurrence of cold-air drainage is dependent on local topographic relief.

Some Sonoran Desert plant species are frost-tolerant and are relicts from a cooler, wetter time thousands of years ago. These species have since been relegated to higher elevations and north-facing slopes, where they find favorable microclimates (Brown 1978). Some of these unique plant assemblages are found only on the highest elevations of select mountain ranges in the Sonoran Desert, including the Sand Tank and Table Top Mountains on the Sonoran Desert National Monument (Brown 1978, Morrison and others 2003). The characteristic plant species of these high-elevation plant communities include crucifixion thorn (*Canotia holacantha*) and Arizona rosewood (*Vauquelinia californica*). Whether these species continue to persistence, in what are currently relatively cool Sonoran Desert sites, could be a sensitive indicator of global climate change expressed at a regional scale.

Cold air masses infrequently travel through the Great Basin and into the Sonoran Desert, bringing subfreezing temperatures and potentially causing significant changes to plant community composition and structure (Búrquez and others 1999). A catastrophic freeze occurs when low minimum temperatures and many consecutive hours of freezing interact (Bowers 1981). A catastrophic freeze is one that has the potential to kill or injure many species of plants, particularly species that have tropical affinities and reach their northern range limits within the Sonoran Desert. Species prone to catastrophic freeze include hallmark Sonoran Desert species such as saguaro, triangle-leaf bursage, foothill paloverde (*Cercidium microphyllum*), and blue paloverde (Bowers 1981).

As indicated previously, Turner and others (2003) defined the eastern and northern boundaries of the Sonoran Desert on the basis that within these boundaries and below certain elevations temperatures never stayed below freezing throughout the day, though they could drop below freezing for portions of a day. So what is of interest in the shaping of Sonoran Desert plant communities is not whether freezing occurs, but rather its frequency, intensity, and duration and how these factors interact to cause catastrophic freezes. Although catastrophic freezes are relatively infrequent, they nonetheless can be responsible for great changes in plant communities at a local scale. Bowers (1981) documented four catastrophic freezes in the Sonoran Desert from 1946 to 1979, with resultant widespread frost damage to Sonoran Desert plants. For example, approximately 18 hours of subfreezing temperatures (reaching a low of 21ºF [-6ºC]) at Organ Pipe Cactus National Monument in 1978 resulted in the injury or death of numerous plants, including brittlebush, ironwood (*Olneya tesota*), and Mexican jumping bean (*Sebastiana bilocularis*), as well as the loss of entire populations of elephant tree (*Bursera microphylla*) and limberbush (*Jatropha cinerea*) (Bowers 1981, Warren and Anderson 1992). Microsite characteristics such as the presence of nurse plants or a bedrock shelter can moderate climatic fluctuations at a local scale and improve the chances that plants will be protected from catastrophic freeze.

Freezes that kill numerous individuals or populations can induce competitive release at a site, which can lead to species turnover and changes in composition over time. Catastrophic freeze also can alter community structure. At a site in the San Pedro Valley in Arizona (located within a transition zone between the Sonoran Desert and Apache Highlands Ecoregions), over four days of subfreeezing temperatures in December 1978 had differential effects on mesquite depending on elevation. Below 3,115 feet (950 m) elevation mesquites were leafed out and appeared healthy, but above this elevation and at upstream sites mesquites had higher rates of mortality, less leaf sprouting, presence of malformed emerging leaves, and greater dieback of limbs. Some trees were not expected to survive, whereas others were expected to have a shrub-like form rather than their former tree-form (Glinski and Brown 1982).

4.1.4 Fire

For a wildfire to occur both an ignition source and adequate fuel conditions are necessary. Lightning is a common ignition source during the summer monsoons, but human-related ignition is likely increasing the overall opportunities for fire initiation within portions of the Sonoran Desert (Schmid and Rogers 1988, Brooks and Esque 2002). Factors that influence fuel condition (and the properties of a fire) include: plant tissue flammability, overall fuel load, horizontal and vertical connectivity of the fuels, and the fuel packing ratio (Brooks and others 2004).

Humphrey (1963, 1974) identified the generally limited role of fire in shaping the plant communities of the Sonoran Desert. With the exception of tobosa grass in periodically flooded swales, that he thought burned periodically but less frequently than semidesert grasslands, he considered perennial grasses (and forbs) too widely spaced to serve as a fuel source adequate to carry fire. Humphrey (1974) also suggested that annual forbs and grasses produce too little biomass and occur in insufficient densities to carry fire in the Sonoran Desert. He noted that most fires occur within the ecotone between desertscrub and semidesert grassland. Sufficient precipitation could result in a flush of annuals during extremely wet years. These areas, however, Humphrey (1974) considered the deteriorated lower fringes of semidesert grassland, subjected to historic grazing and fire control, rather than true Sonoran Desert desertscrub.

Although some native plant species show adaptations to fire, either they are not strongly developed (Rogers and Steele 1980) or they are typically limited to species that are not restricted in their distribution to the Sonoran Desert (McAuliffe 1997). Adaptation at the community level would require that recovery to pre-fire community composition and structure occur before the next fire occurred. Many of the characteristic Sonoran Desert plants, including woody legumes, shrubs, saguaro, and many other species of cacti, are fire-intolerant and exhibit high rates of mortality after experiencing fire either through the direct effects of the fire or subsequent indirect effects (Humphrey 1974, McLaughlin and Bowers 1982, Rogers 1985, Wilson and others 1996, McAuliffe 1997). For example, in a Paloverde-Mixed Cacti-Mixed Scrub Community southeast of Florence, Arizona, McLaughlin and Bowers (1982) found significantly reduced overall plant density and cover on a burned site compared with an unburned site. Nearly all trees and shrubs were shoot-killed (tops completely burned). In addition, mortality was high among the smaller cacti and the smallest size classes of saguaro. Triangle-leaf bursage had the highest rate of mortality (92%) of the shrubs and tress and the most dramatic decrease in density, with 2,749 plants/acre (6,790 plants/ha) on an unburned site compared with 192 plants/acre (475 plants/ha) and 219 plants/acre (540/ha) seven months and eighteen months after the fire on the burned site, respectively. In addition, resprouting occurred in only one percent of the shoot-killed bursage. Although McLaughlin and Bowers (1982) observed relatively small levels of mortality among the larger size classes of saguaro, a lag between injury and depth is possible. Rogers' (1985) repeat sampling of the same area 54 months after the fire indicated increased saguaro mortality attributable to the effects of the fire. He predicted that saguaro could be eliminated from stands that had fire-return intervals less than 30 years.

Some researchers have suggested that under certain restricted conditions—such as the occurrence of two consecutive unusually wet winters within the Arizona Upland subdivision that leads to high production of winter annuals—a sufficient fuel load can develop to sustain fire (McLaughlin and Bowers 1982, Rogers and Vint 1987). McLaughlin and Bowers (1982) hypothesized that at least two consecutive wet winters may be required to produce enough ephemeral production to carry fire. The first wet winter would increase the production of annual plants and add to the seed bank (that may have declined after several dry winters), which would further serve to increase ephemeral production after the subsequent wet winter. The low frequency of occurrence of such events, as well as their spatial pattern and areal coverage, leave open the question of whether a characteristic fire-return interval is meaningful for characterizing Sonoran Desert plant communities. Moreover, both McLaughlin and Bowers (1982) and Rogers and Vint (1987) failed to indicate whether the presence of non-native plant species, such as red brome (*Bromus madritensis rubens*), contributed to the fuel load.

The only detailed study of fire-return intervals in the Sonoran Desert took place on the desert portion of the Tonto National Forest (Schmid and Rogers 1988). The investigators concluded that over the period of the study, 1955 to 1983, the frequency of fire was sufficiently low (recurrence interval of 294 years) to support past impressions that natural fire in the Sonoran Desert is a rare event. Of concern, however, was the increase in return interval between the first and second halves of the study period. Schmid and Rogers (1988) attributed this increase in part to the fuel provided by unspecified non-native annual plants.

Invasive non-native plants pose the greatest threat to altering the historic fire regimes of the Sonoran Desert (Brooks and Pyke 2001, Brooks and others 2004). Alteration can involve increases in the frequency, size, and intensity of fires. Although invasive non-native plants can impact the native biodiversity of an area through many different mechanisms, it is when they alter broad-scale ecological processes, such as natural fire regimes, that they pose their greatest threat. Altered fire regimes can result in dramatic shifts in community composition, structure, and function. The invasive non-native plants that pose a risk of altering fire regimes differ according to location in the Sonoran Desert. Depending on locale Mediterranean grass (*Schismus* spp.), buffelgrass (*Pennisetum ciliare*), fountain grass (*P. setaceum*), and red brome are of the most concern (Brooks and Pyke 2001). These species increase the biomass and continuity of fine fuels by their presence. Of these species, red brome tends to require mesic conditions, whereas Mediterranean grass can establish in even the most arid portions of the Sonoran Desert. As a winter annual grass, red brome is sensitive to winter rainfall amounts and can rapidly increase its biomass in wet years (Brooks and Pyke 2001). All of these grasses are adapted to fire and, as a result, their invasion potentially can set in motion a positive feedback cycle that leads from a non-flammable, mostly native dominated and diverse desertscrub community to a highly flammable, low diversity, non-native grassland community with recurrent fire (D'Antonio and Vitousek 1992, Brooks and Pyke 2001).

The introduction, establishment, and subsequent ecological role of invasive non-native plants in native ecosystems involve many factors that determine successful invasion and subsequent ecological impact. Brooks and Pyke (2001) identified livestock grazing as one of a number of land use practices that can influence the interaction between invasive non-native plants and altered fire regimes. Livestock can facilitate the spread and establishment of invasive non-native species by dispersing seeds (and other propagules) in fur and dung, creating suitable habitats that favor species that thrive in disturbed sites, and by providing non-native species a competitive advantage by selectively foraging on native species (Fleischner 1994). In particular, the foraging patterns of livestock can facilitate invasion by creating favorable microsites through soil and biological soil crust disturbance and nutrient enrichment. Livestock management practices also can play a role. For example, areas in the vicinity of livestock water developments tend to support relatively high richness and abundance of non-native plants (Morrison and others 2003, Brooks and others In Press). These areas can provide source populations of invasive non-native plants and thereby facilitate their subsequent spread to other areas. Purposeful introduction of non-native forage species such as buffelgrass can contribute directly to altered fire regimes.

4.1.5 Herbivore-Plant Community Interactions, Cattle Diets, and Herbivory as a Selection Pressure

Interactions between a herbivore and those plant communities with which it has an evolutionary or contemporary relationship are not just limited to herbivory of individual plant species. Ancillary effects, such as the trampling activity of large hooved mammals, create ground-disturbance regimes that also may select for particular plant characteristics. Such disturbance regimes may be fundamentally different than the ground disturbances caused by insects and small mammals, which may select for (or not influence) different plant characteristics (Mack and Thompson 1982). Moreover, although selection occurs at the individual species level, at any point in time community composition, structure, and function will reflect the integration of different selection pressures across multiple species. Finally, even for plant communities that do not have an evolutionary history of interactions with large-hooved native herbivores, some of the constituent species, especially subdominants, may possess characteristics that seemingly pre-adapt them to this interaction but that can be attributed to other selection pressures (Mack and Thompson 1982, Milchunas and others 1988).

This section briefly addresses the issue of large hooved herbivore-plant community interactions in the Sonoran Desert. This is followed by a description of herbivory and cattle diets in the Southwest, especially site-specific information from the Sonoran Desert National Monument. The section concludes with a brief overview of the evolutionary role of herbivory and how that may relate to the impacts of grazing by domestic livestock. The effect of herbivory on plants is somewhat controversial. Some authors suggest that plants respond favorably to or have co-evolved with herbivory, whereas others suggest that herbivory can have negative effects on plant growth, reproduction, and survival.

Interaction of Large-Hooved Mammalian Herbivores with Sonoran Desert Plant Communities: The Role of Evolutionary History

Some scientists theorize that the degree to which plant communities are impacted by or tolerate grazing by large mammalian herbivores depends in part on the evolutionary history of the community with grazing. As a result, plant communities that supposedly do not have an evolutionary history of grazing by large mammalian herbivores should exhibit characteristics of degradation when exposed to such grazing by domesticated equivalents. Tolerance to or intolerance to grazing generally focuses on the responses of grasses. For the plant communities that are generally considered intolerant of grazing, the grasses tend to be caespitose rather than rhizomatous or stoloniferus, defoliation reduces competitive interactions, and production of new tillers in response to defoliation is not well developed (Milchunas and others 1988; see also Mack and Thompson 1982:table 1, in which additional features are identified that may affect degree of susceptibility to an adverse impact from grazing).

Milchunas and others (1988) have suggested, however, that evolutionary grazing history alone is not a good predictor of plant-herbivore interactions and that environmental moisture gradients also affect the nature of the interaction (and consequently the selection regime under which the grasses have evolved). For example, grass species in semiarid grasslands with long evolutionary histories of grazing experience convergent selection pressure in which evolved traits that enable the plant to tolerate grazing also enable it to use moisture more effectively. Conversely, grasses in semihumid grasslands with long histories of grazing experience divergent selection pressure. The increased moisture favors taller grasses that enhance the competition for light but make individual plants more vulnerable to grazing by large herbivores. The implications of the preceding hypothesis for desert ecosystems—at the arid end of the moisture gradient—could be that individual plant species (at least grasses) have evolved characteristics as an adaptation to low moisture levels that also may enable them to tolerate grazing whether or not they co-evolved with large mammalian herbivores. Such a conclusion, however, may or may not extend to other biotic components and associated ecological processes of desert ecosystems.

As part of their study, Milchunas and others (1988) developed a conceptual model for grasslands that attempted to relate community characteristics and responses to grazing along gradients of moisture and of evolutionary history of grazing divided into four quadrants: long history-semiarid, long history-subhumid, short history-semiarid, and short history-subhumid. Community characteristics associated with the short history-semiarid quadrant included short and mid-stature grasses, past selection for aridity (versus canopy), and competition for soil resources (versus canopy space). Among the community responses to grazing predicted for short history-semiarid grasslands were: regrowth potential of grasses is moderate but vertical (lack of horizontal tillering), moderate effects on community composition and physiognomy, species diversity increases are small at light grazing intensity and decline slowly from the peak as intensity increases, and potential for invasion by non-native species is moderately high. Mack and Thompson (1982) also associated the presence of biological soil crusts as a feature of this community type and suggested that disturbance of the crust by large herbivorous mammals makes the community susceptible to invasion by non-native species (see also Mack 1981).

Milchunas and Lauenroth (1993) attempted to in part quantitatively assess the conceptual model of Milchunas and others (1988) and otherwise further elucidate the relationship between ecological theories of plant-herbivore interactions and conceptual frameworks for managing rangelands. To do so, they used multiple regression techniques to analyze 276 datasets from 236 sites worldwide that compared plant species composition, abundance of dominant species, ANPP, root biomass, and soil nutrients at grazed (year-long or during the growing season) and control (ungrazed) areas. They extended their analysis beyond grasslands and included study sites from deserts, shrublands, forests, and high-elevation (mountains) areas as well. The authors' objective was to quantitatively assess factors relating to differential sensitivities of ecosystems to grazing by large herbivores. As a result, the preceding dependent variables were assessed for their response to grazing variables such as grazing intensity and years of protection from grazing and to ecosystem-environmental variables such as mean annual precipitation, high and low temperatures, latitude, ANPP, and evolutionary history of grazing. The evolutionary history of grazing by large herbivores at a study site included considerations of both grazing intensity and the length of time of grazing (from the early Pleistocene Epoch, approximately one million years ago, up to until the early 1890s). Based on the preceding criteria, the evolutionary history of grazing was estimated by five independent scientists who ranked each site from 1 to 4 (from least to greatest evolutionary history of grazing) and the degree of certainty of their estimate from 1 to 4 (low to high certainty). One percent (3) of the community types considered were classified as desert, two of which were Sonoran Desert study sites (Blydenstein and others 1957 and Waser and Price 1987). Desert data did not include measures of ANPP.

Milchunas and Lauenroth (1993) found that the evolutionary history of an ecosystem with grazing explained a significant portion of the variance in changes in species composition, dominant species, and ANPP between grazed and ungrazed sites; however, in contrast to the conceptual model of Milchunas and others (1988) no notable interaction between evolutionary history and ANPP was detectable. As a result, increasing evolutionary history of grazing produced increasing dissimilarity in species composition with grazing regardless of ANPP levels. Percentage differences in ANPP between grazed and ungrazed sites decreased with increasingly long evolutionary histories of grazing. The data and models support the controversial hypothesis that grazing can increase ANPP in some situations (see below). Conditions under which grazing was more likely to increase or have no or small effect on ANPP were low productivity ecosystems and a long evolutionary history of grazing. Notably, changes in the ecosystem-environmental independent variables, including evolutionary history of grazing in the ecosystem, explained more of the variation in species composition and dominance patterns and percent differences in ANPP at the grazed and ungrazed sites than did recent grazing intensity or the years of protection from grazing. The authors concluded that, within limits not considered to be overgrazing, the geographic location of grazing may be more important than how the site is grazed in determining responses.

The immediate relevance of Milchunas and Laurenroth (1993) analysis is somewhat limited for desert ecosystems. Because they lacked ANPP data for the desert sites, they were not included in many of the analyses. We can only infer that the findings for deserts may be similar to the low end of the aridity/ANPP gradient that was analyzed, but must do so with caution. Desert ecosystems were ranked the lowest of all global habitats (grasslands, shrublands, forests, and mountains) in terms of the length and intensity of their evolutionary history with grazing, with the two Sonoran Desert studies ranked 1.45 (Waser and Price 1981) and 1.17 (Blydenstein and others 1957), respectively.

To determine the actual evolutionary history of grazing within a region—in which native, large mammalian herbivores currently are not present—requires a good fossil record and an understanding of the abiotic features and plant community characteristics that were contemporary with such species in the past, if they existed, and how current conditions correspond. Martin (1999) details the loss of the late Pleistocene megafauna from the Southwest. The larger species went extinct—not necessarily on account of climate change, but the proximate cause is controversial—prior to the beginning of the Holocene Epoch (last 10,000 years) and were survived by their smaller brethren (Martin 1999:table 8.1). Martin (1999) proposes, however, that western land managers should consider introducing the contemporary Old World relatives of the extinct megafauna on the basis that they are a missing piece of the region's ecology. Although the modern climate and vegetation is distinctly different from the period in which these mammals went extinct, the argument made is that they had experienced and endured comparable (interglacial) conditions earlier in their evolutionary history (Martin 1999).

For the Sonoran Desert in particular, the contemporary plant communities and many of the individual floral elements are of recent origin (McLaughlin 1986, Van Devender 2000). Regardless of potentially similar climate between today and prior interglacial periods, the current assemblages of plant and animal communities evolved in the absence of large mammalian herbivores. Although Old World ecological equivalents may be pre-adapted to survive in the Sonoran Desert today, it by no means indicates that the current Sonoran Desert biota is pre-adapted to interact with such newcomers beyond general responses to any herbivore (Noy-Meir 1993). Those mammalian herbivores that survived the Pleistocene extinctions and exist today within the Sonoran Desert were the smaller herbivores (Martin 1999:table 8.1), such as pronghorn (*Antilocapra americana*) and mule deer (*Odocoileus hemionus*). Besides their smaller sizes, native ungulates within the Sonoran Desert also would have to be relatively nomadic in responding to the spatially and temporally variable production of the Sonoran Desert. As such, their impact to plant community composition, structure, and function is likely quite different than domestic livestock that are concentrated spatially and temporally by fencing, water developments, and stocking rate practices. In natural ecosystems, herbivore biomass and average herbivore body size are correlated with changes in primary productivity; that is, less productive ecosystems are associated with lower overall herbivore biomass and smaller herbivores on average (East 1984, Oesterheld and others 1992). In summary, the evidence is weak that Sonoran Desert plant and animal communities have a long evolutionary relationship with grazing by large, hooved mammalian herbivores.

Herbivory and Cattle Diets in Arid and Semiarid Ecosystems

Herbivory is an ecological process that affects plant community composition, structure, and function. Noy-Meir (1974) and Hadley and Szarek (1981) reviewed some of the literature on consumption of plant primary production in desert ecosystems. In general the information reported addressed consumption by individual species or taxonomic groups, but it did not provide estimates of total consumption by native consumers at the community level. In contrast to herbivory, some insects, birds, and small mammals may have a greater effect on plant communities through seed predation. Predation of seedlings by native herbivores in the Sonoran Desert can be a major factor affecting seedling survivorship. For example, Bowers and others (2004) found that the probability of survivorship of 15 species of perennial seedlings was 0.1% in the first four years after emergence, with 37.4% of seedlings dying from predation (in comparison to 12.9% from desiccation). Almost a third (32%) of saguaro seedlings are lost to herbivorous insects in the first two years following germination (Steenbergh and Lowe 1969). Noy-Meir (1974) estimated that domestic mammalian grazers animals consumed between five to 75% of total primary production under the different grazing intensities practiced; however, he did not identify any specific studies to confirm these values nor did he identify the specific conditions under which the range of values was based.

Herbivores can be characterized by the type of plant material they consume. “Grazers” primarily consume grasses, whereas “browsers” consume primarily forbs[11] and shrubs. “Intermediate feeders” are herbivores that consume near equal amounts of grasses, shrubs, and forbs (Holechek and others 2004b). In general, cattle are considered to be grazers: that is, grasses dominate their diet. On some ranges, however, cattle are browsers and consume large amounts of forbs and shrubs, primarily when green grasses are unavailable.[12] Cattle have evolved avoidance behaviors to preclude them from eating shrubs that are high in volatile oils, as they lack mechanisms to deal with the toxicity. Because cattle are the type of domestic livestock that graze on the Sonoran Desert National Monument, we focus the remainder of our discussion here on cattle diets.

Holechek and others (2004b) present the results from 14 studies that examined cattle diet composition in different locations and habitats. Although there were no studies from the Sonoran Desert, results demonstrated the great variability in the relative percentage of grasses, forbs, and shrubs consumed by cattle, depending largely on the site. Grass consumption ranged from a low of 26% in a salt desert habitat in Nevada to 86% in a semidesert grassland site in Arizona. Forb consumption ranged from zero to 1% in a salt desert habitat in Nevada and semidesert grassland in Arizona to 44% in a shortgrass prairie in Nebraska. Consumption of shrubs ranged from 4% in a shortgrass prairie in Nebraska to 40% in a salt desert habitat in Utah. It seems from the data presented in Holechek and others (2004b) that cattle are grazers at sites where grasses are abundant and available, but that they shift to browsing in habitats where forbs and shrubs predominate or after they remove available grasses.

Within the Sonoran Desert, cattle are apparently opportunistic feeders with seasonal shifts in diet and patterns of consumption that depend largely on the characteristics of the site. Browse species are the most reliable and available plant material year-round and include the leaves, twigs, flowers, and fruit of numerous shrubs or trees, including paloverde, ironwood, mesquite,

---

[11] A forb is defined as any broad-leafed herbaceous plant other than grasses, sedges, or rushes (Holechek and others 2004).

[12] In this report we generally use the term “grazing” loosely (as in “cattle grazing” or “livestock grazing”) to mean consumption of plant material, whether grasses, forbs, shrubs, or trees.

catclaw acacia, jojoba, ratany (*Krameria* spp.), Mormon tea (*Ephedra trifurca*), white bursage (*Ambrosia dumosa*) and saltbush (*Atriplex* spp.) (D. Robinett, personal communication).

When and where available, green annuals (grasses and forbs) and perennial grasses are the "ice cream plants" that are preferred by cattle. Based on the preceding discussion of precipitation variability, it would seem that in general the production of winter annuals would be more dependable in the Mojave Desert, whereas as one approaches the eastern extent of the Sonoran Desert the production of summer annuals becomes more dependable. It may be difficult, however, for cattle to exploit annual production in the summer at some sites in the Sonoran Desert because of the extreme temperatures (P. Ogden, personal communication). Some of the plants that are most preferred by cattle in the Sonoran Desert include globemallow (*Sphaeralcea ambigua*), poreleaf (*Porophyllum* spp.), dogweed (*Dyssodia spp.*), buckwheat (*Eriogonum* spp.), silverbush (*Ditaxis* spp. [*Argythamnia* spp.]), slender janusia (*Janusia gracilis*), bush muhly (*Muhlenbergia porteri*), three-awn (*Aristida* spp.), and big galleta (*Pleuraphis rigida*) (D. Robinett, personal communication.). Indian wheat (*Plantago* spp.) is another important winter annual and is one of the few native annuals that cattle will consume after its maturity when it is dry (G. Ruyle, personal communication).

The majority of cattle foraging activity is centered around watering points and in drainages or xeroriparian areas, where perennial grasses may be available as well as abundant browse and shade (G. Ruyle, personal communication). Preferred forage species may be eliminated or remain present only beneath protective shrubs at sites where they are heavily used by cattle (D. Robinett, personal communication).

Table 4.2 provides diet data for cattle on the Sonoran Desert National Monument. Diet composition was determined through microhistological analysis of fecal samples. The data illustrate definite seasonal shifts in what cattle are eating on the monument. During the pre-monsoon seasonal drought and once the monsoon rains have ended and herbaceous vegetation has dried, cattle are primarily browsing on trees (mostly ironwood during the pre-monsoon period and a mix of ironwood, mesquite, and paloverde during the post-monsoon period). Mediterranean grass is a significant component of the diet during the late winter and early spring, whereas grama grasses (*Bouteloua* spp.) and big galleta are important after the monsoon season starts and the grasses respond. On the monument, non-native plants are contributing a significant amount to cattle diets. The data cover a period that reflects an above average summer monsoon rainfall during 1982 (see Figures 3.9 and 3.13), average winter rainfall in 1982 and well above average winter rainfall in 1983 (see Figures 3.8 and 3.12), and above average total annual precipitation in both 1982 and 1983 (see Figures 3.6 and 3.10).

Herbivory as a Selection Pressure and the Herbivore Optimization Hypothesis

Herbivory is the selective removal of biomass from plants. What are the effects of biomass removal on plants? Some plants are sensitive to damage from herbivory; that is, they lack chemical or mechanical protection or are unable to regrow after vegetation removal (see Belsky and others [1993] for an overview of sensitivity and resistance of plants to herbivory). Other plants have evolved adaptations to herbivory in two main ways: by avoidance or tolerance. Characteristics of plants that avoid herbivory include the presence of thorns or spines or

TABLE 4.2 Plant Life-Form Composition of Cattle Diets on the Sonoran Desert National Monument[1]

Life Form	**Date**											
		Spring			Summer			Fall			Winter	
	3–82 n = 2[2]	4–82 n = 3	5–82 n = 2	6–82 n = 3	7–82 n = 3	8–82 n = 2	9–82 n = 2	10–82 n = 2	11–82 n = 1	12–82 n = 1	1–83 n = 1	2–83 n = 1
Perennial Grasses	1	10	8	2	3	28	40	60	64	3	2	0
Annual Grasses and Forbs	68	82	40	28	5	2	12	4	10	0	1	94
Perennial Forbs, Vines, and Shrubs	19	4	24	12	20	22	14	24	1	37	14	5
Cacti	5	1	1	2	8	0	0	2	0	3	7	0
Trees	5	1	24	52	66	47	30	10	16	56	75	0
Totals	98	98	97	96	102	99	96	100	91	99	99	99

[1] Data are from sites associated with the Bighorn Allotment (see Figure 3.1), except for December 1982 and January 2003, which are from the Vekol Allotment. Data are the percentage of the diet attributable to that life form during a particular month of sampling rounded to the nearest whole number. Percentages do not necessarily add up to 100% primarily because of rounding errors. Shading of a cell indicates the life form that constitutes the highest percentage of the diet during a particular month. Raw data provided by B. Lambeth of the Bureau of Land Management's, Phoenix Field Office. See text for additional details.

[2] Number of sites sampled within the allotment. At each site, five subsamples were collected with one exception. Only three subsamples were collected at one of the sites during October 1982.

chemical defenses that make plants unpalatable to herbivores. Species that tolerate herbivory are those that can sustain some portion of their aboveground biomass removed and regrow. The portion of biomass that can be removed and still enable the plant to regrow depends on the species, the time of year (dormant or growing season), and other environmental factors (Holechek and others 2004b).

Moderate levels of grazing may encourage new growth in at least some species of plants (compensatory growth). For example, Roundy and Ruyle (1989) showed that jojoba tolerates cattle grazing by regrowing twigs from lateral or apical buds. The authors found that because of jojoba's compensatory growth in response to grazing, grazed and ungrazed shrubs had similar net increases in twig length and biomass. A tradeoff, however, may exist between increased growth in response to grazing and reproduction. Grazed jojoba shrubs had lower male and female flower densities than ungrazed shrubs (Roundy and Ruyle 1989).

The above example of jojoba describes how some plants tolerate grazing. Some authors go a step further and suggest that grazing is beneficial to plants, and that loss of plant tissue to herbivores leads to increased total productivity, longevity, or reproductive potential of grazed plants compared to ungrazed plants. The possibility that herbivory maximizes the fitness of plants or that plants and their herbivores have a co-evolved mutualistic relationship has been considered since the mid-1970s (Belsky 1986). The possibility that grazing is beneficial to plants has been referred to as “overcompensation” or the “herbivore optimization” hypothesis.[13] The underlying conceptual model is the herbivore-optimization curve—based in part on studies by McNaughton of native mammalian herbivores and grasses on the Serengeti Plains of East Africa (see Belsky [1986] for a detailed bibliography), in which net primary productivity or ANPP of grazed plants increases at low to moderate levels of herbivory until a maximum is reached (optimal grazing level). After reaching this level, productivity declines to the point that under high grazing intensities productivity falls below ungrazed levels (Belsky 1986:figure 1 shows the curve and adds to it regions in which overcompensation and undercompensation occur).

The herbivore optimization hypothesis is controversial. Ambiguity of the term “compensatory growth” has in part confounded the debate over whether herbivory increases plant productivity and fitness because of the range of plant responses attributed to it (Belsky 1986). Moreover, Milchunas and Lauenroth (1993) noted that tests of the hypothesis are confounded by the “scale” of observation: (1) individual plant versus community, (2) short-term versus long-term, and (3) aboveground, belowground, or total plant biomass. For example, herbivore optimization is often viewed in the context of aboveground productivity only (Painter and Belsky 1993). Some long-lived perennial plants, however, have the majority of their biomass belowground, so any observed increase in aboveground biomass in response to grazing may represent a small proportional increase in total biomass. In addition, Painter and Belsky (1993) claimed that grazing often reduces belowground biomass and therefore could negate any compensatory aboveground production. In one study on the Santa Rita Experimental Range in southern Arizona, Blydenstein (1966) found that defoliation of desert grasses resulted in reduction of total root mass and root density and decreased root branching. The author speculated that these changes in root structure could inhibit the uptake of moisture and nutrients. Long-term reduction in root biomass could compromise water use efficiency at the plant and community level (T. Burgess, personal communication). In contrast, McNaughton (1986) and Milchunas and Laurenroth (1993) both summarize studies in which often the belowground response to defoliation was neutral or positive (except at severe levels of grazing).

Some authors have suggested that the herbivore optimization hypothesis has been used inappropriately to justify high stocking rates of livestock (such as in the short-duration grazing system, which is discussed in Chapter 10), especially on western North American rangelands (Painter and Belsky 1993), but this contention is not shared by others (for example, see McNaughton 1993). Others have voiced concern that the debate over the hypothesis and how it is used by resource managers not obscure the more fundamental issue of sustainability of grazed ecosystems (Briske 1993). We suggest here that the controversy, both over the hypothesis and how it supposedly relates to resource management, also exists in part because the different players in the debate are not necessarily arguing the same issue.

---

[13] *Herbivore optimization* refers to positive effects of grazing on plant productivity and fitness (Belsky 1986). It is a hypothesis based on a conceptual model (the herbivore-optimization curve) that describes the relationship between grazing intensity and its effect on productivity. See text for additional detail. *Overcompensation* is defined as a net increase in biomass (including removed tissue) in response to grazing (Belsky 1986). The two terms have slightly different conceptual underpinnings but describe the same general phenomenon. Belsky (1986) also defines *undercompensation* as when a net decrease in biomass occurs in response to grazing. Undercompensation can occur in three different ways: *partial compensation* (some regrowth occurs), *no compensation* (no further growth), and *damage* (further decline in productivity after grazing).

Belsky (1986) and Belsky and others (1993) argument against overcompensation or herbivore optimization is mostly from an evolutionary perspective. Moreover, these authors narrow the focus of their criticism regarding the supposed benefits to plants of herbivore-plant interactions to the act of herbivory only. As a result, Belsky (1986) concluded, based on a review of over 40 studies, that no evidence exists that demonstrates herbivory maximizes the fitness of plants or that plants and their herbivores have a coevolved mutualist relationship on the basis of herbivory. Further, Belsky and others (1993) concluded that compensatory responses by plants, which they acknowledged could even lead under certain favorable conditions to overcompensation, was more likely explained, based on evolutionary theory, as a general response by plants to tissue damage and not as a specific response to herbivory that increases fitness over ungrazed plants.

Conversely, Dyer and others (1993) do not restrict their argument for herbivore optimization to the direct effects of herbivory. Nor do they restrict themselves to consider only “a strict reductionist plant-fitness context.” Instead, optimization is considered at a community level in which other ecological processes (non-heritable) also play a role in determining the “grazing system” response. Supposedly the nonlinear, compensatory response that certain plants have in relation to different levels of grazing intensity translates into a system-level optimization curve; however, Dyer and others (1993) note that not all grazer-plant systems may respond this way, the response may occur only under a specific range of environmental conditions in those systems in which the response does occur, and the underlying mechanism that determines the nonlinear response is unknown. Similarly, McNaughton (1986) states that “nowhere [has he] written that the mere act of herbivory is beneficial to any affected plant.” Instead, he argues that vegetation responses to “herbivory” must encompass processes from the individual to the ecosystem level and include effects of grazing beyond the removal of plant biomass (for example, nutrient recycling through dung and urine or changes in species composition). Within these contexts, McNaughton (1993) argues that grazing “benefits” many grasses and other plants in *grassland* ecosystems and that moderate grazing promotes the productivity of many *grasslands* compared to ungrazed levels. In sum, although the preceding authors at times invoke plant fitness arguments, they do not consider herbivory in isolation to other herbivore-related factors when assessing whether plant fitness is increased (which may decouple species fitness arguments from an optimality or plant-herbivore mutualism perspective). Optimality (maximum productivity) then is considered primarily a community level phenomenon that results from a number of interacting ecological conditions in which the direct removal of plant tissue may not be under direct selection pressure beyond the fitness benefits accrued to the plant by the ability to compensate for tissue damage no matter what the source.

So what are the bounds of our knowledge regarding overcompensation or herbivore optimization and what does it mean to domestic livestock management in hot deserts such as the Sonoran Desert? That many plants can at least partially compensate for the loss of tissue resulting from herbivory by regrowing tissue does not seem to be in dispute (though this does not imply agreement on the manner of selection that may be involved). Mechanisms of compensation are summarized in Noy-Meir (1993) and Briske and Richards (1995) and can include both intrinsic (herbivore-induced physiological processes) and extrinsic (herbivore-mediated environmental modifications) mechanisms. The spatial pattern and timing of defoliation can have a significant effect on the degree of regrowth (Gold and Cadwell 1989). In their assessment of the literature on overcompensation, Briske and Richards (1995) concluded that beyond containerized plant investigations conducted under controlled conditions, examples of overcompensation, though they do occur, were limited for individual plants in field settings and for whole communities. The specific conditions under which overcompensation occurs also are of relevance and may limit the general applicability of the phenomenon. Compensatory growth seems to be promoted by limited competition, increased nutrient availability, and grazing only during the early portion of the growing season (Briske and Richards 1995).

The above paragraph speaks mainly to plant-level considerations. At the community level, presumably the level at which the proponents of herbivore optimization suggest it occurs, McNaughton (1993) emphasized that his research focused on natural grazing systems that, compared to managed domestic-livestock grazing systems, are characterized by lower herbivore biomass and greater herbivore mobility (see also Oesterheld and others 1992). As a result, although McNaughton (1993) doesn't rule out that herbivore optimization can occur in managed *grassland* grazing systems when moderately grazed, contemporary livestock husbandry practices would seem to make it less likely. Noy-Meir (1993) points out what is likely a general consensus, whether a proponent of overcompensation or not, that the mechanisms by which plants compensate for losses to grazing break down when the frequency and intensity at which individual plants are grazed (or otherwise are damaged) exceeds certain critical threshold values. Heavy grazing, and by extension other intensities of grazing, do not have the same meaning between natural and managed grazing ecosystems (McNaughton 1993). Oesterheld and others (1992) found that across a 25-fold gradient of ANPP in South American rangelands, the biomass of herbivores supported per unit of ANPP was about an order of magnitude greater in managed (domestic livestock) versus natural ecosystems for a given level of ANPP. They concluded that other factors besides ANPP must be limiting native herbivore numbers. Finally, other authors have pointed out that overcompensation or herbivore optimization are likely to occur only in highly productive ecosystems and not in semiarid or arid ecosystems (Bartolome 1993, Holechek and others 2004b) and for natural ecosystems only in those ecosystems that had a long evolutionary history of grazing (Milchunas and Lauenroth 1993).

In conclusion, compensatory growth by plants can occur subsequent to, but does not depend on, herbivory. Whether and to what degree any level of compensatory growth occurs, including overcompensation, depends on the plant species, the pattern and timing of the tissue damage, and ecological conditions at the time of and after herbivory. Some Sonoran Desert plant species, especially perennial grasses, likely demonstrate at least partial compensation. At the community level, arguments that herbivore optimization occurs generally focus on highly productive grassland ecosystems. Moreover, managed grazing even in these productive ecosystems may frequently exceed the optimal intensity required to consistently stimulate primary production (Briske 1993, Briske and Richards 1995). The herbivore optimization hypothesis would seem to have little relevance to livestock grazing management decisions in the hot deserts of the American Southwest.

4.2 IMPACTS OF LIVESTOCK GRAZING ON SONORAN DESERT PLANT COMMUNITIES

A large body of literature exists that addresses the effects of livestock grazing on plant communities; however, a much more limited set of studies considers the effects of grazing on plant communities within the Sonoran Desert. As discussed in the previous sections, Sonoran Desert plant communities are shaped by unique biotic and abiotic features that make them stand out from other North American deserts. The Sonoran Desert does share a number of features characteristic of other hot deserts, such as low overall primary productivity and aridity, but these same features and others also makes it quite distinct from grassland ecosystems. As a result, Sonoran Desert plant communities are likely to have different responses to grazing than plant communities in other regions in which grass is a significant component, productivity overall is higher, and precipitation is less variable. We limited our review and interpretations primarily to studies that focus specifically on the Sonoran Desert (18 papers). We included a limited number of other studies conducted outside the ecoregion if they included some general insights on a topic that was not well addressed by Sonoran Desert specific literature. Some of the literature includes information on the impact of livestock grazing on saguaro, but we discuss these papers in Chapter 5.

4.2.1 General Limitations of Studies Reviewed

The literature that addresses the effects of grazing on Sonoran Desert plant communities has some general limitations. Many of the studies were conducted at sites where historic grazing pressure was considered high (but intensity and other attributes of the grazing systems were typically not quantified) and vegetation was subjected to other simultaneous stresses such as drought. Livestock (cattle, or in some areas a mixture of cattle, horses, and feral burros) were subsequently removed from these sites. Researchers then compared the site prior to cattle removal and the same site after removal. This generalized description characterizes most of the studies conducted at the Carnegie Desert Laboratory on Tumamoc Hill near Tucson (including Shreve 1929, Shreve and Hinckley 1937, Murray 1959, Goldberg and Turner 1986, Burgess and others 1991), as well as research projects conducted at Organ Pipe Cactus National Monument near Ajo, Arizona (Warren and Anderson 1992). The limitation to these studies is that they compare places through time but “control” sites often, but not always, were lacking to enable comparisons of how plants change on adjacent sites with different land uses over the same period of time. Therefore, causes of plant community change must be inferred from knowledge of past climatic conditions and land-use history, including livestock grazing.

Other research compared adjacent or nearby sites that had different land-use histories and current uses (including Blydenstein and others 1957, Hovorka 1996, McAuliffe 1998, Waser and Price 1981, Turner and others 2003). Comparisons between sites with different grazing histories or intensities (such as grazed and ungrazed) are more robust than observing vegetation change over time at a single site because the impacts of climate and other environmental factors can be accounted for and comparisons over space and time are feasible; however, these types of studies often lack pre-grazing data or other information that offer assurances the grazed or ungrazed sites would have been similar if not for livestock grazing. In some cases the putative ungrazed sites experienced historic grazing. As a result, these studies have their own limitations.

Although in some cases the intensity of grazing may have been described, typically the description was qualitative and also may have lacked additional specifics in terms of season, duration, and frequency. Study site descriptions may be fairly complete and detailed, and include a description of the plant communities, soils, and other features, or they may be cursory.

Incomplete or inconsistent descriptions may limit the ability to generalize some interpretations of study findings. In addition to the total number of studies, the amount of areas studied in the Sonoran Desert is quite limited. This also limits the amount of inference, but does not rule out the ability to discern some response patterns that may be more broadly applicable. Finally, the distribution of studies among Sonoran Desert plant communities that may be grazed is uneven. Xeroriparian plant communities are especially under-represented.

Although the dominant species in Sonoran Desert communities are predictable over a broad geographic scale, on a local (plot) scale community composition is neither stable nor necessarily predictable in most natural communities in the Sonoran Desert. As shown by Turner (1990) in his study of plant community change in a fully protected site (MacDougal Crater), relatively infrequent but high levels of species turnover may occur in relation to climatic events, whether or not livestock grazing is present. Conversely, Bowers and Turner (2002) provide local-scale data for foothill paloverde population age structure and seedling survival that suggests that local population dynamics may reflect biotic factors to such an extent that population age structure might not be concordant with past climatic influences. Although they hypothesize that complex historic interactions with domestic livestock may have influenced the changes in the population dynamics of foothill paloverde, they also suggest other biotic factors that could have been equally at play. As a result, it is often difficult to discern how livestock grazing induces vegetation change independent of climatic and other biotic events.

Nonetheless, because livestock selectively remove biomass of some plants, grazing potentially can result in reductions in productivity, density, cover, and dominance of preferred forage species. In addition to impacts resulting from herbivory, livestock also can impact plant communities: (1) directly through trampling and other mechanical disturbances of the vegetation; (2) indirectly through impacts to soil resources that alter ecological processes such as hydrologic regimes, nutrient cycles, disturbance regimes, or competitive interactions (including those involving invasion by non-native species); and (3) through the effects of associated water developments and other range improvements. Most importantly the spatial pattern of each impact may not be expressed congruently, and multiple assessment scales may need to be considered. The above impacts cover the full spectrum of how livestock grazing may affect plant community composition, structure, and function (the latter of which refers to ecological processes that are attributes of the community and have their own characteristic ranges of natural variability). With detailed knowledge of climatic events, land use history (grazing and otherwise), biotic interactions, and the biology of particular plants and their expected response to a given event, the causes of vegetation change may be deduced more reliably and convincingly (Martin and Turner 1977, Turner and others 2003).

Finally, few studies approached the assessment of livestock impacts from the standpoint of evaluating alternative grazing management approaches. That was not necessarily the purpose of the studies at the time they were conducted. We will discuss this aspect in more detail in Chapter 10; however, we point this out here to emphasize that we consider this a critical shortcoming of the literature in general, and not just a limit of the plant community literature. The lack of this particular research perspective ultimately undermines attempts to assess and compare grazing management strategies that are directly applicable to a hot desert such as the Sonoran Desert.

4.2.2 Studies by Plant Functional Types, Plant Community Type, or Spatial Pattern of Livestock Use

We have grouped the studies by plant functional type as much as possible as a way of distinguishing the potentially differential impacts of livestock grazing on components of a plant community. These types are broadly defined groupings and are not necessarily as finely subdivided as the plant functional types discussed in section 4.1.2. Because individual studies may report on more than one plant functional type, at times we may briefly refer to other functional types within a section. We try to keep, however, the discussion primarily focused on the plant functional type under consideration. In addition, we treat xeroriparian plant communities as their own separate section. The literature, especially related to the Sonoran Desert, is quite sparse relative to these communities. We highlight them here to call attention to what we consider a critical knowledge gap. Finally, an important set of studies, which are applicable to arid environments and whose approach unfortunately has yet to be extensively applied in the Sonoran Desert, are presented as a separate topic. Such studies use a gradient analysis approach in which distance to a livestock watering point is used as a proxy for grazing intensity. The zone of ecological impact around a livestock watering point is identified as the "piosphere" (from *pios*; Greek for "drink").

Woody Perennials

As previously mentioned, studies observing changes in plant community attributes after the cessation of livestock grazing in 1907 at Tumamoc Hill offer some insight on the relative importance of livestock grazing versus other factors (such as temperature and rainfall) on plant community composition and structure. Goldberg and Turner (1986) provide a general description of the area. The slopes of the hill correspond to paloverde-mixed cacti-mixed scrub. Although the vegetation of the surrounding plain is not described, Bowers and Turner (2002) indicate the entire area is typical of the Arizona Upland subdivision. Soils range from clay studded with rocks to sandy, rock-free soil. Rainfall averages about 10 inches (250 mm) primarily during the summer months. Grazing by horses, cattle, and burros probably began about 1858. Its intensity prior to complete removal and exclusion in 1907 has been described as "light to moderate" (Shreve and Hinckley 1937); however, stocking rates are unknown (Bowers and Turner 2002). Native herbivores, including mule deer, still use the area.

Shreve (1929) first reported changes in the vegetation subsequent to livestock exclusion from Tumamoc Hill and the surrounding area after 21 years of release from grazing. On the surrounding plain (three sample areas) perennial plants increased from 33 to 164 percent, but on the hill slopes (three sample areas) both gains and losses were observed. Changes in the number of large woody perennials were small; however, some of the small, relatively short-lived perennials, such as janusia, triangle-leaf bursage, and white ratany (*Krameria canescens* [= *K. grayi*]), experienced relatively large increases. He concluded evidence of successional change was lacking. Shreve and Hinckley (1937) recorded plant composition and abundance on the same plots as Shreve (1929) and additional plots during 1936. They continued to observe essentially small to no changes in the larger perennial species but substantial increases in the small perennials and some shifting in numerical dominance. Changes in composition did occur at the plot scale, but new additions generally already were present in the local flora. Shreve and

Hinckley (1937) also reported what they apparently regarded as significant increases in perennial grasses since protection occurred. The authors could not attribute the preceding changes to annual rainfall fluctuations. They speculated that the plain "suffered" more from the effects of grazing than the hill and that the intensity of historic grazing was sufficient to adversely impact the smaller woody perennials and grasses but not the larger woody perennials. The abundance and species richness data were not statistically analyzed in any manner. Despite this, these were still fairly rigorous population enumeration studies accomplished over multiple time periods.

Blydenstein and others (1957) found changes in vegetation density on plots on Tumamoc Hill after fifty years of protection from grazing. Their study is distinguished from others in that they compare vegetation on an ungrazed plot on Tumamoc Hill with that on an adjoining grazed site. The study area description seems to describe a paloverde-mixed cacti-mixed scrub community on thin soils overlying a caliche layer (consistent with the Arizona Upland description of other authors). Blydenstein and others (1957) found that the main difference between plant communities at the two sites was that the ungrazed area had higher overall vegetation density and less bare ground than the grazed site. The species composition was mostly the same between sites in approximately the same rank order of abundance or dominance. A higher frequency (density) of many perennial species was found on the ungrazed site, with the greatest increases in density recorded for white ratany and three species of perennial grass: red grama (*Bouteloua trifida*), slim tridens (*Tridens muticus*), and low woollygrass (*T. pulchellus* [*Dasyochloa pulchella*]). No dramatic shift occurred in the dominance of species between sites and creosotebush density did not differ significantly, though the authors noted that creosotebush looked less vigorous on the protected site. The only plant that decreased in density at the protected site was triangle-leaf bursage, though it remained the dominant plant on both plots. Presumably the observed differences in perennial species density at grazed and ungrazed sites were not due to climatic factors because the sites are adjacent to one another. Blydenstein and others (1957) did not find any difference in annual plant density between sites, but the vegetation was sampled after two years of drought when annual production was minimal. One limitation to Blydenstein and others' (1957) study is that they do not discuss grazing intensity or management on the unprotected site. In addition, their study only measures differences between the sites at one point in time. Blydenstein and others' (1957) study and those of Shreve (1929) and Shreve and Hinckley (1937) support the hypothesis that after livestock removal, changes in the woody perennial plant component of Sonoran Desert plant communities are manifested as increases in perennial plant density, particularly of palatable species, and not necessarily as changes in composition. The cessation of grazing served to increase species evenness and decrease dominance (a measure of increased species diversity), though (Shreve and Hinckley 1937) did observe shifts in numerical dominance over shorter time periods (see above).

Subsequent studies on Tumamoc Hill (Murray 1959, Goldberg and Turner 1986) limited their comparisons to changes in vegetation over time within the area protected from grazing, but included climatic data in their analyses. These studies' findings also supported the general patterns described by Blydenstein and others (1957), with some exceptions. Murray (1959) did not observe any changes in perennial species richness on plots from 1928 to 1957, 21 and 50 years after the cessation of grazing. She found that shifts in cover and density could be correlated with climate, in which increases in canopy cover of individual species largely corresponded to winter rainfall patterns, and plant establishment (increases in density) occurred when a prolonged wet period occurred in the fall between the summer and winter rains. The two exceptions to this pattern were for triangle-leaf bursage and white ratany, which both showed steady gains in density and relative abundance since livestock exclusion in 1907. The increase in triangle-leaf bursage observed by Murray (1959) stands in contrast to Blydenstein's (1957) results and may be due to recruitment events resulting from prolonged wet periods occurring during the study. The increase in white ratany on sites protected from grazing is a result consistent with the findings of other studies.

Goldberg and Turner (1986) observed that between 1906 and 1978 the woody and succulent perennial vegetation on Tumamoc Hill permanent study plots showed no consistent directional change in composition, despite large fluctuations in absolute cover and density of the species present. Most species exhibited multi-decadal fluctuations in density and cover during the study period, which seemed to correspond to sequences of extremely wet or dry years. Despite these fluctuations, total cover, density, and species diversity increased more or less continuously on many of the plots. Moreover, Goldberg and Turner (1986) also found white ratany and janusia seemed to increase more or less continuously over the study period. They speculated that the increases in these two species, as well as the overall increases in total vegetation cover and density on many of the plots, were responses to protection from grazing. They acknowledged, however, that they did not have plots outside the protected area to assess temporal changes with and without grazing. The recovery of white ratany and janusia from grazing apparently is a slow process that requires decades as well as favorable climatic conditions to take place.

Turner and others (2003:plate 81) included a series of matched photographs from a plot at Tumamoc Hill from 1928, 1985, and 1998. Although determining the causes of vegetation change from matched photos can only be speculative, the patterns these photos reveal are some that other researchers have described in quantitative studies. The dominant plant in 1928 was creosotebush. By 1985 most of the creosotebush had died back or was gone and dominance shifted to small shrubs, including triangle-leaf bursage and range (or littleleaf) ratany (*Krameria parvifolia* [= *K. erecta*]). Other species appearing at the site included fairy duster (*Calliandra eriophylla*) and fluff grass (*Erioneuron pulchellum*). By 1998 little recovery of creosotebush had occurred, but the density of species palatable to livestock, including fairy duster and range ratany had increased.[14] Turner and others (2003) speculated that the shift in dominance from creosotebush to the palatable shrubs might reflect cessation of grazing at the site. The cause of the creosotebush die-off is unknown, but the authors hypothesized that the comeback of the root parasitic range ratany could have contributed to its decline. As a study involving matched photos, the Turner and others (2003) study lacks empirical data and a complete site description. As a result, although matched photos can provide useful information about vegetation change with time, they should be used with caution when assigning cause and effect.

The degree to which Sonoran Desert plant communities change in cover, density, and composition after the cessation of livestock grazing is also community dependent. Warren and Anderson (1992) documented changes in plant communities at Organ Pipe Cactus National Monument over a nine- to 10-year period. The authors compared plant community composition, cover, and density on permanent plots established and sampled in 1975 and 1976 several years

---

[14] Increases in palatable species after livestock removal may not always be the norm. For plant communities that have experienced a long evolutionary history of grazing, grazing-resistant palatable species may increase with grazing (D. Milchunas, personal communication). See previous section relating to plant-herbivore interactions.

prior to cattle and burro removal during 1978 and 1979 with data on the same plots from 1987 and 1988. Livestock grazing in the area had begun around 1918. A mid-1960s evaluation of range condition determined that the monument-wide stocking rate should be about 300 cows. When livestock were removed, the actual stocking was determined to be 1500 cows and 200 wild burros.

Warren and Anderson (1992) found that of the five community types they studied, creosotebush-bursage showed the least change in perennial plant cover, density, and species composition during the study period. This community is dominated by species that are unpalatable to livestock (creosotebush and triangle-leaf bursage) and occurrences are located at sites that generally have the lowest rainfall on the monument. Most of the changes in plant cover and density were attributed to precipitation, though some species exhibited increases in cover at sites where grazing previously was heaviest (near livestock waters). In contrast, saltbush communities were dominated by species palatable to livestock (saltbush and seepweed [*Suaeda torreyana*]) and showed increases of over 300% in plant cover, likely because of a combination of grazing rest and rain.

In a project comparing grazed and ungrazed Sonoran Desert sites in the Tucson Basin and in the Rincon Mountains, Hovorka (1996) also found that the effects of livestock grazing depended upon the plant community and abiotic features. The sites considered ungrazed had been grazed historically with at least the Rincon site potentially overgrazed prior livestock removal in 1958. The Tucson ungrazed site, Saguaro National Park, had not been grazed since 1929. Stocking rates at the paired Rincon site and the Tucson Basin site near the Silver Bell Mountains were not described. At each location Horvorka (1966) sampled woody and succulent perennial species and categorized them as palatable or unpalatable or characteristic of undisturbed or disturbed sites based on the literature. He also collected abiotic data. His multivariate analyses of the data indicated that elevation, not grazing history, best explained the variation in cover and species composition in the Tucson Basin, whereas grazing history accounted for a significant portion of the plant community variation in the Rincon Mountains. Similar to the results described by other authors, Hovorka (1996) found that differences in composition between the sites were principally in the greater species richness, diversity, and cover of palatable species in ungrazed sites versus the greater abundance of unpalatable and disturbance-related species in grazed sites.

Perennial Grasses

Hayes (2004) compared perennial forage grass densities at five distances from developed waters (sample distances ranging from 1,640 to 16,250 feet [500 to 5000 m]) within three sandy loam upland sites on the Sif-Oidak District, Tohono O’odham Nation. Transects located at 328 feet (100 m) from water were considered sacrifice zones and eliminated from analyses. Hayes (2004) did not detect significant differences in grass densities—bush muhly, three-awns, and total perennial grasses—as distance from water increased. Bivariate correlations, but not a Kruskal-Wallis test, indicated a significant but extremely weak trend for perennial grasses as a group and bush muhly densities to be negatively associated with distance from water. The relationship (bivariate correlation) between distance from water and percent ungrazed grass (used as a proxy measure of grazing intensity) was significant but not strong, though a Kruskal-Wallis test of the same data was non-significant. A second measure of grazing intensity—frequency distribution of livestock activity values—did not detect any decrease in livestock activity as distance from water increased. The author's overall conclusion was that grass densities did not change as grazing intensity decreased, which he suggested indicates the perennial grasses are functioning within a non-equilibrium vegetation dynamic (equilibrium and non-equilibrium vegetation dynamics, and their significance for range management, are addressed in Chapter 10). Livestock management within the Sif-Oidak District reflects a communal land tenure system under which livestock mobility and spatial distribution differ significantly from a range unit approach of fenced pastures/allotments (Hayes 2004). Study limitations included study sites in only fair condition (overall low grass densities), sampling occurring during a drought, potential historical overgrazing, not adequately capturing the grazing intensity gradient, and measuring only density versus some other attribute (Hayes 2004).

Warren and Anderson (1992) documented shifts in species composition since cessation of grazing at plots in a saguaro-paloverde community on Organ Pipe Cactus National Monument, which they attributed to recovery from grazing and favorable rainfall. Although plots had little change in total species richness, compositional shifts were observed with the addition of numerous species to the site—mostly those that are palatable to livestock—and stochastic losses of uncommon species. Species that became established included perennial grasses such as bush muhly, spider three-awn (*Aristida turnipes*), and fluff grass, as well as desert hibiscus (*Hibiscus coulteri*), longflower tubetongue (*Siphonoglossa longiflora*), and California trixis (*Trixis californicus*). In areas where cattle are present, these species tend to only grow beneath protective shrubs. Warren and Anderson (1992), however, observed these species growing out in the open after nine to 10 years of protection from grazing. Total vegetation density in these plots increased substantially because of additions of the palatable grasses and forbs, and the authors attributed this change to cessation of livestock grazing and favorable climatic conditions.

Full recovery at Organ Pipe Cactus National Monument, if even feasible, is expected to take decades, as even the control exclosure plots had experienced accelerated erosion resulting from the adjacent grazed areas (S. Rutman, personal communication). Moreover, the poor condition of the range at the time of livestock removal makes it difficult to evaluate the effects of exclosures or distance from livestock waters (S. Rutman, personal communication).

McAuliffe (1998) documented a loss of perennial grasses at sites near the northern boundary of the Sonoran Desert northwest of Wickenburg, Arizona based on data from historic photographs and descriptions and recent plot data. Based on the composition of the existing vegetation, McAuliffe (1998) described the general area as a semiarid shrubland, which suggests the area may be near the transition to interior chaparral. Historic livestock grazing coupled with drought at some sites reduced perennial grass cover to the degree that it induced accelerated erosion with long-term effects on soils, hydrology, and vegetation. McAuliffe (1998) hypothesized that these changes were induced by construction of rangeland water developments (since passage of the Taylor Grazing Act in 1934) that served to distribute cattle widely and into areas formerly not impacted by grazing. The loss of perennial grasses because of a combination of historic overgrazing coupled with drought initiated a positive feedback cycle causing further loss of grass cover and abundance. The loss of grasses limited the soil's ability to absorb rainfall, which led to increased intensities and quantities of runoff, an increase in erosion and gullying, and further loss of infiltration and soil moisture. Ultimately, this chain of events caused widespread mortality of tobosa grass, in particular. Data presented by McAuliffe (1998) from plots and historic descriptions corroborate these results. A complete loss of tobosa grass since 1950 occurred at one particular grazed site (at other sites perennial grasses were uncommon), which had been replaced by a sparse (~10% cover) of woody vegetation. In contrast, McAuliffe's (1998) three reference (ungrazed) sites were characterized by patchy but relatively abundant perennial grasses up to 50% cover, with differences based on site-specific characteristics, including soils.

Caldwell (1984) suggested that clipping and grazing studies generally revealed that rangeland forage species were much less susceptible to defoliation during dormancy or periods of reduced activity as compared to the most active stages of vegetative growth. McAuliffe (1998), however, distinguished the growth behavior of warm season, perennial grass species characteristic of semiarid and arid environments from those in less arid environs. He suggested that livestock grazing can induce losses of perennial grass cover and abundance in semiarid and arid ecosystems because the associated plants rely on a particular carbohydrate storage mechanism. For example, a number of grasses that occur within the Sonoran Desert, including tobosa, big galleta, and bush muhly are "suffrutescent," which means they store carbohydrates in dormant aboveground biomass during drought and winter (in contrast, the dominant grasses of less arid areas store carbohydrates at or below the surface). The plants rely on this storage to initiate new growth during the following growing season. This strategy enables these grasses to respond to the relatively small, unpredictable supplies of summer rain in arid environments (Burgess 1995). Consequently, McAuliffe (1998) concluded that grazing of suffrutescent grasses during the non-growing season reduces the capacity for future regrowth and survivability during drought and, as a result, grazing during this time has a greater negative impact on these grasses than on grasses found on less arid ranges that store their carbohydrates differently. Excessive use during the growing season would have the same negative effect (McAuliffe 1998).

How much of an issue dormant season grazing of these grasses would be in the Sonoran Desert is unclear. First, the palatability to cattle of both tobosa and big galleta is greatest when they are actively growing, whereas bush muhly, because it is capable of remaining green yearlong, could be grazed by livestock at any time (Ruyle and Young 1997). As a result, bush muhly may be the most susceptible to the effects of dormant season grazing. Second, McAuliffe's (1998) hypothesis about the importance of the suffrutescent mode of carbohydrate storage remains to be verified. Briske and Richard's (1995) review of the literature on carbohydrate depletion in plants implies that much work remains to be done on establishing definitive relationships between the size, location, and role of carbohydrate pools and plant growth (see also Caldwell 1984); however, their analysis was specific to actively growing plants and their responses to defoliation and may or may not relate to the growth of suffrutescent grasses coming out of dormancy.

Annual Plants

The previous studies focused on analysis of changes in perennial plant cover and density due to livestock grazing. Do annual plant communities change due to livestock grazing? Blydenstein and others (1957) were unable to collect meaningful data because they sampled annuals in an unproductive year. Waser and Price (1981), however, were able to compare changes in winter annual species over two years (one relatively wet and one dry) at five sites near Organ Pipe Cactus National Monument that differed in livestock grazing history. Study plots consisted of two plots located in areas where cattle grazing was ongoing and at high intensities (the authors did not quantify what they meant by high intensity), two plots on the monument where cattle and burros had been removed for two to three years, and one livestock exclosure on the monument that had been fenced 16 to 17 years earlier. As would be expected, the authors found that the density and composition of annual plants changed with rainfall, with markedly reduced density and species richness after a dry year; however, they concluded the species richness of winter annuals declined consistently as a function of increasingly recent grazing by cattle. All plots were dominated by the same species (desert Indian wheat [*Plantago insularis* (*Plantago ovata*)] and hairypod pepperweed [*Lepidium lasiocarpum*]) independent of the year surveyed or grazing history. A group of about 19 species, however, that were relatively rare on the surveys and fluctuated inconsistently between years and plots. These species were most likely to drop out on sites with more recent grazing history or poor winter rainfall.

Unlike the data on perennial plants, Waser and Price's (1981) study shows that livestock grazing can affect community composition. Recovery of annual plants from grazing seems to involve the addition of mostly uncommon species, and this pattern is most apparent immediately following the removal of cattle. The authors hypothesize that the pattern of species recruitment results because grazing over long periods of time may deplete the local seed bank of some native annual plants. To recolonize a site after cattle removal, recruitment must occur either from remnant dormant seeds (if any still exist) or dispersal from ungrazed refuges. Because seed dispersal rates are presumably low, this results in infrequent recruitment and little opportunity for additional seed-set until livestock are removed. Long-term research (for more than two years) on changes in annual plant composition after release from grazing is needed to continue to evaluate the patterns of annual plant dynamics observed by Waser and Price (1981) and their hypothesis.

Compositional shifts have occurred on Tumamoc Hill and the level to gently rolling plain to the west (880 acres [352 ha] in all constituting the Carnegie Desert Laboratory) through the addition of non-native plants. Burgess and others (1991) identified 52 non-native species occurring on the Desert Laboratory grounds, six of which (5 annuals and one perennial) they identified reproducing in undisturbed habitats where they occur as frequently as the common native species. They speculated that grazing before 1907 could have created conditions that favored the initial invasion by non-native annuals, though they acknowledged they could not provide quantitative evidence and that other factors, such as favorable climate and the biology of the non-native plants themselves, likely contributed to successful invasion. The preceding demonstrates that successful invasion of native ecosystems by non-native plants often is coincident with many other factors whose individual contribution to invasion is difficult to tease apart.

Xeroriparian Plant Communities

Xeroriparian habitats within the Sonoran Desert, especially when associated with Lower Colorado River subdivision plant communities, typically are more species rich, structurally diverse, and productive than the surrounding uplands. These habitats are important wildlife habitat that relative to their areal extent receive disproportionate use. The characteristics that attract the native fauna, including available forage and thermal cover, also seem to attract domestic livestock (and feral burros). Despite their disproportionate importance to native wildlife and domestic livestock, these habitats rarely have been evaluated for usage and impacts associated with livestock or non-native feral species. In a review of livestock grazing in the southwestern United States, Milchunas (In Press) located only four studies that addressed xeroriparian habitats, two of which dealt with feral burros and not cattle and only one of which occurred within the Sonoran Desert. We assessed three of these studies.

The two cattle-related studies did not have as their primary purpose a description and discussion of xeroriparian (dry wash)-related impacts, but they do include some data that provide some insights. One study from the San Simon Valley of southeastern Arizona, compared washes protected from livestock grazing within exclosures for 18 to 19 years with those not protected and compared these differences with creosotebush and tarbush (*Flourensia cernua*) communities inside and outside the exclosures (Chew 1982). Stocking rates ranged from none to heavy outside the exclosures. Perennial grass density and basal areas (other than fluff grass) for washes, creosotebush, and tarbush always were greater inside the exclosure than outside; however, the greatest differences occurred between the protected and unprotected washes. Chew (1982) concluded that washes are better sites for grass production than adjacent areas and that they have a grazing potential out of proportion to their relative area in the landscape. Gardner (1951), in a study of a creosotebush area of the Rio Grande Valley, New Mexico, found that grasses were more abundant and shrub species richness and evenness greater in dry washes that were only lightly grazed compared with washes that had “uncontrolled” grazing. The only Sonoran Desert paper, Hanley and Brady (1977), addressed grazing by feral burros in secondary washes (defined simply as washes receiving less frequent and intense precipitation runoff than primary washes) located north of Parker, Arizona near the eastern margin of Lake Havasu. Grazing reduced total canopy cover and in particular the canopy cover of white bursage . Grazing impacts were most pronounced in the secondary washes as compared to the other communities. Hanley and Brady (1977) considered these washes the most important forage resource in the area.

Because the above studies either dealt with non-Sonoran Desert areas or feral burros, they only elucidate potential patterns of livestock impacts on Sonoran Desert xeroriparian habitats. The arborescent nature of Sonoran Desert xeroriparian habitats, as compared to the wash communities from the two cattle studies described above, could intensify these patterns. In addition, a secondary impact to xeroriparian habitats may result from water development activities that create an impoundment or berm across a wash or other type of drainage. We did not find any literature that evaluated effects on vegetation down-gradient from an impoundment. The lack of studies on Sonoran Desert xeroriparian habitat is a significant data gap in our understanding of livestock impacts in the Sonoran Desert.

Piosphere Studies

The most noticeable effect of livestock grazing on plant communities in the Sonoran Desert occurs around areas where livestock congregate, particularly around watering sites. The ecological zone of impact extends beyond the denuded area immediately surrounding the livestock water, which is sometimes referred to as the “sacrifice zone.” As a result, the complete zone of ecological impact, beyond which exceeds the grazing range of the animal or the impacts of livestock grazing cannot be distinguished, is by definition identified as the piosphere (Lange 1969, Andrew 1988).

Andrew (1988) suggests the piosphere provides a good context for assessing the ecological impacts of large herbivores and applying ecological information to land management, especially in arid areas where water is a major limiting factor to livestock survival and growth. The basic premise is that livestock use and associated impacts are concentrated near to water and attenuate with distance from water. As a result, livestock usage and vegetation and soil responses would be expected to follow a gradient. If indeed the preceding gradients are real, then Andrew (1988) suggested that using spatially averaged stocking intensities across an allotment may provide an inaccurate basis for assessment and comparison of ecological impacts. Andrew (1988) described the use of the sigmoid logistic curve as the idealized form of the piosphere response of an ecological variable with distance from water. Close to water the response shows little variation with distance. This represents the sacrifice zone. From the edge of the sacrifice zone to the limit of the piosphere the response in the ecological variable is predicted to be essentially linear with distance. The distance of the sacrifice zone and piosphere edge from water may differ with the ecological variable under consideration. The actual pattern of impact for each variable also may be affected by topographic features, plant community differences, and the pattern of animal activity in response to environmental conditions. Finally, the intensity of ecological impact also depends on the stocking rate and the spatial pattern of water access in relation to allotment area and fencing—for example, whether water is available at the corner of an allotment or at its center will affect the concentration of animals. In the Sonoran Desert the pattern and intensity of ecological impact around livestock waters is likely to depend on the amount and distribution of xeroriparian plant communities and their accessibility to livestock in proximity to the watering site.

We discuss three studies that provide information in a piosphere context. Two of these studies are from the Sonoran Desert and one is from the Mohave Desert. Hayes (2004) used a piosphere context to assess livestock impact to perennial grass density on the Sif-Oidak District, Tohono O’odham Nation. This study was discussed above, but in summary Hayes’ (2004) data do not support the hypothesis of a linear change in the response variable with distance from water. Hayes (2004) mentions but does not analyze the data corresponding to a presumed sacrifice zone occurring at 328 feet (100 m) from water. The measures of grazing intensity used by Hayes (2004) showed at best only a weak correlation with distance from water. The free-roaming nature of cattle on the Sif-Oidak District and the overall low densities of perennial grasses and their tendency not to be evenly distributed on the study areas potentially created conditions in which the piosphere effect would not dictate the spatial pattern of livestock use and perennial grass response.

Brooks and others (In Press) sampled annual and perennial plants in the Mojave Desert in California along transects emanating from the edge of the sacrifice zone of nine livestock watering sites to 2624 feet (800 m) distant from the center. Sacrifice zone diameters ranged from 66 feet to 230 feet (20 to 70 m). They did not sample beyond 2624 feet to avoid the effects of dirt roads (which potentially means the whole piosphere was not sampled). Sampling occurred subsequent to both an above average winter rainfall in 1998 and a below average winter rainfall in 2000. The authors found that during a high rainfall year total non-native annual plant cover, but not species richness, increased significantly with proximity to watering sites, whereas both native annual plant richness and cover decreased significantly with proximity to the watering site. In contrast to the other non-natives, red brome decreased with proximity to watering sites, possibly because of competitive interactions with the other non-native species. Effects on annual plants, especially the non-natives, were more dramatic when measured within the interspaces between shrubs versus within the beneath-canopy microhabitat. Native perennial plant richness, cover, and structural diversity all declined with proximity to watering sites. The decline in structural diversity was primarily due to the loss of small shrubs. Significant effects were primarily isolated to within 656 feet (200 m) of the watering source, with significant effects related to perennial plants localized to within 164 feet (50 m) of watering sites. The data overall do provide support to the hypothesis that particular ecological variables, such as native plant richness and cover, may show a linear relationship with distance from water outside the sacrifice zone. Brooks and others (In Press) suggested that invasive non-native annuals can colonize and are favored around livestock waters because conditions created by livestock result in reduced competition, low native species cover, greater moisture availability, and greater opportunities for dispersal by livestock or vehicles. Livestock also may alter nitrogen cycle rates and intensities, which can favor non-native plants that may be more nitrogen limited than natives, through redistribution of removed plant nitrogen to the vicinity of watering sites (Senft 1983). Brooks and others (In Press) recommended that efforts to control invasive non-native plants in the Mojave Desert should be focused within the 656-foot (200-m) radius surrounding the livestock water.

Morrison and others (2003) characterized and mapped the natural communities (plant communities and habitats; see section 3.3 and Figure 3.2) of the Sonoran Desert National Monument and adjoining areas. As part of this work, they collected data on vegetation composition and structure, abiotic features, and livestock usage (hoof prints plus dung piles) on 313 plots. Sample design for a significant portion of these plots included establishing 13 plot locations along a gradient of distance from what they defined as livestock congregation areas (either a livestock water development or corral). Plot locations ranged from within the sacrifice zone out to as far as 3.1 miles (5 km), when not constrained by landscape features or an unrelated disturbance feature, from the edge of the sacrifice zone. The extent of the sacrifice zone was not quantified, but was implied to be greater than 164 feet (50 m) on some occasions. Nearly all of the livestock congregation areas occurred within the Creosotebush-Bursage Desert Scrub community. Based on linear regressions of the vegetation data, Morrison and others (2003) found that their measure of livestock usage indicated a significant negative relationship with distance from a congregation area. Of the vegetation variables assessed, total native species richness and cover and native grass species richness showed significant positive relationships with distance from a congregation area, whereas species richness and cover of non-native species showed significant negative relationships with distance. These patterns for the most part mirror the results of Brooks and others (In Press); however, the findings have a few limitations. First, Morrison and others (2003), although their sample design in part followed a gradient approach, didn’t analyze their data within a piosphere context as described by Andrew (1988). The sacrifice zone plots were included in the regression analyses, which if eliminated likely would alter the nature of any linear relationship between response variables and distance from livestock congregation areas. Second, livestock congregation areas were broadly defined to include corrals, which may exhibit different patterns of surrounding livestock usage than water developments. Third, knowledge of the service status of water developments was incomplete. As a result, whether a water development was currently active or how long inactive waters had been out of service were not factored into the data analyses.

4.3 Conclusions

We began this chapter with a detailed, but not exhaustive, review of the literature pertaining to Sonoran Desert ecological processes and plant community dynamics. The information from this review was meant to provide a context within which we could better understand and quantify plant community-livestock interactions. The broad conclusion that we draw from that review is that the Sonoran Desert—as an arid and low-productivity, hot desert ecosystem—deserves individual attention when considering the nature of plant community-livestock interactions and their relevance to the development of appropriate grazing management strategies. Unfortunately, the weakest aspect of the livestock impact literature that we reviewed was that most of the individual studies were not conceived from the standpoint of assessing grazing management alternatives within the Sonoran Desert. Most studies assessed the effects of release from historic grazing, few studies compared grazed and ungrazed sites simultaneously (the latter of which typically had experienced historic grazing), and only one study (McAuliffe 1998) attempted to compare grazed sites with sites that had never been grazed. For all of these studies, detailed knowledge of historic or current stocking rates, timing and duration of grazing if not year-round, and how often grazing occurred generally were lacking. In some cases associated climatic information and site conditions were considered that enabled a more robust interpretation of a study's findings. Finally, investigations involving Sonoran Desert xeroriparian plant communities and domestic livestock interactions, despite the relative importance of these communities for wildlife and livestock, have not been reported in the literature. We briefly outline some additional conclusions in the sections that follow.

4.3.1 Ecological Processes and Plant Community Dynamics

The review of ecological information in section 4.1 has important implications for understanding livestock grazing impacts and for designing and implementing appropriate grazing management strategies. Although a few studies provided productivity estimates for a number of Sonoran Desert plant communities, these studies generally reflected conditions in the wetter, eastern portions of the Sonoran Desert and did not address how productivity may be spatially distributed across a heterogeneous landscape. Compared to semidesert grasslands, Sonoran Desert plant communities have—even when based on data biased toward the eastern portion of the desert—lower total productivity, more of their biomass aboveground, and less annual turnover of aboveground biomass (high aboveground biomass/ANPP ratio). In addition, for a given increase in the amount of rain, productivity increases will be lower in the Sonoran Desert as compared to semidesert grasslands. Under certain climactic conditions, annual plants can contribute a significant amount of the annual ANPP. Whether the contribution is from winter or summer annuals or both depends on location and the seasonal pattern of rainfall more so than the total amount of rainfall. Plant litter is an important component of Sonoran Desert plant communities that can influence seedling establishment and nutrient cycling; as such, litter management should be an important consideration in drought planning.

Precipitation patterns, soils, and plant functional types interact in complex ways in the Sonoran Desert to determine plant growth and recruitment events. Although regarded as having a bimodal rainfall pattern, most of the Sonoran Desert shares affinities with the Mojave Desert in having a winter rainfall-dominated climate (Comrie and Glenn 1998). Variation exists in this pattern, with some locales such as the Tucson area receiving a more significant portion of its rainfall during the summer (Table 3.2). Still, overall summer rainfall tends to be less of a contributor to annual rainfall totals and less reliable than winter rainfall in most of the Sonoran Desert. In general, the lower the average amount of annual or seasonal rainfall, the less predictable is its occurrence on a year to year basis; however, at regional scales multi-year dry and wet cycles show some degree of periodicity and predictability. Soil properties at multiple scales interact with precipitation regimes to determine plant available moisture levels (and susceptibility to accelerated erosion; see Chapter 7). Drought is a "normal" recurrent phenomenon in the Sonoran Desert that should be appropriately accounted for in livestock grazing management plans. Various perspectives on drought exist, none of which may fully account, in isolation or in combination, for an ecological perspective on drought in the Sonoran Desert. Drought planning in the Sonoran Desert needs to account for the three periods of drought: entry, during, and leaving. The concept of pulse dynamics has heuristic value in identifying key process variables and plant responses that shape the communities of desert ecosystems and in improving our ability to develop appropriate land management strategies.

Catastrophic freeze and fire are two disturbance regimes that can have a significant impact on plant community composition, structure, and function in the Sonoran Desert. Freezing temperatures set the limit for the distribution of many Sonoran Desert plants. With only limited exceptions, Sonoran Desert plant communities are not adapted to fire. Livestock grazing and management practices can exacerbate the adverse impacts of these two disturbance regimes by (1) altering microhabitat conditions—for example, by damaging nurse plants or altering plant litter distribution—that may mitigate the effects of freezing temperatures on sensitive plants and (2) providing conditions favorable to the introduction and persistence of those invasive non-native plants that can increase fine fuel loads and their spatial connectivity.

The evidence is weak that Sonoran Desert plant and animal communities have a long evolutionary relationship with grazing by large, hooved mammalian herbivores. Native mammalian herbivores tend to be relatively small-bodied and nomadic in their movement and foraging patterns. Although individual forage species may exhibit at least partial compensatory responses to livestock herbivory, the herbivore optimization hypothesis would seem to have little relevance to livestock grazing management decisions in the hot deserts of the American Southwest. Cattle are grazers at sites where grasses are abundant and available, but they shift to browsing in habitats where forbs and shrubs predominate or after they remove available grasses. Cattle diet data from the Sonoran Desert National Monument indicate that significant seasonal components of the diet include browse species, including trees, and non-native species.

4.3.2 Impacts of Livestock Grazing on Sonoran Desert Plant Communities

We have previously described the general limitations of the Sonoran Desert livestock impact studies that we reviewed and in our opening paragraph to section 4.3 identified what we considered to be the primary limitations of the literature as a whole. Here, we briefly describe our conclusions regarding the topics discussed in section 4.2.2. Before proceeding, we note that those studies that enabled a comparison between grazed and ungrazed sites (for example, Blydenstein and others 1957, McAuliffe 1998, Waser and Price 1981) tended to provide more discernible response patterns, especially when climate data were factored in (notwithstanding the limitations of inadequate quantification of livestock use on grazed sites or historic use even for supposedly ungrazed sites). Release studies provided more variable information and were influenced in their findings by the plant community type considered. For example, saltbush communities showed dramatic increases in plant cover after protection from grazing, though a wetter period of weather also likely played a role (Warren and Anderson 1992). The inherent problem with release studies, beyond often not considering grazed sites for comparison, is not knowing whether lack of recovery indicates a negligible effect of prior grazing, insufficient time for recovery to have elapsed, or recovery at the site to pre-grazing conditions is no longer possible. Evidence of recovery is more likely to occur during a wet period and to be more evident within communities that have high relative productivity.

The studies involving woody perennials, which mostly took place on Tumamoc Hill, indicate that after protection from grazing certain species, such as janusia and ratany (*Krameria* spp.), increase in cover and density. Overall woody perennial plant composition mostly shows no directional change; however, overall plant density and cover increase and bare ground decreases. Perennial grass responses were not often studied. The work by Shreve and Hinckley (1937) and Blydenstein and others (1957) on Tumamoc Hill indicate that perennial grass richness and abundance likely increase in the absence of grazing; however, these studies were snap shots in time and long-term trends were not tracked and always correlated with climate patterns. Hayes (2004) study of perennial grasses on the Sif-Oidak District, Tohono O'odham Nation does not support the hypothesis that livestock impact perennial grass density under different stocking rates; however, evidence for a gradient in grazing intensity was not strong, grass densities overall were low, and study site conditions were only rated as fair. McAuliffe's (1998) study provides the strongest evidence for an impact of livestock on perennial grasses; however, as the grazed sites may have been overgrazed, this study, as well as that of Warren and Anderson (1992), do not provide any indication of stocking rates that may be appropriate for maintaining perennial grasses in the Sonoran Desert.

The most infrequently studied group of plants from the standpoint of livestock impacts are annual plants. This may be because annual plants have the most dependency for their recruitment and growth on the infrequent times in which precipitation timing and amount is sufficient to meet their life-cycle needs. Waser and Price's (1981) study provides the most compelling evidence that livestock grazing can affect community composition through its effect on annual plants. By having studied recovery in both a wet and dry year, and having grazed sites for comparison, Waser and Price (1981) demonstrated that recovery of winter annual plants from grazing seems to involve the addition of mostly uncommon species, and that this pattern is most apparent immediately following the removal of cattle.

Only one Sonoran Desert study addressed grazing impacts to xeroriparian plant communities and that study considered only feral burros. We reviewed two cattle-related studies from other ecosystems to illustrate potential patterns of impact that may be relevant to the Sonoran Desert. Clearly, studies that investigate livestock-xeroriparian plant community interactions are needed for the Sonoran Desert and should include the down-gradient impacts of water development impoundments.

Piosphere studies, appropriately adjusted to reflect Sonoran Desert conditions and conducted in conjunction with exclosure studies, may enable evaluation of the impacts of different livestock stocking rates and practices. Current evidence from the Mojave and Sonoran Deserts indicates the existence of a mostly denuded area (sacrifice zone) in proximity to a livestock water. Theoretical models (Andrew 1988) predict that outside the sacrifice zone livestock impacts should change linearly with an ecological response variable until an asymptote is reached. Some evidence from the Mojave demonstrates this type of response. The point at which an asymptote is reached likely differs depending on the ecological response variable measured and stocking rates may affect the slope and intensity of the relationship. For the Sonoran Desert, cattle use of xeroriparian plant communities likely will need to be factored into the design of piosphere studies.

Despite the limitations of Sonoran Desert livestock impact studies described above, in combination they do indicate that livestock grazing can adversely impact plant community composition, structure, and function at the sites that were studied. Specific cause and effect—historic grazing versus current grazing versus cyclical weather patterns—were not always possible to tease out. As a result, uncertainty may exist relative to the applicability of findings to specific current grazing practices (which typically were not quantified) and the small breadth of the studies considered in terms of locales and plant communities; however, this uncertainty should not be viewed as evidence that livestock grazing, as currently practiced in the Sonoran Desert, does not have clear, demonstrated significant impact on Sonoran Desert plant communities. The lack of studies and confounding factors that can obscure clear study results can cut both ways. Most importantly, we did not find, based on the available literature, evidence to support what appropriate managed livestock grazing may look like in the Sonoran Desert because apparently such studies have not been conducted. We revisit the implications of this last finding in Chapter 10.

CHAPTER 5 SAGUARO RECRUITMENT AND SURVIVAL

The saguaro cactus (*Carnegiea gigantea*) is the signature plant of the Sonoran Desert. The eastern unit (Rincon Mountain District) of Saguaro National Monument (now Saguaro National Park) was established in 1933 and the Tucson Mountain District in 1961 to protect its extensive stands. The Sonoran Desert National Monument also was designated in part because of its dense and abundant stands of the columnar cactus that rival those found in Saguaro National Park (see the Monument Proclamation in Appendix A). The biology of the saguaro is well studied not only because of broad scientific and public interest in the species, but also because of the fear beginning in the 1940s that populations at Saguaro National Park East were severely declining because of disease or other factors (McAuliffe 1996). Studies focused on the decline have since shown that frost damage, not disease, was responsible for tissue necrosis. Decades of ecological studies at Saguaro National Park have contributed much to our current state of knowledge on the saguaro (McAuliffe 1993). To understand the mechanisms by which livestock grazing could potentially impact saguaro populations, we first present information on the factors affecting saguaro seedling recruitment and survival. We then discuss the literature that evaluates impacts on saguaro due to livestock grazing.

5.1 FACTORS AFFECTING SAGUARO RECRUITMENT AND SURVIVAL

In the sections that follow, we assess saguaro survivorship by age group, factors affecting fruit production and seed germination, and factors affecting seedling establishment and subsequent survival.

5.1.1 Saguaro Age-Survival Relationship

The probability of saguaro mortality is highly age or size-dependent (for saguaro age and size are highly correlated). Only a tiny fraction, if any, of the 2,000 to 2,500 seeds produced from a single saguaro fruit ever encounters conditions appropriate for germination. During the seedling stage, the young saguaro plant is succulent and vulnerable to herbivory. The mean life expectancy of a newly emerged saguaro seedling is two to six weeks and less than 1% of seedlings survive the first year of life (Steenbergh and Lowe 1983). The seedling is “the emerged young plant after the rupture of the seed coat at germination—that remains relatively vulnerable without benefit of the self-sustaining features that characterize later life as an established juvenile plant” (Steenbergh and Lowe 1977).

Seedling establishment, and initiation of the juvenile phase, is typically reached by 12 to 14 months of age, when the juvenile saguaro becomes a “well-rooted, self supporting young plant in which a certain continuance is assured” (Steenbergh and Lowe 1977). Mortality rates, however, remain high until the saguaro completes its fifth year, when only 0.25% of the original seedling cohort remains (Steenbergh and Lowe 1983). Survivorship is fairly constant after a saguaro’s fifth year of life until it reaches around 75 to 80 years of age, when older individuals in the population slowly succumb to death by 140 to 200 years of age (Steenbergh and Lowe 1983). A healthy saguaro is estimated to produce on the order of 40 million viable seeds during its reproductive life span (Steenbergh and Lowe 1983).

For a population of saguaro to maintain itself or grow, at least one seed from each saguaro must germinate and survive to reproductive maturity (which occurs at about 30 years of age). Because of the extremely low rates of saguaro seed germination and seedling survivorship, we focus most of our discussion on factors affecting these life stages.

5.1.2 Fruit Production and Seed Germination

Saguaro seed germination and seedling establishment occurs only in a minute fraction of the abundant seeds produced in any given year. The factors that are most critical in determining saguaro germination and seedling survival or mortality are temperature, rainfall timing and abundance, and predation. Reproduction (flower and fruit production) also plays a role and determines the potential seed supply for germination events.

Saguaro flower and fruit production depends largely on the age of the saguaro and the number of its buds (arms; Steenbergh and Lowe 1977). Flower and fruit abundance may be determined in part by rainfall and temperature. Winter and spring drought have little effect on reproductive growth (Steenbergh and Lowe 1977), but precipitation above about seven inches (180 mm) in July to August may lead to a surge in reproduction (McAuliffe 1996). Injuries to saguaros due to winter freezes can cause significant reductions in fruit production in the following spring and can affect flower production for one to two years (Steenbergh and Lowe 1977). A severe decline in the production of saguaro flowers and fruit (estimated to have declined to 5 to 10% of average production) was observed in the spring of 2004 in some parts of the Sonoran Desert, including Organ Pipe Cactus National Monument (T. Tibbitts, personal communication). The cause is unknown, but is speculated to be due to consecutive years of severe drought (T. Tibbitts, personal communication).

Saguaro fruit and seeds are a critical seasonal food source for numerous Sonoran Desert species. The main consumers of saguaro fruit and seeds at Saguaro National Monument are white winged doves (*Zenaida asiatica*), mourning doves (*Zenaida aurita*), harvester ants (*Pogonomyrmex spp.*), and Harris' antelope squirrels (*Ammospermophilus harrisii*) (Steenbergh and Lowe 1977). Many species of mammals, birds, and insects consume saguaro fruit and seeds, which potentially reduces the number of seeds available for germination (Steenbergh and Lowe 1969, 1977). Many species of birds and mammals, however, may eat saguaro seeds and pass the seeds through their gut, undigested and still viable. This enables dispersal of the seeds to potentially suitable germination sites. Possible saguaro seed dispersers include coyote (*Canis latrans*), javelina (*Pecari tajacu*), curve-billed thrasher (*Toxostoma curvirostre*), cactus wren (*Campylorhynchus bunneicapillus*), Gila woodpecker (*Melanerpes uropygialis*), and gilded flicker (*Colaptes chrysoides*) (Steenbergh and Lowe 1977). Summer rainfall also can play a role in dislodging seeds from fruit and transporting them to favorable germination sites (Steenbergh and Lowe 1969). High temperatures inhibit germination, restricting most germination to shaded sites, especially beneath nurse plants (Steenbergh and Lowe 1977). Germination also depends upon the timing and abundance of rainfall. Germination requires two to three continuous days of high moisture levels at the soil surface (Steenbergh and Lowe 1977). Seedlings emerge after two or more rainfalls within five days, where rainfall totals 0.85 to 3.00 inches (22 to 76 mm) (Steenbergh and Lowe 1969).

5.1.3 Seedling Establishment and Subsequent Survival

Approximately 1% of seedlings survive their first year, and about a quarter of these will survive past their fifth year (Steenbergh and Lowe 1977). The primary factors influencing seedling survivorship or mortality are temperature, rainfall, and herbivory. In one study of seedling mortality at Saguaro National Park East, Steenbergh and Lowe (1969) found that in the first two years following germination, seedling death was primarily due to drought (32%) and predation by insects (32%). Other causes of mortality were erosion (7%), rodent digging (8%), and other causes including rodent consumption and removal by birds (2%).

Microsite conditions including temperature and shade are essential for saguaro seedling survival. Nurse plants create microclimates that protect young saguaro from freezing in winter and lethal high temperatures in summer (McAuliffe 1993, 1996). Freezing temperatures critically limit seedling survival (Steenbergh and Lowe 1977, McAuliffe 1993). The northern distribution and elevational boundary of saguaro are largely determined by temperature, and saguaro is excluded from sites where periods of continuous subfreezing temperatures exceed 20 to 36 hours (Turner and others 2003). Freezes disproportionately injure saguaro under 6.6 feet (2 m) tall, with high rates of mortality. Experimental results in the laboratory reveal that saguaro seedlings are killed by “catastrophic freezes”—that is, temperatures of 27°F to 12°F (-3°C to -11°C) for greater than 29 continuous hours, but are not killed if temperatures are sustained for only six to 15 hours (Shreve 1911). During the catastrophic freezes of 1962 and 1971, individuals less than 1.5 feet (0.45 m) tall had a mortality rate of 15.4% (McAuliffe 1993). Similarly, catastrophic freezes are the primary cause of adult mortality in the Arizona Upland subdivision of the Sonoran Desert (Dimmitt 2000) and can cause tissue necrosis and decay (McAuliffe 1993). South-facing and rocky slopes typically have favorable climates and minimize the effect of winter freezes (Steenbergh and Lowe 1977).

In addition to suitable temperatures, saguaro seedlings require shade for survival. Shade decreases soil temperatures by 9 to 17° F (Turner and others 1966). In an experiment to determine factors important for saguaro seedling establishment, Turner and others (1966) found that saguaro seedlings transplanted to unshaded sites versus shaded sites in mid-July died within a year of germination. Most seedlings beneath paloverdes (*Cercidium* spp.) and on soil between tree openings survived the initial summer rainy season regardless of whether shade was available, but unshaded seedlings died at an accelerated rate during the following year’s pre-monsoon drought during May and June. They also observed that saguaro seedlings grown in lighter colored soils (taken from beneath paloverdes) absorb less heat and have increased survivorship compared to darker, more heat absorbent soils that are located beneath ironwood and mesquite. In a field examination of saguaro seedlings at Saguaro National Park East, Steenbergh and Lowe (1969) found that all saguaros 0.1 to 0.4 inches (3 to 10 mm) in diameter (177 individuals) received shade between 9 a.m. and 2 p.m. Plants provided shade to 98% of the individuals, whereas 2% had shade from rocks.

Initial saguaro seedling growth is highly dependent upon soil moisture levels (Steenbergh and Lowe 1969), but prolonged exposure to saturated soils results in seedling death (Steenbergh and Lowe 1977). Seedling death occurs mostly just after germination during the summer growth period. The mortality rate drops significantly after the summer monsoons in September (Steenbergh and Lowe 1977). Seedlings that germinate later than average (in late August and September), however, do not develop adequate water-storage capacity to survive post-monsoon drought (Steenbergh and Lowe 1977). Under favorable soil and shade conditions, additional irrigation does not increase survivorship and average rainfall alone is sufficient to ensure survivorship (Turner and others 1966).

Predation by herbivores is a major source of saguaro seedling mortality. Numerous species of insects from the Lepidoptera (butterflies and moths), Orthoptera (grasshoppers, crickets, and katydids), and Coleoptera (beetles) have been found to consume entire juvenile saguaro seedlings. The insect larvae enter the base of the seedling in the humid weeks following germination and feed on the succulent tissue (Steenbergh and Lowe 1977). Turner and others (1966) also found that insects played an important role in seedling mortality, with over 20% of seedling mortality at shaded sites due to consumption by the weevil *Gerstaeckeria turbida*. Rodents, lagomorphs, and birds may uproot or consume saguaro seedlings, but nurse plants provide some protection and concealment from seedling predators (Steenbergh and Lowe 1969).

Similar to many other plants in the Sonoran Desert, saguaros are not adapted to withstand fire. Saguaro seedlings and juveniles are particularly sensitive to fire. Section 4.1.4 provides additional details about the effects of fire on saguaro.

5.2 IMPACTS OF LIVESTOCK GRAZING ON SAGUARO

It is generally thought that livestock grazing is detrimental to saguaro populations. Livestock can directly impact saguaro by trampling and consuming seedlings, especially beneath nurse trees such as mesquite (*Prosopis* spp.) and paloverde where livestock seek shade and forage (Steenbergh and Lowe 1977, McAuliffe 1996). Livestock also can impact saguaro indirectly by altering plant community structure. Grazing can reduce the multi-storied structure of plant communities by decreasing litter, understory cover, and nurse plant cover. The resultant changes in plant community structure can limit the quality and number of sites suitable for germination and seedling and juvenile survival, and it can increase a young saguaro's exposure to natural mortality factors such as harsh climate and herbivory (Steenbergh and Lowe 1977, 1983). Despite the generally accepted view that livestock grazing has the potential to impact saguaro recruitment and survival in the ways described above, few studies exist that specifically test this hypothesis or evaluate the conditions under which grazing is likely to exert the greatest effects on saguaro populations.

We evaluated eight studies that addressed the effect of livestock grazing on saguaro population demographics. All of the studies took place in the Sonoran Desert: four in the Rincon Mountains at Saguaro National Park East, two in the Tucson Mountains at Tumamoc Hill and Saguaro National Park West, one at Organ Pipe Cactus National Monument, and one in the Pinacate region in Sonora, Mexico. Some papers only peripherally mentioned livestock grazing, whereas others were more directly related to the topic and had a primary goal of elucidating the role of livestock grazing in observed patterns of saguaro recruitment. Because saguaros are such long-lived plants, it is difficult to conduct controlled, long-term experiments to test how livestock grazing affects saguaro recruitment and survival. Instead, biologists, including the authors of the studies we reviewed, relied on post-hoc analyses of “natural” experiments. Saguaros have well-documented growth rates, age-dependent mortality rates, and a predictable relationship between age and height for a particular site (Steenbergh and Lowe 1983, 1997; Turner and Funicelli 2004). These relationships enable scientists to interpolate the year when individuals in a population were established based on their heights and to track trends in regeneration and mortality over time. Some studies compared saguaro populations at one site at multiple points in time and interpret demographics based on natural and anthropogenic events at the site in the interim. Other studies compared saguaro populations at two nearby areas with different land-use histories. The main limitation to these types of studies is that they can only show correlations and not conclusive causal effects. Given this inherent limitation to studies of saguaro, analyses of climatic patterns and land-use history at a site can offer only strong circumstantial evidence and probable explanations to account for observed patterns.

The most convincing case that livestock grazing impacted saguaro recruitment and survival comes from research done in the Rincon Mountain District of Saguaro National Park (SNP). The gradual loss of the dense saguaro stands in the “Cactus Forest” area of SNP is well documented by Turner and others (2003) in numerous sets of matched photo points. Similar losses in saguaro density and abundance were not observed at nearby sites in the Catalina Mountains (Turner and others 2003). Cattle grazed the Cactus Forest and other parts of SNP year-round until 1958. Livestock grazing was considered heavy and the range was severely depleted (Clemensen 1987). Woodcutting was also a common activity until the 1940s, and mesquites and paloverdes throughout the park were cut to fuel lime kilns and provide fuel for Tucson (Clemensen 1987). Although matched photos demonstrate a pattern, they do not explain its cause.

One of the more enlightening studies on saguaro demographics and livestock grazing in SNP was conducted by Abou-Haidar (1989). This is the only study that we reviewed that compared two adjoining areas with different amounts of time since protection from grazing.[15] Abou-Haidar (1989) compared saguaro populations on parallel belt transects on either side of a fence that divided an area that had been grazed until 1978 (“grazed”) from an area that had been protected from grazing 20 years prior in 1958 (“ungrazed”). Utilization on the grazed portion was recorded in 1976 as over 65%. Abou-Haidar (1989) found no significant difference in saguaro density between sites or in nurse plant density or canopy cover. The two sites, however, had highly divergent saguaro age structures (based on age-height correlations), with the greatest difference in the number of saguaros in the 0 to 10 and 10 to 20 year age classes. Almost half of the population of the ungrazed plot was less than 20 years old, whereas there were only three juvenile saguaros of the same age in the grazed plot. The timing of the surge in recruitment at the ungrazed plot is correlated with the cessation of grazing in 1958, but with a 10-year lag period that may account for the time needed for recovery of vegetation and microsite conditions and a favorable climate for recruitment. Abou-Haidar’s results are unlikely explained by climatic events because the plots are adjacent, yet show such divergent recruitment patterns. Other historic land uses, such as woodcutting, were not eliminated as a cause of the observed

---

[15] Abou-Haidar’s master’s research (1989) also was published in a conference proceeding in 1992. Both the 1989 and 1992 publications are cited in the scientific literature. We include both of them in our compilation, though they include the same data. From this point forward we only refer to the 1989 thesis, as it is a more inclusive work.

pattern, except to the extent that the surge in recruitment at the ungrazed site is correlated with the cessation of grazing at the site. The grazed plot was situated less than a mile from a salt lick and spring, so the results may not be applicable to sites with lower intensity livestock grazing.

Other studies conducted at SNP support Abou-Haidar's (1989) findings. Helbsing and Fisher (1991) sampled saguaro density at two plots in the Cactus Forest, which were last grazed in 1958. The authors found that 77 to 85% of the population was less than 20 years old (based on the age-height correlation). Similar to Abou-Haidar's findings, this study suggests that the saguaro population is rebounding with a burst of new recruitment that began approximately ten to twelve years after cattle were eliminated from the site. Helbsing and Fisher (1991) noted that all of the juvenile plants were found beneath nurse plants and numerous adult saguaros showed signs of lethal and non-lethal freezing damage. The authors speculated that saguaro may be limited at the site by cold temperatures and that the impacts of historic livestock grazing were greatest during cold winters when juvenile saguaro survival was likely compromised by a lower quantity or quality of protective sites beneath nurse plants.

Studies by Parker (1993) and Pierson and Turner (1998) also suggest that there is an interaction between the effects of livestock grazing with climatic conditions on saguaro recruitment. Although extreme overgrazing occurred on Organ Pipe Cactus National Monument until 1978, Parker (1993) found little correlational evidence suggesting that patterns of saguaro recruitment coincided with livestock grazing alone and not also with climatic events. Based on saguaro age-size relationships and regression models, Parker (1993) found that the main peaks in recruitment were in unseasonably wet years and mild winters despite the increase in stocking rate during the same period. The author found that although declines in saguaro regeneration occurred during the peak in grazing intensity in the early 1960s and 1970s, this also coincided with severe winter freezes. Pierson and Turner (1998) also found that recruitment events in the saguaro population on Tumamoc Hill corresponded with relatively wet conditions, and poorer regeneration coincided with drier periods. Declines in recruitment, however, during relatively wet years around the turn of the 20th century suggest that other factors, such as cold winters, livestock grazing, or other anthropogenic activities such as rock quarrying, affected saguaro recruitment or juvenile survival (Pierson and Turner 1998). Turner and others (1966) found that shade was critical for the survival of experimentally transplanted juvenile saguaros, and they speculated that a loss of shade-producing perennial plants because of forces such as livestock grazing or climate change would be reflected in saguaro population declines.

Other studies on saguaro populations do not have conclusive evidence of an effect of livestock grazing. In a matched photo series from 1907, 1959, and 1970 in the Pinacate of Sonora, Martin and Turner (1977) show an increase in saguaros since 1907 and a high percentage loss of nurse plants due to severe drought and woodcutting. They predict an eventual resultant decline in saguaro recruitment; however, such a decline was not evident at the time of the last photograph. Grazing had occurred at the site since 1964, but its impacts on the saguaro population at the site, if any, were not apparent. The cause of change in the saguaro populations is not well understood, as detailed climatic data and land-use history information at the site were unavailable.

Across a widespread area in the Sonoran Desert, a general pattern of decreasing saguaro abundance in the latter half of this century seems apparent. Turner and others (2003) calculated a net percentage change in saguaro at 82 matched photo station pairs for the period before 1962 and at 91 matched photo station pairs for the post-1962 period. The net percentage change in biomass was calculated by adding the percentage of photographs in which increased biomass occurred, subtracting the percentage in which a decrease was observed, and assigning a zero to the percentage showing no change in biomass. They found a net biomass change of –10% in the period before 1962, with a further decrease of –31% in the period after 1962. Declines in saguaro abundance are also documented on plots from nine Sonoran Desert sites, independent of grazing history (R. Turner, unpublished data). Gradual declines in saguaro abundance occurred at all sites since 1980, with the exception of Saguaro National Park West in the Tucson Mountains. This locale has experienced dramatic increases in saguaro abundance during the same period (R. Turner, unpublished data). The general decline in saguaro abundance is apparently not a localized phenomenon and suggests that some persistent regional factor may be responsible (Turner and others 2003). Turner and others (2003) did not specifically identify what this regional factor might be; however, the implication is that though livestock grazing cannot be ruled out as a contributing cause at some locales, causation is more complicated and grazing may act only synergistically with other proximate factors.

5.3 CONCLUSIONS

The conditions under which livestock grazing affects saguaro recruitment and survival are not completely understood. It is clear that grazing impacts potentially are greatest on saguaro germination and seedling and juvenile survival. Little, if any, impacts from grazing likely occur to adult saguaro, except to the extent that livestock grazing and management practices may be responsible for contributing to the increase in the distribution and abundance of invasive non-native grasses and forbs that can carry fire. The impacts of livestock grazing on saguaro are likely to be more dependent on grazing intensity rather than season of use, because seedlings and juveniles are vulnerable to trampling, herbivory, and adverse impacts to nurse plants for the first five years of life.

The literature suggests that under most circumstances climate is the primary factor affecting trends in saguaro populations, with periodic bursts in recruitment during years of above average precipitation and moderate winter temperatures and lulls in recruitment or increased mortality in years of severe freezes or drought. The literature also suggests that an interaction exists between livestock grazing and climate such that grazing exacerbates the effect of unfavorable periods of weather on saguaro recruitment. Protective nurse plants are critical for saguaro recruitment and seedling and juvenile survival, so a loss in nurse plant cover or abundance caused by livestock grazing (or other activities, such as woodcutting) may be disproportionately expressed during drought years or cold winters with long-term effects on saguaro demographics. This is especially the case in microsites lacking boulders and rocks, which also can serve as protective germination sites. Although livestock grazing is not likely the proximate cause of apparent declines in saguaro abundance at a regional scale, grazing can nonetheless contribute to declines of saguaro on a local scale, as was clearly observed at Saguaro National Park East.

CHAPTER 6 OTHER PLANT SPECIES

In Chapter 4 we reviewed how livestock grazing can impact Sonoran Desert plant communities, and Chapter 5 focused on the impacts on saguaro (*Carnegiea gigantea*). In addition to these topics, the Bureau of Land Management (BLM) is interested in how livestock grazing might impact other components of Sonoran Desert plant communities, such as rare plants. In this chapter we briefly review what constitutes a limited literature on the subject, with a focus on those rare plants that occur on the Sonoran Desert National Monument (SDNM). We consider rare plants as those taxa that are identified one way or another as a species of concern.

6.1 RARE PLANTS, LIVESTOCK GRAZING, AND GRAZING REFUGES

Livestock grazing has the potential to impact rare plants directly, by trampling them or eating them, or indirectly, by affecting the quality and quantity of potential habitat and sites for germination, growth, and survival. These mechanisms obviously are not unique to rare plants, but take on greater importance when dealing with low abundance populations.

As was discussed in section 4.1.5, plants can adapt to herbivore interactions through avoidance or tolerance. In areas accessible to native or domestic herbivores, avoidance is still possible through a variety of mechanisms. Some of these, such as spines or chemical defenses, we already have mentioned and can be considered as avoidance mechanisms developed internal to the plant. Milchunas and Noy-Meir (2002) provide a conceptual framework for external plant avoidances that includes foraging selection impedances (associational avoidances; for example, "hiding" with unpalatable species), behavioral impedances (indirect avoidances; for example, herbivore behaviors that manifest independent of dietary selection), and physical impedances (refuges). It is the refuge concept that is of interest from the standpoint of rare plant-herbivore interactions. Three types of refuges are possible: (1) biotic refuge, in which the presence of certain plants (the host or nurse) protects other plants; (2) small geologic refuge, such as rock outcrops and cliffs; and (3) large geologic refuge, such as mesas, buttes, and islands. The impedance (resistance to herbivore interaction) caused by a refuge may be particularly effective against large mammalian herbivores. Both biotic and geologic refuges may alter the microhabitat conditions either favorably or unfavorably from the perspective of the protected plant; however, even within a biotic refuge when competition with the host plant occurs, positive benefit to the protected plant may increase as the stress imposed by the herbivore (by herbivory or trampling) increases. Milchunas and Noy-Meir (2002) predicted that the likelihood of species persisting that may otherwise go locally extinct in the presence of herbivores will increase as the non-probabilistic nature and higher efficiency of the external avoidance increases (that is, large geologic refuges offer the greatest probability of complete protection, whereas small geologic refuges, then biotic refuges, then indirect avoidance, then associational avoidance offer less).

Refuges may have their greatest potential for protecting rare species when the ecosystem under consideration is both a productive ecosystem and it has a short evolutionary history with grazing (Milchunas and Noy-Meir 2002); however, their importance may not be limited to these conditions. A number of studies have evaluated refuge effects relative to protection from herbivores. We mention two here from the Sonoran Desert. McAuliffe (1984) reported that two small cacti, *Mammillaria microcarpa* and *Echinocereus englemannii,* are found significantly more often amidst the beds of spine-covered stem joints that fall off beneath the canopies of chain-fruit cholla (*Opuntia fulgida*) than would be expected if they were randomly dispersed. He concluded that protection from small mammalian herbivores was critical to the survival of these small cacti beyond the protection that they may have been afforded from abiotic factors. In grazed shortgrass steppe plant communities in Colorado, Rebollo and others (2002) found that the spiny cactus *Opuntia polyacantha* provided a refuge effect for barrel cacti. Cattle do not graze barrel cacti in the shortgrass steppe so the refuge effect may have been due to reduced trampling (Rebollo and others 2002). Refuges also may be important for relatively common plants. McAuliffe (1986) suggested that consumption of foothill paloverde (*Cercidium microphyllum*) seedlings by herbivores limits successful establishment of this species to refuges provided by canopies of other established perennial plants.

In conclusion, although refuges, biotic or geologic, may be more important for maintaining viable populations of rare plants in productive ecosystems with a short evolutionary history of grazing, they also could play a role in rare plant population dynamics for a low productivity ecosystem with a short evolutionary history of grazing such as the Sonoran Desert. In the next section we assess the vulnerability of rare plants on the SDNM from the standpoint of their accessibility to cattle.

6.2 RARE PLANTS ON THE SONORAN DESERT NATIONAL MONUMENT AND THEIR RELATIONSHIPS TO LIVESTOCK GRAZING

Three rare plants are known to occur on the SDNM: Kofa barberry (*Berberis harrisoniana*), acuña cactus (*Echinomastus erectrocentrus* var. *acunensis*), and Tumamoc globeberry (*Tumamoca macdougalii*). Acuña cactus is a candidate species for protection under the Endangered Species Act (global rank [GR]: G3T1Q; state rank [SR]: S1).[16] Tumamoc globeberry (GR: G4; SR: S3) and Kofa barberry (GR: G1G2; SR: S1S2) have no current federal status but are on the BLM's sensitive species list. We did not find any literature that explicitly studied how livestock grazing impacts any of these three species either directly or indirectly. Some literature, however, briefly mentions the possibility or speculates that livestock grazing may be a threat to these plants. In the next few sections we provide summary information on the biology of the three rare plants on the monument and consider the potential for livestock grazing to impact these plants.

6.2.1 Kofa Barberry

Kofa barberry is a globally rare species that is known only from remote, rugged sites on several Sonoran Desert mountaintops. The plant is likely a relict species from cooler, wetter climes that existed thousands of years ago in the Sonoran Desert, and which today remain only at high elevations, within shady canyons, and on north-facing slopes on a few Sonoran Desert mountain

---

[16] Global and state rarity ranks are assigned by the state network of Natural Heritage Programs. The ranks here are taken from Arizona Game and Fish Department, Heritage Data Management System (latest revision 6/30/98). The Department's compilation of rarity ranks also contains the definitions of the various ranking categories.

ranges (Brown 1978, Morrison and others 2003). A population of Kofa barberry is located on the SDNM in the Sand Tanks Mountains, associated with the Mountain Upland natural community (Morrison and others 2003). Livestock are unlikely to access these sites because of their steep slopes and ruggedness. Furthermore, Kofa barberry is located on the SDNM only in areas south of Interstate 8, where livestock grazing will be terminated after the expiration of current grazing permits. In sum, the impacts of livestock on Kofa barberry are expected to be minimal on the SDNM.

6.2.2 Acuña Cactus

The following information is taken from Pima County's Sonoran Desert Conservation Plan (Pima County 2001). Acuña cactus is known from only five sites in the world, all of which are in the Sonoran Desert in southern Arizona and northern Sonora. It has been found only in relatively pristine desert areas and does not occur in areas with substrate disturbances. Off-road vehicular traffic, grazing, and land development have the potential to alter acuña cactus habitat or cause direct mortality, but scientific studies or documented evidence that this has occurred are lacking. Nonetheless, Pima County (2001) describes declines in acuña cactus populations that are presumed to be caused by different sources at different locations, including livestock and wild burro grazing, illegal collection, a general decline in habitat quality, and historic impacts associated with mining.

On the SDNM, the acuña cactus is known from only one remote and rugged site that is unlikely to have surface disturbances from cattle or other sources (considering existing rates and intensity of uses on the monument). This small cactus is easily overlooked, however, and little of its potential habitat has been mapped or surveyed (Geraghty and Miller 1997, Pima County 2001). Potential habitat of the acuña cactus is at elevations between 1,200 and 2,600 feet (366 to 792 m) and slopes from zero to 30% (Geraghty and Miller 1997), so it is feasible that cattle could access areas of potential acuña cactus habitat elsewhere on the SDNM.

6.2.3 Tumamoc Globeberry

Tumamoc globeberry is a tuberous perennial vine that is visible above ground only during the growing and reproductive season, which occurs after the summer monsoons. Even during the growing season, the plant is highly cryptic because it grows beneath a variety of shrub and tree nurse plants (FWIE 1996). The U.S. Fish and Wildlife Service listed the Tumamoc globeberry as endangered in 1986. At the time of listing, only 30 known populations of the plant occurred within its restricted U.S. distribution (wholly contained within Pima County, Arizona), and five populations composed of 60 individuals were known from Sonora, Mexico (USFWS 1986). At the time of listing, all but one of the known populations in the United States were facing imminent threat from urban and agricultural expansion. Other threats to known populations included collection or vandalism, disease or predation, and livestock grazing, which caused trampling of individuals located under trees or shrubs (USFWS 1986).

Additional surveys for Tumamoc globeberry conducted after 1986 expanded the known geographic range of the species northward to southern Pinal and Maricopa Counties, Arizona, and southward to southern Sonora (Reichenbacher 1990). The northern extent of the plant's range is in the Vekol Valley on the SDNM. Studies also found that Tumamoc globeberry was less habitat-specific and more abundant than initially thought, with populations occurring in a variety of soil types and habitat associations in the Sonoran Desert. Based on this information, the species was removed from protection under the Endangered Species Act in 1993 (USFWS 1993).

The impact of livestock grazing in Tumamoc globeberry habitat has not been studied explicitly, but some observations suggest that grazing could potentially have negative impacts on the vine. Tumamoc globeberry is highly dependent upon nurse plants for favorable microclimates and protection from herbivores (FWIE 1996). Therefore, Tumamoc globeberry is vulnerable to trampling by shade-seeking livestock. Livestock may reduce the area of suitable habitat or germination by reducing groundcover and nurse plant cover and, once the understory is opened up by livestock, Tumamoc globeberry tubers may be vulnerable to predation by foraging animals such as javelina (*Tayassu tajuca*) (FWIE 1996). Furthermore, Tumamoc globeberry is usually found in undisturbed soils, so any soil-surface disturbance, such as that caused by livestock grazing or vehicular traffic, could negatively impact the plant (Pima County 2001). Areas around livestock waters are likely to be most vulnerable to disturbance and negative impacts. Livestock grazing in Sonora has been indirectly responsible for extensive loss of former Tumamoc globeberry habitat as large areas have been converted to buffelgrass pastures (*Pennisetum ciliare*) for cattle production (S. Rutman, personal communication).

Tumamoc globeberry was monitored on the SDNM from 1990 to 2000. Thirty-seven plants were located and tagged in 1990, but few individuals were found in subsequent years (between three and 12 plants) (BLM, unpublished data). The cause of the apparent decline in Tumamoc globeberry on the SDNM is not known.

6.3 CONCLUSIONS

Biotic and geologic refuges could be important for maintaining rare plant populations in the presence of both native and non-native herbivores. Limited information is available that addresses the potential impact of domestic livestock grazing on rare plants occurring on the SDNM (Kofa barberry, acuña cactus, and Tumamoc globeberry). Although anecdotal information suggests that livestock grazing could potentially negatively impact acuña cactus and Tumamoc globeberry, the studies we reviewed provided no empirical data that addressed the impacts of livestock grazing on these species. Of the three rare plants known from the SDNM, only Tumamoc globeberry is found in areas easily accessible to livestock. Because of its dependence upon nurse plants for its growth and survival, Tumamoc globeberry has the greatest potential to be negatively impacted by cattle because of the latter's propensity to seek shade and rest beneath large shrubs and trees that may serve as Tumamoc globeberry nurse plants.

CHAPTER 7 SOILS AND BIOLOGICAL SOIL CRUSTS

This chapter first considers the ecological characteristics and importance of soils and biological soil crusts in the Sonoran Desert. Based on this information and the available literature, it then assesses the potential impacts of livestock grazing on Sonoran Desert soils and biological soil crusts.

7.1 PROPERTIES OF SONORAN DESERT SOILS

Major differences in floral composition across the Sonoran Desert are due to mostly climatic and historical factors, such as geographic isolation. Differences in soil characteristics, however, can be responsible for considerable local variation in plant community composition (McAuliffe 1991, 1999). Soil texture affects infiltration and moisture availability in desert soils. Differences in soil characteristics that influence plant-water availability have a profound effect on determining the vegetation that can exist at a site. Although casual observation may suggest that there is a simple relationship between soil texture and elevation along a bajada (broadly encompasses the piedmont slope of Peterson 1981) in which fine soils settle toward the valley bottom and coarser textured soils characterize the upper slopes, the relationship between soil texture and its distribution is more complex. The distribution of soil coarseness along a bajada reflects historic landscape patterns, multiple alluvial deposition events, parent material of the alluvium, and the time since deposition for erosion and soil formation to occur (McAuliffe 1999). As a result, bajada plant community composition may show complex patterns of distribution in response to different ages of alluvial surfaces (McAuliffe 1999). Finally, the parent material of the alluvium that forms piedmont slopes determines in part the resultant soil's susceptibility to erosion and landscape incision (McAuliffe 1995). For example, highly weatherable rock types, such as granite, form alluvium that is much more susceptible to erosion than alluvium derived from basalt rocks (McAuliffe 1995).

Compared with other biomes, desert soils are generally low in total nitrogen, which likely is a result of characteristically low soil moisture and high temperatures (West and Klemmedson 1978). The vertical and horizontal distribution patterns of nitrogen in deserts suggests that nitrogen may be present in limiting quantities relative to the effect on overall ecosystem productivity (West and Klemmedson and 1978); however, this limitation likely is secondary to available soil moisture and may only occur during relatively wet years (West and Skujiņš 1978, Hadley and Szarek 1981). Nitrogen tends to be concentrated in the upper part of the soil profile when the vegetation shoot:root ratio is high (which is more typical of the Sonoran Desert than the Great Basin and Chihuahuan Deserts where this particular soil pattern is less pronounced because root system biomass proportions tend to be higher) and horizontally is concentrated in "islands of fertility" associated with the scattered occurrence of vegetation (West and Klemmedson 1978). The concentration of nitrogen in the upper soil profile makes it susceptible to loss by erosion, which could be significant in southern Arizona at least at locale scales, especially when the soil is destabilized by disturbance (Fletcher and others 1978).

In many ecosystems, a primary source of soil nitrogen is from fixation by leguminous plants via symbiotic bacteria (*Rhizobium*) found in root nodules. In the hot deserts of North America (Chihuahuan, Mojave, and Sonoran), however, little evidence existed as late as the late 70s that the dominant leguminous shrubs (including species from the genera *Acacia*, *Cercidium*, and *Prosopis*) were nitrogen fixers (West and Klemmedson 1978). Many of these plants seemingly lacked root nodules and the symbiotic nitrogen-fixing bacteria typically found therein. Although through greenhouse studies Felker and Clark (1980) found that 12 species of mesquite (*Prosopis*), including two species that occur in the Sonoran Desert of Arizona, developed root nodules and fixed nitrogen, they still indicated that nodulation had yet to be reported from natural ecosystems. Barth and Klemmedson (1982) found that velvet mesquite (*P. velutina*) contributed substantially to both nitrogen and carbon levels in the soil; however, they did not discover nodules and concluded fixation was not a factor in nitrogen accrual in their study; rather, the source of nitrogen was external and a root absorption-litter deposition mechanism was hypothesized as the most plausible mechanism of nitrogen accumulation. Felker and Clark (1981), again through greenhouse studies, reported that nodulation and nitrogen fixation occurred in ironwood (*Olneya tesota*), but not in catclaw (*Acacia greggi*) or in blue paloverde (*Cercidium floridum*). Some evidence also indicates that certain Sonoran Desert non-leguminous plants, including creosotebush (*Larrea tridentata*) and various species of *Opuntia*, contribute to soil nitrogen by fixation in root nodules or by fixation by free-living bacteria that live at the soil-root interface (Farnsworth and others 1978).

A potential major source of nitrogen in desert soils is from biological soil crusts containing nitrogen-fixing cyanolichen or cyanobacteria (blue-green algae) (Rychert and others 1978, Evans and Lange 2001), the latter of which is the main component of Sonoran Desert biological soil crusts (Rosentreter and Belnap 2001). The ranges of nitrogen fixation rates for Sonoran Desert biological soil crusts provided by Rychert and others (1978) and Evans and Lange (2001) were based on studies by Mayland and others (1966; crusts obtained from a semidesert grassland site near Oracle, Arizona) and MacGregor and Johnson (1971; crusts obtained from a semidesert grassland site in the foothills of the Santa Rita Mountains near Tucson, Arizona). Because the values obtained are for semidesert habitats that are not the focus of this report, the nitrogen fixation rates may or may not be typical of the plant communities considered herein. Clearly, more research is needed to understand the importance of and relative contribution of biologically available soil nitrogen from Sonoran Desert biological soil crusts versus vascular plants and their affiliated bacteria.

7.2 BIOLOGICAL SOIL CRUSTS

This section first describes some of the characteristics of Sonoran Desert biological soil crusts and then provides a more general description of the ecological functions of biological soil crusts. Sonoran Desert specific information is noted when available.

7.2.1 Characteristics of Sonoran Desert Biological Soil Crusts

Biotic or biological soil crusts are also known by many other names including cryptogamic, microbiotic, cryptobiotic, and microphytic crusts. These names all refer to a highly specialized community of living organisms found on the surface of soils throughout much of the world's semiarid and desert environments. In this report we will use the term “biological soil crusts” because this term is the most general and inclusive. Biological soil crusts are composed of various species of cyanobacteria, algae, mosses, lichens, bacteria, or fungi. These organisms bind with soil particles to form a crust. Biological soil crusts should not be confused with physical or chemical crusts, such as salt crusts, which are composed of inorganic materials.

The composition and structure of biological crusts differ throughout the world (Belnap and Lange 2001). As a hot desert, Sonoran Desert biological crusts differ from those in cool deserts (such as the Great Basin) in that they lack frost-heaved soils and have less lichen cover and abundance. (Lichen relative abundance is strongly correlated with rainfall abundance.) Sonoran Desert crusts are rugose (surface roughness between 0.4 to 1.2 inches) in morphology and dominated by cyanobacteria, with green algae and fungi also present (Belnap 2001a, Rosentreter and Belnap 2001). Soil lichens and mosses, which contribute to surface roughness, are typically found in sparse patches in the Sonoran Desert, except at higher elevations and north facing slopes where temperatures are lower and relative humidity is higher (Nash and others 1977). At these sites, lichens and moss species also common to the Colorado Plateau are found (Rosentreter and Belnap 2001, J. Belnap, personal communication). Cyanobacteria diversity (species richness and evenness) is higher in the Sonoran Desert than in other hot deserts. For example, at numerous sites across the Sonoran Desert (and some adjoining areas to the south and east), Cameron (1960) found taxa representing five divisions, 32 genera, and 72 species, typically with one to 10 species per site. In contrast, Mojave Desert biological crusts are usually dominated by a single species (Rosentreter and Belnap 2001).

In contrast to cool deserts that have conspicuous biological crusts, it is often difficult to detect the presence of biological crusts in the Sonoran Desert because of the relative rarity or absence of lichens and the relatively flat surface topography of the crust. Sonoran Desert biological crusts are most apparent when soil moisture is high and cyanobacteria are photosynthetically active and visible as a dark layer on the soil surface (Belnap and others 2001b). During dry periods Sonoran Desert biological crusts are inconspicuous. They are also brittle, easily crushed, and vulnerable to disturbance when dry (Belnap 1995). Biological crusts can occur on any aspect or slope. They are most developed in areas where plant cover is sparse. In a study of lichens and mosses (both free-living and biological crust-associated species), Nash and others (1977) found that Sonoran Desert biological crusts had their greatest cover on north-facing slopes. Although biological crusts had low total cover on south-facing slopes, they comprised the greatest proportion (over 80%) of the total lichen and moss cover at these sites (Nash and others 1977). On Organ Pipe Cactus National Monument biological soil crusts reach their greatest cover values on flat or low-slope surfaces (S. Rutman, personal communication).

At present, we have insufficient knowledge about Sonoran Desert biological crusts to be able to predict the species composition, abundance, or total percent cover that would be expected to occur at a particular site. Therefore, we can only infer impacts to biological crusts based on the presence of disturbance factors or by taking measurements prior to and after disturbances (J. Belnap, personal communication). Cool desert biological crusts are more susceptible to trampling and have slower recovery times than hot desert crusts (generally on the order of centuries rather than decades) because of the greater vulnerability of frost-heaved soils and lichens to soil disturbance than algae and other dominant components of hot desert biological crusts. Nonetheless, biological crusts in the Sonoran Desert are vulnerable to disturbances that can affect their ecological functions.

7.2.2 Ecological Functions of Biological Soil Crusts

Biological crusts are located at the soil surface where they affect ecological processes taking place at the soil-air interface. Some of the processes that biological crusts influence include: nutrient cycling, nitrogen fixation, and nutrient availability to plants; seedling germination and vascular plant growth; water infiltration and runoff; and soil stabilization and erosion. We first need to understand how biological crusts influence the above mentioned processes to be able to develop a clearer picture of how livestock grazing or other disturbances to biological crusts could affect Sonoran Desert ecosystems.

Nutrient Cycling, Nitrogen Fixation, and Nutrient Availability to Plants

Biological soil crusts influence the cycling and biological availability of several plant-essential nutrients (Belnap and others 2001a). Although competition for limited nutrients between soil-crust organisms and vascular plants is possible, the presence of biological soil crusts generally seems to enhance plant uptake of several nutrients. In addition, at least for some plants crusted surfaces may enhance mycorrhizal infestations, which in turn may result in increased nutrient availability to these plants. Because vascular plant productivity in most arid and semiarid plant communities tends to be low, biological soil crusts may make a substantial contribution to the carbon budget of these ecosystems, especially in plant interspaces where water and nutrient limitations otherwise restrict such inputs (Evans and Lange 2001).

Biological soil crusts can contribute significant amounts of fixed nitrogen to soils and ultimately to plants. Belnap and others (2001a) reviewed multiple studies from different geographies that reported the presence of biological soil crusts increases surrounding soil nitrogen by up to 200%. In addition, these authors reported that stable isotope studies indicated that crust-derived nitrogen can be the dominant source of nitrogen for desert soils and plants. For the Sonoran Desert in particular, Fletcher and Martin (1948), Cameron and Fuller (1960), and Fuller and others (1960) reported that biological soil crusts were higher in nitrogen than subsurface layers, in some cases by as much as 400%, and Faust (1970) reported higher soil nitrogen values (absent statistical tests) from two soil types that differed in sand and clay content (fine- versus coarse-textured soil) when biological soil crusts were present versus absent. The range in nitrogen values between surface soils containing biological soil crusts and subsurface soils reflects both degree of crust development and differences in species composition of the crust with different soil types (Fuller and others 1960). Finally, Fuller and others (1960) demonstrated that fixed nitrogen derived from Sonoran Desert crusts was available to plants.

Estimates of soil nitrogen input from biological soil crusts are obtained through estimates of nitrogen fixation by crust organisms. Direct measurements using isotope studies are best; however, most studies have relied on a less accurate surrogate approach that relies on the ability of the nitrogenase enzyme to reduce acetylene to ethylene (Evans and Johansen 1999). Spatial variation in nitrogen fixation may result from changes in species composition (Evans and Lange

2001), so fixation estimates also may need to account for beta diversity patterns of crust organisms that have different fixation rate capacities.

As mentioned above, values for nitrogen fixation by biological soil crusts in the Sonoran Desert (Rychert and others [1978] and Evans and Lange [2001] citing information from Mayland and others [1966] and MacGregor and Johnson [1971]) are more accurately attributable to semidesert grassland sites adjacent to the Sonoran Desert as we have defined its extent here. As a result, the values on average may typify wetter and more productive ecosystems than those considered herein for the Sonoran Desert. In both studies the crusts had to be moistened first before fixation could occur, so periods of drought may limit fixation amounts. Still, the findings from these two studies may be of interest and should be discussed as they are now the reported values for biological soil crust nitrogen fixation in the Sonoran Desert. Estimated fixation rates ranged from about 6.2 to 9.6 pounds of nitrogen fixed per acre per year (7 to 11 kgN ha^{-1} yr^{-1}; Mayland and others 1966) to 11.6 to 16.1 pounds of nitrogen fixed per acre per year (13 to 18 kgN ha^{-1} yr^{-1}; MacGregor and Johnson 1971) as reported by Evans and Lange (2001); however, the reported values are problematic in that the assumptions considered and methods to measure fixation differed between studies and were not adequately considered. The Mayland and others (1966) estimate was obtained via isotope analysis, whereas the MacGregor and Johnson (1971) estimate was obtained via the acetylene-ethylene method. Moreover, the Mayland and others' (1966) estimate range (for cycling wet-dry and continuous wet conditions, respectively) reflects a situation in which biological soil crusts cover the entire surface, which they do not under natural conditions. MacGregor and Johnson (1971), who applied a surface cover correction, determined mean crust coverage in their study to be 4.25%. If we apply this correction to Mayland and others' (1966) data, the low estimate of fixation rate (cycling wet-dry conditions) would decrease to about 0.26 pounds of nitrogen fixed per acre per year (0.30 kgN ha^{-1} yr^{-1}). Mayland and others (1966) adjusted their fixation estimates to account for when they thought natural conditions of rainfall and temperature would be conducive for crust growth and fixation (about one sixth of the year). MacGregor and Johnson (1971) did not make this adjustment. If we apply this correction, the high estimate of fixation rate—notwithstanding issues associated with the acetylene-ethylene method for estimating fixation rates—would decrease to about 3.1 pounds of nitrogen fixed per acre per year (3.5 kgN ha^{-1} yr^{-1}). Despite the problems in the reported values and their interpretation, we note that both Mayland and others (1966) and MacGregor and Johnson (1971) concluded that the biological soil crusts were an important source of fixed nitrogen. Moreover, Mayland and McIntosh (1966) determined that the fixed nitrogen was in a form available to plants and was taken up by plants. To put any fixation values into an ecological perspective requires the development of a nitrogen cycle model and budget for the Sonoran Desert similar to that attempted by Wallace and others (1978) for the Mojave Desert.

Environmental controls on nitrogen fixation are hierarchical. Nitrogen fixation by cyanobacteria is ultimately limited by moisture because moisture (liquid water) is required in photosynthesis to produce the energy required for nitrogen fixation (Belnap 2001b). In addition to moisture, nitrogen fixation rates also depend upon intracellular carbon stores, light availability, and temperature. A positive correlation exists between temperature and rates of nitrogen fixation and photosynthesis (Belnap and others 2001b); however, once an upper temperature limit is reached, rates decline rapidly (Belnap 2001b). High soil salinity, high soil nitrogen, and low pH depress nitrogen fixation rates, and phosphorus additions stimulate fixation rates (Belnap 2001b).

The soil nutrient supply is largely confined to the upper two inches of soil, making it vulnerable to loss to the atmosphere via erosion and volatilization (Fletcher and others 1978, West and Klemmedson 1978, Hadley and Szarek 1981). Up to approximately 70% of the nitrogen fixed by biological crust species is released soon after fixation and is available to be used by surrounding organisms including vascular plants, fungi, and bacteria (reviewed by Belnap 1995, 2001b). In hot deserts, however, times at which nitrogen fixation and release are greatest also may correspond to times when nitrogen losses are the greatest (Belnap 2001b). Losses of plant-available soil nitrogen can occur through volatilization, denitrification, or nitrification of fixed nitrogen (Evans and Johansen 1999). Moreover, cyanobacteria photosynthesize at the soil surface, so any event that impacts soil surfaces and cyanobacterial activity could also impact soil nitrogen availability.

Seedling Germination and Vascular Plant Growth

The increased surface relief of biological soil crusts (compared to bare soil surfaces) is presumed to provide favorable microclimate and germination sites for many types of seeds. Although Sonoran Desert biological crust surfaces have less microtopographic relief than the pinnacled biological crusts typical of cool desert systems (Belnap 2001a), Sonoran Desert biological crusts may significantly aid in plant germination and initial establishment of native annual plants and plants whose seeds lack burial mechanisms (Belnap and others 2001a). In contrast, biological soil crusts in hot deserts may hinder the germination and establishment of non-native annual grasses that lack burial mechanisms and require disturbed microsites, such as *Schismus* spp. As a result, intact biological crusts are thought to play a role in limiting invasions of such invasive non-native species (Belnap and others 2001a). McIlvanie (1942) found in greenhouse tests that biological soil crusts from two samples of a semidesert grassland site near Tucson, Arizona inhibited germination of both a small- (Lehmann lovegrass [*Eragrostis lehmanniana*]) and a large-seeded (blue panic [*Panicum antidotale*]) non-native grass species.

Plant growth and cell division is promoted by cyanobacteria in biological crusts that secrete various vitamins and auxin-like substances. Studies show that there is a positive relationship between biological soil crusts and plant survival and biomass in cool and cold (arctic) deserts, but generally comparable studies are lacking in hot deserts (Belnap and others 2001a). In pot tests using soil from the same semidesert grassland site mentioned above, McIlvanie (1942) found that soil with biological soil crusts obtained from a conservatively grazed area showed increased yields for each of four plant species evaluated compared with bare soil obtained from an overgrazed area.

Water Infiltration and Runoff

Biological crusts may alter water infiltration and runoff, but studies show mixed results that may depend on factors such as soil texture and chemistry and site location (Belnap and Lange 2001, Belnap and others 2001b). Furthermore, the results of some studies that evaluate infiltration rates at sites with and without biological crusts are confounded in that sites lacking biological crusts also are disturbed (Warren 2001a). In general, infiltration is greater on pinnacled textured biological crusts typical of cool deserts than on the relatively flat biological crusts of hot deserts (Belnap and others 2001b). In some cases water infiltration may be reduced by biological crusts because of the water holding capacity of cyanobacteria at the soil surface. The polysaccharide sheathes of cyanobacteria adhere to soil particles even when soils are dry or after the cyanobacteria die. The sheathe can absorb up to eight times its weight in water, increasing the water-holding capacity of the soil but limiting infiltration to deeper soil layers (Belnap 1995). For hot deserts this negative effect may be limited to soils in which sand content exceeds 80% (Warren 2001b). Where desert soils contain a high silt content, the soils are prone to the development of vesicular horizon that slows infiltration and may mask any potential effects of biological soil crusts (Warren 2001b).

In the Sonoran Desert the effect of biological crusts on water infiltration and runoff seems to depend on both soil texture and rainfall intensity. No significant difference in infiltration or runoff occurred on coarse-textured (sandy loam) soils with and without biological soil crusts; however, fine-textured (clay loam) soils with biological soil crusts had significantly greater infiltration than soils without crusts (Faust 1970). The latter effect was significant only for low intensity simulated rainfall (one inch per hour) and not for high intensity simulated rainfall (two inches per hour). Higher intensity rainfall potentially disrupts biological soil crusts and breaks down soil aggregates; which can subsequently lead to pore clogging (Faust 1970, Warren 2001a). The presence of biological soil crusts did not have a statistically significant effect on runoff amounts for the fine-textured soil (Faust 1970). Similarly, Fletcher (1960) found for soils and biological soil crusts near Tucson, Arizona that the magnitude of runoff was dramatically different when crusts were present versus when they were removed on fine-textured alluvial soils compared with a coarser gravelly granitic soil. Fletcher (1960) also suggested that the relationship between biological soil crusts and soil hydrology may have a seasonal dependence in which the infiltration and runoff characteristics of the crust are affected by the cycle of wet and dry periods that dictate the crust’s surface structure.

Soil Stabilization and Erosion

In contrast to the mixed results on infiltration, all studies conducted in arid and semiarid regions of North America without exception indicate that biological soil crusts are effective in reducing soil erosion by water, whether from raindrop impact or surface runoff (Warren 2001a). This seems also to be the general pattern with respect to wind-induced erosion; however, the protection afforded by biological soil crusts from wind may be more important on coarse soils that tend not to form physical crusts (Belnap 2001c). Crusts contribute cover and roughness to the soil surface, which can reduce the impact energy of falling raindrops, slow runoff, and provide detention storage (Warren 2001b). The physical properties of biological crust organisms help to bind soil particles thereby limiting soil erosion by water and wind. Free-living fungi and those associated with lichens contribute to soil stability by binding particles with hyphae. Lichens and mosses also bind soil particles with rhizoids. Numerous algal species are common under fine textured rocks and serve to hold the rocks firmly to the soil surface (Rosentreter and Belnap 2001). Many species of cyanobacteria in biological crusts have filamentous growth habits and polysaccharide sheaths surrounding the filaments that bind surface soils (Belnap 2001a). In comparison to other soil crust organisms such as lichens, cyanobacteria are less effective in protecting soil surfaces from water erosion (Eldridge 2001); however, the presence of biological soil crusts significantly reduced the amount of suspended sediment present in runoff water from fine-textured, but not coarse-textured, soil from the Sonoran Desert (Faust 1970).

7.3 IMPACTS OF LIVESTOCK GRAZING ON SOILS AND BIOLOGICAL SOIL CRUSTS

The majority of research on impacts to biological soil crusts has taken place in cool deserts (primarily the Colorado Plateau region of the Great Basin Desert). Based on a basic knowledge of the differences in biological crust properties and ecological functions between cool and hot deserts, we can cautiously interpret results from studies that took place outside the Sonoran Desert for their applicability to the Sonoran Desert as a supplement to the more meager research conducted in the Sonoran Desert. We evaluate below 22 papers that addressed impacts to soils and biological soil crusts, nine of which took place in or included review information from the Sonoran Desert. Finally, one paper (Belnap 1992) that we did not include in the above tallies suggested a pollutant effect on biological soil crusts located on Saguaro National Park near Tucson, Arizona.

Most of the papers we reviewed assessed primary or secondary effects of disturbance on biological soil crusts and their associated ecological processes. Whether caused by livestock grazing, off-road vehicle (ORV) use, or some other source of disturbance, the degree of impact to biological soil crusts depends on the intensity, duration, return interval, and spatial extent and pattern of the disturbance (overall severity) rather than just its type (for example, mechanical disturbance). Although different sources of disturbance of a similar type may differ in the severity of their impacts, non-livestock grazing disturbance sources still can be used to illustrate the nature of biological soil crust responses to particular types of disturbance. Moreover, different disturbance sources, when they are present in the same area, may act in concert to produce an overall impact of greater severity. Therefore, we included some papers in our analysis that addressed impacts to biological crusts caused by disturbance sources other than livestock grazing that create comparable types of disturbance. Impacts to biological crusts are discussed in the following sections and are organized thematically by ecological process or environmental feature.

In addition to impacts on biological soil crusts, some papers included in our analysis evaluated the impacts of livestock grazing on soil physical properties, which are correlated with soil stability and erosion, water infiltration, and runoff. We address a portion of these findings in section 7.3.2 *Soil Compaction and Soil Moisture Relations*. Several key studies described the circumstances under which livestock grazing can cause accelerated soil erosion and associated long-term irreversible impacts to plant communities. We included a discussion of these studies in section 7.3.5 *Accelerated Soil Erosion*.

7.3.1 Biological Soil Crust Vulnerability to and Recovery from Mechanical Disturbance

Recent literature and quantitative reviews show overwhelming consensus that mechanical disturbance is detrimental to biological soil crusts throughout the arid regions of the world, with marked reductions in crust cover, frequency, biomass, species richness and diversity, and ecological function in areas subjected to livestock grazing, ORV and military vehicle use, and/or other sources of mechanical disturbance compared with areas protected from such uses (Belnap 1995, Evans and Johansen 1999, Jones 2000, Belnap and Eldridge 2001, Belnap and others 2001b, Warren and Eldridge 2001).

The vulnerability and degree of impact of biological soil crusts to mechanical disturbance depends in part on the species composition of the biological crust (largely determined by regional climate), site specific factors such as soil texture, and seasonal moisture. Trampling and other compressional disturbances break the sheathes and filaments that bind the crust organisms to the soil surface, which makes them directly vulnerable to wind- and water-induced soil erosion or indirectly to burial to depths where photosynthesis is not possible through increased sediment movement when crusts nearby are damaged (Belnap and Eldridge 2001). Even light to moderate soil surface disturbances (such as caused by foot traffic) break up biological soil crusts and reduce their cover and functionality (Belnap 1995). Nash and others (1977) speculated that livestock grazing contributed to reductions in biological soil crust cover on bajadas at their Silverbell study site northwest of Tucson, Arizona.

Because the goal of many studies on biological soil crusts is to compare disturbed soils to undisturbed soils, by definition the sites that are selected for study typically include areas with less biological soil crust cover and/or impaired function. This limits our understanding of the resilience of biological soil crusts to disturbance and whether a threshold of soil surface disturbance exists that a crust can withstand before it is damaged beyond recovery or loss of function. Moreover, determining when recovery has taken place may itself be problematic, as restoration of ecosystem function, rather than the more visible measures of cover and biomass return, may be the best way to measure recovery (Evans and Johansen 1999). Although biological soil crusts are considered a natural late-successional feature of most arid ecosystems, in mesic ecosystems their presence may signal a degraded or early-successional status (Warren and Eldridge 2001).[17] Keeping the preceding limitations to the studies in mind, we present below the results of some reviews and empirical studies that evaluate biological soil crust damage and recovery.

Studies by Brotherson and others (1983) and Johansen and St. Clair (1986) compared biological crusts at cool desert sites (central Utah and northeastern Arizona, respectively) that had been protected from grazing for different amounts of time. Neither study described the current or historic grazing systems or intensities at the sites. Both studies found that cyanobacteria, the dominant component of Sonoran Desert biological soil crusts, are more resistant to disturbance from livestock grazing and recover more quickly than other biological crust organisms such as lichens and mosses. As shown by Johansen and St. Clair (1986), however, recovery from disturbance even for these resistant components of soil crusts is measured in years or decades. A site that had been protected from grazing for seven years still had lower levels of cyanobacteria than a site protected for 20 years. Similar studies that took place in the Sonoran Desert were not

---

[17] By reporting a feature of biological soil crusts from the literature in terms of a relationship to successional stages, we are not confirming any particular viewpoint of succession within desert ecosystems. Our use of the terminology here merely reflects our interpretation that, dependent on the ecosystem under consideration and the characteristics of its associated biological soil crusts, once a crust is disturbed it may go through several stages of recovery in which compositional shifts may occur before the pre-disturbance condition is reached.

encountered; however, the preceding papers still support the conclusion that though hot desert biological crusts are more resistant to disturbance and faster to recover than cool desert crusts, they nevertheless require decades to recover from trampling and other surface disturbances.

Kade and Warren (2002) showed that biological soil crust recovery from military activities during World War II was slow at Yuma Proving Ground in western Arizona and depended largely on the degree of soil surface disturbance. After 56 years biological crusts at a site of vehicular traffic had recovered to cover levels close to that of undisturbed sites, whereas the crusts had significantly lower cover (16% lower) at a more heavily disturbed foot traffic site that had been leveled with its topsoil removed (Kade and Warren 2002).

Kade and Warren’s (2002) results are consistent with recovery times for biological crust organisms estimated by Belnap (1995). Based on extrapolation of recovery times of biological crusts from disturbance at sites on the Colorado Plateau, Belnap (1995) estimates that recovery times for various biological soil crust components are 35 to 63 years for cynaobacterial biomass, 45 to 85 years for lichen cover, and 250 years for moss cover (see also Belnap and Eldridge [2001:table 27.2], which indicates a more variable range of recovery times when desert type, disturbance severity, soil texture, and other factors are considered). Moreover, biological soil crust recovery depends upon the presence of a nearby innoculant so larger disturbed areas will take longer to recover (Belnap 1995).

In a study of the effects of experimental ORV disturbances on nitrogenase activity of biological soil crusts at sites in the Great Basin, Sonoran, Mojave, and Chihuahuan Deserts, Belnap (2002) found that sites with gypsum soils and high rock cover were resistant to ORV-induced crust damage. Seasonal soil moisture levels are also an important factor that can influence the degree to which disturbances affect biological soil crust damage. In a study of sheep grazing intensity and season of use in the Great Basin Desert of Utah, Marble and Harper (1989) discovered that sheep grazing significantly reduced biological soil crust cover and species richness when grazing occurred during the late winter (February 16 to May 15) in this study area. It is at this time and during the spring when the biological soil crusts here normally rely on low, but adequate soil moisture levels for growth and recovery, which grazing during the late winter apparently prevented from occurring. Warren and Eldridge (2001) interpreted Marble and Harper’s (1989) results to be congruent with their general conclusion that biological soil crusts are most susceptible to damage from livestock grazing during the driest seasons; however, the applicability of their conclusion to the Sonoran Desert is unclear, as a grazing interaction with the period during which crusts grow also may be important. Soil texture and moisture interactions also seem to play a role in determining the vulnerability of soils to compressional and shearing forces. Biological crusts on coarse-textured soils (with higher sand content) are most vulnerable to damage by livestock grazing activities when they are dry (Belnap 1995, Belnap and others 2001b), whereas fine-textured soils (with higher clay content) are more vulnerable when moist or wet (Belnap and Eldridge 2001:figure 27.2, Belnap and others 2001b).

Warren and Eldridge (2001) drew several conclusions, some of which qualify as hypotheses to be tested, relative to livestock interactions with and resultant impacts to biological soil crusts. Of no surprise is their conclusion that the intensity of livestock impact to biological soil crusts through trampling is determined in large part by stocking rate and distance to water sources.

They also recommended a few grazing management strategies commensurate with their conclusions and a land manager's desire to maintain viable biological soil crusts, though suggestions such as the use of supplemental feeding to even out livestock distribution across the landscape should be viewed with caution (Thurow and Taylor [1999] identify pitfalls associated with feed subsidy programs during drought).

7.3.2 Soil Compaction and Soil Moisture Relations

Livestock grazing, ORV use, and other soil surface disturbances can compact soils, thereby affecting soil physical properties. In this section we focus our discussion on how livestock grazing and other soil surface disturbances alter soil physical properties and how these changes affect water infiltration and runoff and soil erosion (a more complete discussion of the topic of soil erosion is included in section 7.3.5). None of the studies that addressed this topic took place in the Sonoran Desert.

In a recent review of the impacts of managed grazing, Holechek and others (2004a) found that 30 papers that assessed the impacts of grazing on soils and watershed properties had consistent results, with light to moderate grazing causing increased soil bulk density, decreased water infiltration, and increased overland flows and soil erosion. The author, however, questioned whether these impacts are long-term and whether recovery from compaction may occur on soils that are subject to shrinking and swelling cycles (which may not be the case in the Sonoran Desert where soils lack frost heaving).

In a quantitative review of livestock grazing impacts across multiple studies, Jones (2000) analyzed differences in soil bulk density (n = 9), water infiltration rate (n = 15), and soil erosion amount (n = 9) between treatments. Studies were only considered if they simultaneously compared grazed areas with nearby ungrazed controls. When grazed treatments included multiple grazing treatments, Jones (2000) selected the lower intensity treatment, when two intensities were considered, and the intermediate intensity, when three intensities were considered, for comparison purposes. Grazed treatments when compared to ungrazed treatments had significantly reduced water infiltration rates and significantly greater soil loss to erosion, whereas changes in bulk density were non-significant (though bulk density tended to be higher in the grazed treatments). Jones (2000) viewed her results "as a basis for understanding which features of North American arid environments are most likely to suffer general impacts of grazing rather than as evidence relevant to the issue of the sustainability (or lack of it) of livestock grazing on western rangelands."

Empirical studies that we reviewed showed similar results to those described by Holechek and others (2004a). In a comparison of soil properties on trampled and untrampled sites on the Colorado Plateau, Belnap (1995) found that soil bulk density was significantly higher at 0 to 2.4 inches (6 cm) soil depth and soil pore size was significantly lower at 1.2 inches (3 cm) to 2.4 inches (6 cm) soil depth on trampled sites. The author did not discuss the source of the trampling disturbances or its severity. Warren and others (1986) found similar results in an experiment designed to simulate cattle grazing at intensities and durations that are typical of short-duration grazing systems (discussed in Chapter 10). They found that in comparison to ungrazed sites, the soils of grazed sites had significantly greater bulk density on both dry and moist soils (with greater effects observed on dry soils), and a positive relationship existed between bulk density and stocking rates. The long-term effects of grazing on bulk density were unclear, as some degree of recovery occurred prior to subsequent trampling events (within 30 days). Warren and others (1986) also found an interaction between soil moisture and soil aggregate size distributions and soil stability. On wet soils, soil aggregate size significantly increased in response to grazing, forming large, unstable "clods." On dry soils, soil aggregate sizes were significantly reduced with grazing, even under low stocking rates. Higher soil bulk density and decreased soil aggregate size are signs of soil compaction and are associated with decreased infiltration and increased runoff; however, neither Warren and others (1986) nor Belnap (1995) measured these variables.

7.3.3 Nitrogen Fixation and Loss

Because arid and semiarid soils are generally nitrogen limited, biological soil crusts can often be a significant source of nitrogen (Belnap 2001b). Mechanical disturbance of the biological soil crusts, whether from livestock grazing or from other types of disturbance activities, result in large decreases in soil nitrogen through reduced fixation rates and elevated losses and ultimately reductions in plant tissue nitrogen (Belnap and Eldridge 2001). Differences in soil texture, components of the biological soil crust, and time since disturbance affect the degree to which fixation rates are reduced from the undisturbed condition. Because most studies of disturbance effects on nitrogen fixation reviewed by Belnap and Eldridge (2001) occurred in the Great Basin Desert, they may best be used to illustrate general patterns rather than specific quantifiable effects transferable to the Sonoran Desert.

As discussed in section 7.2.2, nitrogen fixation rates can be estimated by measurements of nitrogenase activity (NA). Although this approach may not be accurate for estimating absolute fixation rates, it can be used to advantage if the goal is comparative measurements (Evans and Johansen 1999). Belnap (2002) showed that vulnerability to decreases in NA with disturbance depends on soil texture and biological soil crust type (which could be a basis for quantifiable differences in fixation rate decreases as a result of disturbance between cool and hot deserts). Nitrogenase activity is naturally higher in fine-textured soils compared to coarse-textured soils, and coarse-textured soils are more susceptible to NA declines with disturbance. Disturbances at cool desert sites showed greater declines in NA than those at hot desert sites. In the Sonoran Desert at Organ Pipe Cactus National Monument, experimental soil disturbance by ORV traffic immediately caused significant declines in NA by 27 to 42% (Belnap 2002). Short-term declines in NA are often followed by greater declines in NA over time. For example, Belnap (1995) found that immediately after disturbance, by human foot traffic, mountain bikes, four-wheel drive trucks, tanks, or shallow and deep raking, NA was reduced by 40 to 80%. Six to nine months after treatment, the NA of the same areas had declined further with treatments showing an 80 to 100% reduction compared to the pre-disturbance condition. Nitrogenase activity recovery to pre-disturbance levels may occur slowly, with the amount of time involved dependent on the severity of the disturbance and the composition of the biological soil crust characteristic of the area (Belnap 1995).

Losses in NA due to biological soil crust disturbance are reflected in the nitrogen levels in vascular plant tissue, where significantly greater nitrogen levels were recorded in some species of annual grasses and forbs and perennial shrubs and forbs at untrampled sites on the Colorado Plateau (Belnap 1995). These results suggest that reduced nitrogen inputs from biological soil crusts could have long-term impacts on soil and plant nitrogen. Furthermore, trampled sites are expected to have slower decomposition rates and fewer nutrients available to plants than untrampled sites due to significantly lower abundance and species richness of soil microinvertebrates, nematodes, and active bacteria and fungi (Belnap 1995).

As was described in section 7.1, soil nitrogen tends to be concentrated in the upper layers of the soil. So mechanical disturbances can significantly affect the loss side of the equation, especially if such disturbances also lead to increased runoff and soil loss. Sediment movement may also indirectly affect fixation rates when intact biological soil crusts are buried.

7.3.4 Vascular Plants

Several studies evaluated differences in plant cover and species composition in areas where biological soil crusts or soils had been disturbed by livestock grazing or other soil surface disturbances. Kade and Warren (2002) suggested that soil compaction on sandy soils caused by military activity during WWII on Yuma Proving Ground, Arizona served to increase the density and cover of some shallow-rooted plant species by making water more available at the upper soil surface. Durfee (1988) found that in the Mojave Desert, grazed plots had significantly different soil textures than adjoining ungrazed plots (higher mean percent of silt and sand) associated with increased cover of bare ground and greater soil compaction and soil movement. These changes in the soils caused by grazing (as well as compositional changes in the plant community) may have increased the susceptibility of the grazed site to invasion by non-native annual plants (Durfee 1988).

The interpretations from the above and other studies are limited because they generally look at the correlation between soil and plant attributes. As a result, the cause of changes in vascular plant cover and composition may not be due to impacts on soils or biological soil crusts; rather, changes could be caused directly by the disturbance itself or by other confounding variables. Still, soil disturbances can promote the establishment and spread of invasive non-native plants (Sheley and Petroff 1999). Moreover, Mack (1981) specifically attributed the invasion of cheatgrass (*Bromus tectorum*) to destruction of biological soil crusts coincident with the introduction of widespread livestock grazing within steppe vegetation of the intermountain West. Morrison and others (2003) found that the majority of non-native plant species present on the Sonoran Desert National Monument were concentrated along paved roadsides and at disturbed or developed sites such as those surrounding livestock waters.

Effects on plant germination, survival, and nutrition when biological soil crusts are disturbed in hot deserts has resulted in some mixed results for annual plants and smooth cyanobacterial crusts and received little study for rugose crusts (Belnap and Eldridge 2001). Belnap and Eldridge (2001) interpreted McIlvanie's (1942) Sonoran Desert study involving a rugose crust as demonstrating that disturbance lessens survival and biomass of perennial plants; however, the "overgrazed" treatment represented soil samples from a heavily grazed site presumably without any biological soil crusts (McIlvanie 1942), so a direct comparison with a "disturbed" crust is lacking here. Moreover, both the crusted ("protected") soil and overgrazed soil were disturbed (tilled) as part of the study treatment protocol (McIlvanie 1942).

7.3.5 Accelerated Soil Erosion

Soil loss caused by accelerated erosion can be a potentially serious effect of livestock grazing, especially on erodable soils or when stocking rates are inappropriate to the environmental conditions (for example, during drought), with long-term or perhaps permanent consequences on soils and plant communities. Because of their soil stabilizing function, damage to biological soil crusts can exacerbate soil and soil nutrient loss from wind and water erosion (Belnap and others 2001b).

Accelerated erosion also can be initiated by a loss of vegetation cover typically due to livestock grazing but potentially caused by any factor that results in the removal of significant vegetation cover (for example, drought or recreational activities). Accelerated erosion is more likely to occur on some soils than others. Davenport and others (1998) developed a model to describe the synergistic relationship between site erosion potential (SEP; largely determined by climate, geomorphology, and soil erodability), cover, and erosion rates in New Mexico to better understand the conditions under which Piñon-Juniper woodlands contribute to accelerated erosion. In areas with low SEP, changes in ground cover result in gradual and continuous changes in erosion rates; however, in areas with high SEP, the erosion rate is highly sensitive to ground cover. Removal of plant cover beyond a critical threshold induces a rapid and irreversible increase in erosion rates (a "catastrophe cusp surface" model). A positive feedback loop occurs in which high erosion rates increase SEP through channelization and decreased ground cover/litter and subsequently further increase the rate of erosion.

Numerous additional factors affect erosion rates, SEP, and the positive feedback loop. For example, erosion around individual plants can lead to pedestalling, which leaves plants in a harsher microclimate and less able to capture runoff. Decreases in ground cover lead to increases in evaporation rates, which reduces the amount of water available to plants and the probability of establishment and survival of seedlings. This event then maintains or increases groundcover loss. Davenport and others (1998) also present a "percolation theory" that describes the spatial, temporal, and scale-dependent relationship between hillslope runoff and soil storage capacity (infiltration potential). They show that a small decrease in the connectivity of patches where infiltration occurs can lead to a disproportionately large increase in hillslope runoff (for example, according to an example in their model, a 2% decrease in storage capacity can increase runoff by 21%). Although Davenport and others' study did not take place in the Sonoran Desert, the principles of their model are likely applicable to other ecosystems and may explain patterns of accelerated erosion at some sites in the Sonoran Desert.

Studies by McAuliffe (1998) and Rutman (1998) are key to describing land-cover changes at sites in the Sonoran Desert, based on historic accounts and photographs, compared to current conditions. Both authors describe changes in soils, hydrology, and vegetation that were at least in part induced by historic livestock grazing activities. Historic livestock grazing at these sites reduced perennial grass cover to the degree that it induced accelerated erosion at some sites, with long-term effects on soils, hydrology, and vegetation. (The study by McAuliffe [1998] is also described in Chapter 4 in section *4.2.1 Community Composition*.) Because of a combination of historic overgrazing and drought, perennial grass cover was lost. This led to reductions in the soil's ability to absorb rainfall, which itself led to increased intensities and quantities of runoff, an increase in erosion and gullying, further loss of infiltration and soil moisture, and vegetation changes including a permanent loss of perennial grasses (McAuliffe 1998).

Rutman (1998) chronicles similar soil and vegetation changes to that described by McAuliffe (1998) due to gullying and active sheet erosion at two (of six existing) sites at Organ Pipe Cactus National Monument. These sites all occurred on sandy loam soils in valley bottoms and were found in areas centered around livestock water developments, which were locally devegetated by livestock during a period of historic overgrazing. Long-lasting impacts of these activities include: (1) soil loss, which has been dramatic in some areas, with losses of up to 10 inches (25 cm) of sediment in sheet erosion and formation of gullies that are 3.25 to 6.50 feet (1 to 2 meters) deep; (2) hydrologic changes, including active headcuting and gullying, which changes infiltration and water availability to plants; and (3) vegetation change (both perennial grass and perennial woody species cover were reduced; S. Rutman, personal communication). Few plants are able to establish in the devegetated areas between gullies because of physical and biological conditions that affect plant establishment and survivorship (such as poor moisture infiltration, loss of soil and biological soil crusts, loss of the seed bank, low density or absence of nurse plants, and a lack of protection of seedlings from herbivory).

Impacts depend to some degree on soil type and age. Fine-grained alluvial materials are more prone to accelerated erosion than soils composed of coarse, rocky materials (McAuliffe 1998). Deep, loamy, Holocene-age deposits (less than 11,000 years old) on shallow-gradient slopes and valley bottom floodplains are particularly vulnerable to accelerated erosion (Rutman 1998, S. Rutman, personal communication).

7.3.6 Albedo and Climate

Biological crusts have a dark coloring that decreases surface reflectance (albedo) and increases surface insulation and temperatures, which increases seed germination and rates of nitrogen fixation and photosynthesis. Belnap (1995) found that biological soil crust trampling at sites on the Colorado Plateau caused a change in surface energy flux, where trampled surfaces have 50% higher reflectance than untrampled surfaces. Belnap suggests that recovery of normal surface albedo at these sites could take up to 250 years. These sites have biological crusts that are dominated by dark colored lichens and mosses, whereas Sonoran Desert biological crusts are thinner, lighter colored (dark mostly when moist), and more resilient to trampling. Similar studies to that of Belnap (1995) have not been done in the Sonoran Desert, but we would expect that effects on surface energy would be less severe.

The preceding study describes a localized effect of albedo changes from trampling-induced disturbance of biological soil crusts in which the resultant increase in albedo presumably decreases surface temperatures. In contrast, Balling (1988) and Bryant and others (1990) studied the effects of livestock grazing on climate patterns at a landscape scale in the Arizona-Sonora borderlands in semidesert grassland habitat close to and east of Nogales. Higher intensity livestock grazing has occurred on the Mexico side of the border compared with the U.S. Bare soil cover is greater in Sonora, grasses are shorter, and albedo is higher than on adjoining Arizona lands. Bryant and others (1990) found that after summer rainstorms the Sonoran landscape dries more rapidly than that in Arizona, which depletes soil moisture after about three days and leads to higher surface and air temperatures on the Sonora side. Balling (1988) quantified the differences in summertime maximum temperatures as nearly 4.5 °F (2.5 °C) at Sonora weather stations when compared with Arizona stations when latitude and elevation were held constant and about 7.2 °F (4.0 °C) when only elevation was held constant (apparently increases in surface and near-surface air temperatures with increases in albedo are unexpected; however, this could be due to disruptions in the surface energy balance because of reduced soil moistures on the Sonora side of the border [Balling and others 1998]).

Balling and others (1998) extended the above research to the arid and hyperarid areas of northern Sonora and southwestern Arizona (west of the previous study area). They observed that the vegetation discontinuity was more evident along this portion of the Arizona-Sonora border than in the eastern semiarid areas considered by Balling (1988) and Bryant and others (1990). Albedo was higher and surface and near-surface air temperatures were consistently warmer in Sonora by to 3.6 °F (2.0 °C) based on weather station sampling during winter afternoons. The results are consistent with a positive feedback loop in which land degradation in arid and hyperarid landscapes increases local temperatures and potential evapotranspiration levels, which further exacerbates degradation of the landscape (Balling and others 1998).

Significant reductions in vegetation have been suggested to exert a positive feedback role in prolonging and intensifying drought and, when accompanied by increases in albedo, contributing to the desertification process (Balling 1988). Numerous other studies have shown that grazing causes an increase in the mean percent cover of bare ground (as discussed in Chapter 4); however, the effects of increased ground cover on soil moisture or climate were not evaluated.

7.4 CONCLUSIONS

Based on compelling pieces of information from many different arid and semiarid ecosystems around the world, a general hypothesis of the ecological functions of biological soil crusts is emerging. Although the relative importance of biological soil crusts to ecosystem function, their evolutionary history within an ecosystem, and their relative susceptibility to disturbance differs to a potentially significant degree between ecosystems, the literature to date generally assigns biological soil crusts an important role in several ecological processes for most ecosystems studied: nitrogen and other nutrient cycles; vascular plant germination, survival, and growth; soil stability and erosion; and water infiltration and runoff. Moreover, biological soil crusts in general are viewed as highly susceptible to disturbance, including livestock grazing, and slow to recover from disturbance. If we take nitrogen dynamics as an example, however, relatively few studies have adequately assessed the role of biological soil crusts in nitrogen dynamics—when considering the variation in crust species composition and other factors both within and between ecosystems—to enable making broad generalizations that are transferable to less studied ecosystems (Evans and Lange 2001).

As a hot desert, the Sonoran Desert includes both arid and hyperarid portions. It contains both smooth and rugose crusts in which cyanobacteria are the dominant biotic constituent. Besides the taxonomic work of Cameron (for example, see Cameron 1960) and Nash and others (1977), many of the empirical studies relating to the ecological function of biological soil crusts took place in, or involved samples from, the vicinity of Tucson, Arizona. Many of these studies constituted the early work on biological soil crusts but, with the exception of recent studies on the Yuma Proving Ground in western Arizona (which involve well-developed desert pavement surfaces), focused research on Sonoran Desert biological soil crusts has waned for more than three decades. Obviously, the full diversity of biological soil crusts and their ecological functions across the Sonoran Desert has not been studied, especially in the context of our contemporary understanding of their potentially essential ecological role in arid, semiarid, and hyperarid ecosystems. Moreover, some of the studies we reviewed as reportedly applicable to the Sonoran Desert (for example, see Mayland and others 1966, MacGregor and Johnson 1971), we found applicable to semidesert grassland systems that we considered outside our definition of the Sonoran Desert ecosystem (see Chapter 2).

Information on the effects of disturbance on Sonoran Desert biological soil crusts as well as soils, especially from specifically livestock grazing, also are limited. We often have to rely on information that considered other sources of disturbance (such as military vehicle and OHV use) that may cause similar impacts (though severity of the impacts could be significantly different) or infer impacts from studies conducted elsewhere. Some Sonoran Desert specific studies, such as those by Rutman (1998), Balling and others (1998), and McAuliffe (1998), evaluated impacts on soils, albedo, and climate in the context of the effects of historic overgrazing or the results of contemporary differences between grazing intensities in Sonora and Arizona. Although these studies provide baseline information and potential benchmarks for grazing management practices to avoid in the future, they may not necessarily reflect widespread contemporary livestock grazing impacts in the Arizona portion of the Sonoran Desert (though we do not rule out the possibility that overgrazing may be occurring currently at some locales within the Sonoran Desert or that the lessons learned from these studies may be especially applicable during periods of extended drought).

So what do we know, what do we need to know, and how do we move forward in providing management strategies relative to biological soil crusts and soils and their interactions with livestock grazing (and other surface disturbing activities) within the Sonoran Desert? Again, the general presumptions are that desert ecosystems are: (1) generally low in nitrogen (though nitrogen limitation may occur only during wetter than average periods); (2) often have soils that are susceptible to wind and water erosion; and (3) contain biological soil crusts that can be a significant source of fixed nitrogen; facilitate nutrient uptake, survival, and productivity in vascular plants and in some deserts germination (while inhibiting the establishment of non-native plants); stabilize soil and minimize soil erosion; and beneficially affect water infiltration (dependent on soil texture) and runoff properties. With respect to mechanical disturbances, the general presumption is that biological soil crusts are poorly adapted to disturbances that cause trampling, compression, or burial (except in some ecosystems in which they may be facilitated by disturbances that eliminate competition from vascular plants; Warren and Eldridge 2001) and that damage to crusts can result in impaired ecological functions. Finally, with respect to livestock grazing in particular, the general presumption, though perhaps controversial, is that biological soil crusts of most arid ecosystems evolved in the absence of large herds of grazing/browsing ungulates (Warren and Eldridge 2001).

The available literature indicates that Sonoran Desert biological soil crusts: (1) contain species capable of fixing nitrogen (Cameron 1960, Nash and others 1977); (2) contribute to soil nitrogen, which is available to and taken up by plants (Fletcher and Martin 1948, Cameron and Fuller 1960, Fuller and others 1960, Faust 1970); (3) improve water infiltration rates, at least at low simulated rainfall intensities (Faust 1970), (4) reduce the amount of suspended sediment in runoff (Faust 1970); and (5) reduce runoff on fine-textured soils (Fletcher 1960). Moreover, the available evidence does not support a significant role for other potential sources of fixed nitrogen, including leguminous plants. Although disturbance studies that directly assessed impacts to Sonoran Desert biological soil crusts generally were not related to livestock grazing, they did indicate damage to and a slow recovery from mechanical disturbance (Kade and Warren 2002) that is accompanied by a reduction in ecological function (reduced NA; Belnap 2002). In addition, McIlvanie (1942) found that perennial plant productivity was reduced on “overgrazed” soils compared with productivity on “protected” soils containing biological soil crusts. Landscape-scale impacts to soils and presumably biological soil crusts presumably are related to significant overgrazing episodes (Balling and others 1998, McAuliffe 1998, Rutman 1998).

In combination the above studies admittedly tell an incomplete story; nevertheless, their individual pieces are consistent with the general presumptions related to biological soil crusts in hot deserts discussed above and in the preceding sections. A reasonable hypothesis then, that remains to be fully tested and its environmental variations described, is that intact biological soil crusts, at appropriate cover values, distribution, and degree of development (if recovering from a disturbance), play an important role in Sonoran Desert ecosystem dynamics. Moreover, they are susceptible to damage from various disturbance sources, including livestock grazing, with concomitant loss of ecological function. Until such time that a more complete and contemporary ecological model for Sonoran Desert biological soil crusts is developed, grazing and other land management strategies should be conservative with respect to maintaining the presence and ecological function of biological soil crusts, especially when they are associated with soils susceptible to erosion.

CHAPTER 8 WILDLIFE

This chapter begins by providing an overview the mechanisms by which livestock grazing can impact wildlife. It then provides a review of the relevant literature on livestock grazing impacts for those species that occur in the Sonoran Desert.

8.1 POTENTIAL WAYS IN WHICH LIVESTOCK GRAZING CAN IMPACT WILDLIFE

As a result of low and unpredictable plant productivity, food webs in hot desert communities are characterized by high levels of omnivory and diverse linkages between trophic levels (Noy-Meir 1974). Thus, in contrast to other ecosystems that exhibit “top down trophic cascades” in which predators limit herbivores, which limit plants, desert food web dynamics seem to be controlled by “bottom up” processes, whereby plant production controls the abundance of herbivores and predators (Noy-Meir 1974). For example, desert rodent populations are most limited by food availability and therefore display dramatic increases in recruitment and abundance during wet periods regardless of predator levels (Brown and Harney 1993).

Sonoran Desert wildlife[18] are adapted to the climatic conditions that typify the Sonoran Desert, including high aridity and cycles of drought and wet periods. Wildlife species have a variety of behavioral and physiological adaptations to survive in desert climates (Noy-Meir 1974). Some species are specialized physiologically to tolerate a wide range of body temperatures or desiccation. Other animals avoid drought and heat in time and space: they may only be active at favorable times (daily and/or seasonally) when the temperature and/or humidity are within a certain range, and they avoid exposure to unfavorable conditions by retreating into sheltered microhabitats (such as burrows, rock crevices, or under trees or shrubs). Many desert animals exhibit pulses of activity, growth, and reproduction in response to favorable conditions (such as after rain and when vegetation is green), and they pass unfavorable periods in an inactive state (Noy-Meir 1974).

In summary, numerous Sonoran Desert animals are highly dependent upon wet cycles and pulses of productivity for growth and reproduction, much in the same way that Sonoran Desert plants are attune to the return of rains to respond and recover from drought (Noy-Meir 1974). For example, initiation of reproduction in Merriam’s kangaroo rat (*Dipodomys merriami*) is highly dependent upon production of green vegetation in response to winter rainfall (Van de Graaff and Balda 1973). Likewise, the life cycle of the Sonoran Desert tortoise (*Gopherus agassizii*) is dependent upon rainfall and winter forage availability, such that female tortoises emerge from their hibernacula in the spring to forage on spring ephemerals and build up the energy reserves necessary for egg production (AIDTT 2000, Averill-Murray 2002).

---

[18] Here we use the term “wildlife” to refer to any native animal species, including both game and non-game species and invertebrates as well as vertebrates.

Based on data from mountain ranges in La Paz County, Arizona, the lambing period of desert bighorn sheep (*Ovis canadensis mexicana*), though lambing occurred in all months except October, was highest in January or early February with 75% of births occurring during January to March (Witham 1983). In Witham's study, lamb recruitment was strongly correlated with plant availability. Conversely, the overall length of the lambing period in desert bighorn sheep may reflect selective forces that are responding to the overall unpredictable nature of precipitation and forage production in the Sonoran Desert (reviewed in Krausman and others 1999).

The endangered lesser long-nosed bat (*Leptonycteris curasoae yerbabuenae*) is dependent upon the flowering seasons of many plants as the species follows "nectar corridors" on its migration from southern Mexico to southern Arizona. The arrival of the lesser long-nosed bat in the Sonoran Desert is synchronized with the flowering of night-blooming columnar cacti, including saguaro (*Carnegiea gigantea*) (Tyburec 2000), the timing of which, in turn, depends on local climatic conditions. Countless other examples can be provided that depict how the life cycles of Sonoran Desert wildlife are tied to the seasonal rhythm of rainfall and other climatic events in the Sonoran Desert. How does livestock grazing impact the life cycles of Sonoran Desert wildlife?

Livestock grazing directly and indirectly influences the abundance, species richness, and composition of wildlife populations and communities in many ways. The effect of livestock grazing on wildlife may be beneficial, neutral, or negative, depending on the species under consideration, the grazing system and intensity, and the particular habitat (Holechek and others 2004b). Direct impacts to wildlife occur when livestock trample individuals, their nests, or burrows. The very presence of livestock may directly influence the behavior of some wildlife species, as some animals avoid interaction with or areas used by livestock.

Livestock grazing indirectly affects wildlife in numerous ways. Livestock grazing may alter vegetation composition and structure, which can alter wildlife habitat structure or shift the abundance of preferred forage of native herbivores. As described above, the life cycles of Sonoran Desert wildlife have evolved with seasonal pulses in productivity. Therefore, livestock potentially compete with native wildlife by removing biomass at times when native wildlife are most reliant on it for forage, nesting materials, shade, and so on. Because deserts are characterized by "bottom up" food web dynamics, changes in vegetation composition and structure caused by livestock grazing has effects that are seen at higher trophic levels, with potential impacts on herbivore abundance, species richness, or composition, and resultant changes in predator populations. Livestock grazing also influences wildlife indirectly through the construction of range improvement projects such as water developments and fencing.

8.2 IMPACTS OF LIVESTOCK GRAZING ON WILDLIFE

In this section we present an overview of the main impacts of livestock grazing on wildlife species as described in the scientific literature. We evaluated 41 papers that address the impact of livestock grazing on wildlife species. Eight of the studies were conducted in the Sonoran Desert and an additional 14 addressed multiple ecoregions, including the Sonoran. We also focused our review on some studies undertaken in other regions but that evaluate species occurring in the Sonoran Desert. A list of the species evaluated, the studies that address livestock grazing impacts on a particular species, and the overall trend of how grazing impacts the species based on the literature (positive/negative/neutral) are presented in Table 8.1. We present our findings in taxonomic order in the sections that follow.

8.2.1 Insects

We reviewed six papers that evaluated how livestock grazing affects insect communities, one of which addressed a study that took place in the Sonoran Desert. Hovorka (1996) studied vegetation attributes, insects, and insectivorous bat populations at two paired grazed and ungrazed (but had previously been grazed decades earlier) sites in the Sonoran Desert in the Rincon, Silverbell, and Tucson Mountains. The author hypothesized that grazing-induced changes in vegetation might affect the abundance or composition of insects with possible resultant effects on insectivorous bats. Although plant species richness, abundance, cover, palatable species abundance, and saguaro density were greater at the ungrazed site than the grazed site in the Rincon Mountains, Hovorka (1996) did not find any difference in insect order composition or insect abundance using black light trapping techniques. Instead, insect abundance was largely dependent on local ambient conditions, independent of grazing history. Hovorka (1996) did not identify insects to genera or species level, so the effect of grazing at lower taxonomic levels is unknown. It is also possible that any differences in insect communities between the grazed and ungrazed plots is masked by the black lighting collection technique, which might attract insects from distant plots or adjoining areas.

Ants are a diverse group of insects and have the greatest abundance and biomass of any organism. Livestock may impact ants by trampling, altering soil properties, or altering plant composition and structure. Many species of ants in the Sonoran Desert are seed harvesters and therefore grazing could potentially reduce the abundance of the seeds of ants' preferred forage plants. We reviewed five papers that addressed the impacts of cattle grazing on ants. None of the studies were conducted in the Sonoran Desert.

Nash and others (2000) compared ant abundance and composition on control plots and on plots with experimental mesquite (*Prosopis* sp.) removal and high intensity grazing in the summer or in winter in the Chihuahuan Desert in New Mexico. The authors hypothesized that ant genera that feed on plant liquids would be negatively impacted by shrub removal, whereas seed harvesting ants would be negatively impacted by cattle grazing because of consumption or trampling of grasses and forbs. The authors' hypotheses were supported for the dominant species of ants at the sites (pyramid ants [*Conomyrma insana*] and harvester ants [*Pogonomyrmex desertorum*]) but trends for less common species were mixed. Regardless of experimental treatment, most ant species showed annual changes in relative abundance that were directly related to climatic variation. Drought caused death of some colonies and caused some species to increase foraging intensity and distance (Nash and others 2000).

Bestelmeyer and Wiens (2001) also studied ant biodiversity in relation to grazing in several habitats at three sites: (1) shortgrass steppe in Colorado, (2) semidesert grassland in New Mexico, and (3) a transition zone between the two biomes in New Mexico. These authors used grazing treatments that represented the dominant rangeland management practices in the region,

TABLE 8.1 The Impact of Livestock Grazing on Wildlife, as Described in the Literature[1]

Taxon	**Common Name**	***Scientific Name***	**Citations**	**Effect of Grazing (+/-/0)[2]**
Insects	**Insect communities**	***various***	Hovorka 1996	0
	Ant communities	***various***	Heske and Campbell 1991, Nash and others 2000, Bestelmeyer and Wiens 2001, Nash and others 2001, Nash and others 2004	0
Amphibians	Plains leopard frog	*Rana blairi*	Sredl and Saylor 1998	0
	Bullfrog	*Rana catesbeiana*	Sredl and Saylor 1998	+
	Chiricahua leopard frog	*Rana chiricahuensis*	Sredl and Saylor 1998	+
	Northern leopard frog	*Rana pipiens*	Sredl and Saylor 1998	+
	Lowland leopard frog	*Rana yavapaiensis*	Sredl and Saylor 1998	+
Lizards	Sonora spotted whiptail	*Aspidoscelis sonorae*	Germano and Hungerford 1981, Jones 1981	+/-
	Western whiptail	***Aspidoscelis tigris***	Busack and Bury 1974, Germano and Hungerford 1981, Jones 1981, Brooks 1999	-
	Zebra-tailed lizard	***Callisaurus draconoides***	Busack and Bury 1974, Germano and Hungerford 1981, Jones 1981, Brooks 1999	+/-
	Orangethroat whiptail	*Cnemidophorus hyperythrus*	Jones 1981, Romera-Schmidt and Ortega-Rubio 1999	-
	Leopard lizard	*Crotaphytus wislizenii*	Busack and Bury 1974	-
	Long-nosed leopard lizard	***Gambelia wislizenii***	Brooks 1999	0
	Lesser earless lizard	*Holbrookia maculata*	Germano and Hungerford 1981	0
	Desert horned lizard	***Phrynosoma platyrhinos***	Busack and Bury 1974, Brooks 1999	0/-
	Desert spiny lizard	***Sceloporus magister***	Jones 1981, Brooks 1999, Germano and Hungerford 1981, Romera-Schmidt and Ortega-Rubio 1999	+
	Tree lizard	***Urosaurus inornata***	Germano and Hungerford 1981	+
	Baja California brush lizard	*Urosaurus nigricaudus*	Romera-Schmidt and Ortega-Rubio 1999	+
	Side-blotched lizard	***Uta stansburiana***	Busack and Bury 1974, Jones 1981, Brooks 1999, Romera-Schmidt and Ortega-Rubio 1999	-

TABLE 8.1 The Impact of Livestock Grazing on Wildlife, as Described in the Literature[1]—continued

Taxon	**Common Name**	***Scientific Name***	**Citations**	**Effect of Grazing (+/-/0)[2]**
Tortoise	**Desert tortoise**	***Gopherus agassizii***	Barrett and Johnson 1990, Bostick 1990, Grover and DeFalco 1995, Howland and Rorabaugh 2002, Oftedal 2002	+/-
Birds	**Coopers hawk**	***Accipiter cooperii***	Kochert and others 1988	-
	Cassin's sparrow	*Aimophila cassinii*	Bock and Webb 1975, Bock and others 1984	-
	Grasshopper sparrow	*Ammodramus savannarum*	Bock and Webb 1975, Bock and others 1984	-
	Sage sparrow	*Amphispiza belli*	Brooks 1999	-
	Black-throated sparrow	***Amphispiza bilineata***	Bock and others 1984, Brooks 1999	+/0
	Great blue heron	*Ardea herodias*	Knight and others 1980	-
	Short-eared owl	*Asio flammeus*	Fitzner 1975, Knight and others 1980	-
	Burrowing owl	***Athene cunicularia***	Craig and Powers 1976, Brooks 1999, Kochert and others 1988	+/0
	Verdin	***Auriparus flaviceps***	Brooks 1999	-
	Great horned owl	***Bubo virginianus***	Fitzner 1975, Anderson 1977, Knight and others 1980, Kochert and others 1988	+/-
	Swainson's hawk	*Buteo swainsoni*	Kochert and others 1988	+
	Scaled quail	*Callipepla squamata*	Bock and others 1984	+
	Anna's hummingbird	***Calypte anna***	Brooks 1999	0
	Costa's hummingbird	***Calypte costae***	Brooks 1999	0
	Cactus wren	***Campylorhynchus bunneicapillus***	Brooks 1999	-
	House finch	***Carpodacus mexicanus***	Brooks 1999	+
	Lark sparrow	***Chondestes grammacus***	Bock and Webb 1975, Bock and others 1984	+
	Northern flicker	***Colaptes auratus***	Bock and others 1984	+
	Townsend's warbler	***Dendroica townsendi***	Brooks 1999	-
	Black-shouldered kite	*Elanus caeruleus*	Kochert and others 1988	-
	Horned lark	***Eremophila alpestris***	Bock and Webb 1975, Bock and others 1984, Brooks 1999	+
	Prairie falcon	***Falco mexicanus***	Craig and Powers 1976, Kochert and others 1988	+/-
	American kestrel	***Falco sparverius***	Craig and Powers 1976	-

TABLE 8.1 The Impact of Livestock Grazing on Wildlife, as Described in the Literature[1]—continued

Taxon	**Common Name**	***Scientific Name***	**Citations**	**Effect of Grazing (+/-/0)[2]**
Birds, cont.	**Greater roadrunner**	***Geococcyx californianus***	Brooks 1999	+
	Cactus ferruginous pygmy-owl	*Glaucidium brasilianum cactorum*	USFS 1998, Flesch 2003	+/-
	Blue grosbeak	*Guiraca caerulea*	Bock and others 1984	0
	Bald eagle	*Haliaeetus leucocephalus*	Kochert and others 1988	+
	Hooded oriole	***Icterus cucullatus***	Brooks 1999	0
	Loggerhead shrike	***Lanius ludovicainus***	Bock and others 1894, Brooks 1999	-/0
	Mockingbird	***Mimus spp.***	Bock and others 1984	+
	Ash-throated flycatcher	***Myiarchus cinerascens***	Brooks 1999	-
	Osprey	*Pandion haliaetus*	Kochert and others 1988	+
	Harris' hawk	***Parabuteo unicinctus***	Kochert and others 1988	-
	Sora	*Perzana carolina*	Knight and others 1980	-
	Vesper sparrow	*Pooecetes gramineus*	Bock and others 1984	-
	Blue-gray gnatcatcher	***Polioptila caerulea***	Brooks 1999	0
	Crested caracara	*Polyborus plancus*	Kochert and others 1988	-
	Brewer's sparrow	***Spizella breweri***	Bock and others 1984, Brooks 1999	+
	Chipping sparrow	*Spizella passerina*	Bock and others 1984	-
	Eastern meadowlark	*Sturnella magna*	Bock and others 1984	0
	Western meadowlark	***Sturnella neglecta***	Brooks 1999	0
	LeConte's thrasher	***Toxostoma lecontei***	Brooks 1999	-
	Western kingbird	***Tyrannus verticalis***	Bock and others 1984	0
	Cassin's kingbird	*Tyrannys vociferans*	Bock and others 1984	0
	Barn owl	***Tyto alba***	Knight and others 1980	-
	Orange-crowned warbler	***Vermivora celata***	Brooks 1999	0
	Wilson's warbler	***Wilsonia pusilla***	Brooks 1999	0
	Mourning dove	***Zenaida aurita***	Bock and others 1984, Brooks 1999	+
	White-crowned sparrow	***Zonotrichia leucophrys***	Brooks 1999	0

TABLE 8.1 The Impact of Livestock Grazing on Wildlife, as Described in the Literature[1]—continued

Taxon	**Common Name**	***Scientific Name***	**Citations**	**Effect of Grazing (+/-/0)[2]**
Mammals	**Sonoran Desert insectivorous bat communities**	***various***	Hovorka 1996	0
	Apache Highlands rodents	*various*	Jones and others 2003	-
	Colorado Plateau rodent community	*various*	Rosenstock 1996	-
	Pronghorn	*Antilocapra americana*	Yoakum 1975, Stauber and others 1980, McNay and O'Gara 1982, Yoakum and O'Gara 1990, Yoakum and others 1996	-/0
	Sonoran pronghorn	*Antilocapra americana sonoriensis*	Wright and deVos 1986	-
	Northern pygmy mouse	*Baiomys taylori*	Jones and others 2003	-
	Pocket mouse	***Chaetodipus spp., Perognathus spp.***	Bock and others 1984, Heske and Campbell 1991, Warren and Anderson 1992, Brooks 1995, Fagerstone and Ramey 1996, Jones and others 2003	+/-/0
	Merriam kangaroo rat	***Dipodomys merriami***	Reynolds 1950, Reynolds 1958, Bock and others 1984, Heske and Campbell 1991, USFWS 1981, Warren and Anderson 1992, Brooks 1995, Fagerstone and Ramey 1996, Jones and others 2003	+/-
	Ord's kangaroo rat	*Dipodomys ordii*	Heske and Campbell 1991, Fagerstone and Ramey 1996	0
	Lesser long-nosed bat	***Leptonycteris curasoae yerbabuenae***	USFS 1998	-
	Black-tailed jackrabbit	***Lepus californicus***	Taylor and others 1935, Fagerstone and Ramey 1996, Brooks 1999	+
	Mule deer	***Odocoileus hemionus***	USFWS 1981, Ragotzkie and Bailey 1991, Peak and Krausman 1996	+/-
	Grasshopper mouse	*Onychomys spp.*	Bock and others 1984, Heske and Campbell 1991, Brooks 1995, Jones and others 2003	-

TABLE 8.1 The Impact of Livestock Grazing on Wildlife, as Described in the Literature[1]—continued

Taxon	**Common Name**	***Scientific Name***	**Citations**	**Effect of Grazing (+/-/0)[2]**
Mammals, cont.	**Desert bighorn sheep**	***Ovis canadensis mexicana***	USFWS 1981, Dodd and Brady 1986, Monson and Sumner 1990, Bissonette and Steinkamp 1996, Krausman and others 1996, Krausmann 2000, Krausmassn and others In Press	-
	White-throated wood rat	***Neotoma albigula***	Heske and Campbell 1991	0
	Deer mouse	*Peromyscus maniculatus*	Bock and others 1984, Brooks 1995, Jones and others 2003	-/0
	Harvest mouse	*Reithrodontomys spp.*	Bock and others 1984, Jones and others 2003	0/-
	Cotton rat	*Sigmodon spp.*	Bock and others 1984, Jones and others 2003	-
	Cottontail	***Sylvilagus spp.***	Taylor and others 1935, Fagerstone and Ramey 1996	-
	Botta's pocket gopher	***Thomomys bottae***	Hunter 1991, Fagerstone and Ramey 1996	+/-

[1] Species are organized alphabetically by scientific name within a taxon. Species in bold are documented to occur on the Sonoran Desert National Monument (Turner and others 2000).

[2] Overall effect of livestock grazing or associated management practices on species abundance or fitness as shown in the study or studies was positive (+), negative (-), neutral or unknown (0). Multiple or mixed effects indicate different results from different studies or at different scales of analysis.

in contrast to the high intensity treatments used in Nash and others' (2000) study. Bestelmeyer and Wiens (2001) found that although livestock grazing induced significant changes in vegetation structure and life-form composition, grazing treatments had no effect on transect-scale ant richness or diversity at any of the sites. Some habitats within a biome harbored a distinct ant community composition and higher species richness, such as creosotebush (*Larrea tridentata*)-dominated habitats in the semidesert grassland. Natural environmental features such as soil texture and associated vegetation cover were better correlates with ant richness and composition than were grazing-induced vegetation changes (Bestelmeyer and Wiens 2001).

The third study on the impacts of cattle grazing on ants was conducted by Heske and Campbell (1991) in the San Simon Valley in southeast Arizona (in the semidesert grasslands of the Apache Highlands Ecoregion). The authors compared ant colony abundance and species composition on a grazed area and a 20-hectare exclosure left ungrazed for eleven years. They found no significant differences between the sites. Two other studies, one from the eastern Mojave Desert (Nash and others 2004) and one from Great Basin sites in Idaho and Utah (Nash and others 2001), evaluated the potential for ant community metrics to serve as indicators of rangeland condition. Both studies drew similar conclusions in that ant community metrics had limited utility as rangeland condition indicators, as they responded only to large differences in rangeland condition in which severely degraded or poor condition areas were considered as part of the treatments.

8.2.2 Amphibians

Rangeland water developments, such as stock tanks, are important habitat refugia for native frogs such as the Chiricahua and lowland leopard frogs (*Rana chiricahuensis* and *R. yavapaiensis*) that require permanent or semi-permanent aquatic habitat for reproduction and juvenile development (Sredl and Saylor 1998). Rangeland water developments in the Vekol Valley support a species-rich and abundant assemblage of desert amphibians, including the Great Plains narrowmouth toad (*Gastrophryne olivacea*), lowland burrowing tree frog (*Pternohyla fodiens*), and Sonoran green toad (*Bufo retiformis*) (Turner and others 2000). Developed waters in the desert may also shift the competitive interactions between amphibian species, benefiting some species at the expense of others (Woodward 1983), and they have been implicated in the spread of the invasive non-native bullfrog (*R. catesbeiana*) (Bury and Whelan 1984).

8.2.3 Reptiles

We did not encounter any studies that looked at the effects of livestock grazing on snakes in desert ecosystems. Some studies were encountered that evaluated grazing impacts on snakes in riparian areas, but we excluded them from our review. Our review focuses on the desert tortoise and lizards.

Desert Tortoise

The Mojave Desert population of desert tortoise is found on gently sloping bajadas and valley bottoms, whereas the Sonoran Desert population is primarily limited to the paloverde-mixed cacti community on rocky slopes. These different habitat associations characteristic of the two desert tortoise populations have important implications for assessing the impacts of grazing on desert tortoise. Sonoran Desert tortoises are also known to occupy xeroriparian channels on the lower bajadas, particularly where caliche caves are present. In addition, Averill-Murray and Averill-Murray (2002) documented occurrences of desert tortoise on Ironwood Forest National Monument, though at low density, within the floors of inter-mountain valleys. In general, however, grazing is a greater potential threat to the Mojave Desert population of desert tortoise because livestock and tortoise are more likely to overlap in habitat in which the tortoise could be subject to direct or indirect impacts of livestock grazing activities. Nonetheless, livestock have the potential to negatively impact the Sonoran Desert tortoise in areas where their habitats overlap.

One of the most comprehensive sources of information on the impacts of livestock grazing on the desert tortoise is by Grover and DeFalco (1995). The vast majority of the studies reviewed, however, concern grazing and the Mojave population of the desert tortoise. The findings from studies in the Mojave Desert are most relevant to the Sonoran Desert tortoise in areas where livestock and tortoise habitat overlaps, such as in xeroriparian areas, on lower bajadas, or during periods when tortoise undertake long-distance movements across valleys as has occasionally been observed (Stitt and others 2002). Here we limit our review to information on grazing impacts most likely to be relevant to the Sonoran Desert population of the desert tortoise.

To the extent that livestock grazing has caused significant changes in vegetation composition and structure over the past 100 years, desert tortoise populations are not genetically capable of adapting to such rapid environmental change because of their low reproductive rates (Grover and DeFalco 1995). The life cycle and patterns of activity of the desert tortoise are closely tied to rainfall and forage production. Female Sonoran Desert tortoises emerge earlier than males from their winter hibernacula in the spring, which may offer them early foraging opportunities that are important for building up energy reserves for egg production (AIDTT 2000). Both males and females are most active after the onset of the summer monsoons, and it is during this time that tortoises establish a positive moisture and energy balance by drinking water and feeding on dried and fresh forage and when most mating occurs (AIDTT 2000, Averill-Murray 2002). Hatchling survival and juvenile recruitment rates are presumed to be low for Sonoran Desert tortoises, though available data suggests these rates are greater than occur in Mojave Desert populations (Averill-Murray 2002). Hatchling emergence occurs in the spring or fall, when forage and water are more likely to be available. Because the life cycle and survival of the desert tortoise is so dependent upon the seasonal pulses of productivity characteristic of the Sonoran Desert, livestock grazing has the potential to directly and indirectly impact desert tortoise.

Where livestock and desert tortoise habitat overlap, livestock can cause direct impacts to juvenile and adult tortoises by trampling and crushing individuals (Grover and DeFalco 1995, Howland and Rorabaugh 2002). Indirect impacts of livestock grazing to desert tortoise are primarily due to potential competition for forage. The desert tortoise is a generalist feeder that has been documented to consume 199 species of plants associated with the Arizona Upland Subdivision of the Sonoran Desert (Van Devender and others 2002). The desert tortoise, however, is on the physiological edge of survival in the desert and must maintain optimal levels of blood hydration, salt, and mineral levels through its diet (Oftedal 2002) or run the risk of dehydration, starvation, or liver and kidney disease (Dickinson and others 2002).

To the extent that livestock and tortoise overlap in habitat, competition for nutritionally important forage species can be a threat, particularly in the spring after high winter rainfall years (Oftedal 2002). Major forage species in the Sonoran Desert include native grasses, desert vine (*Janusia gracilis*), and mallows, including desert rose mallow (*Hibiscus coulteri*), globe mallow (*Sphaeralcea ambigua*), and Indian mallow (*Albutilon sp.*). Competition with livestock for forage has the potential to impact desert tortoise nutritional condition and water balance. Spring forage availability is associated with female reproduction and hatchling emergence. As a result, ephemeral grazing systems[19] may be particularly detrimental to desert tortoise because their growth and reproduction depends on years of above average annual forage production (Grover and DeFalco 1995). In the eastern portions of the Sonoran Desert and especially within the Arizona Upland Subdivision, warm season plants, including C_4 grasses, may usurp the dietary importance of winter annuals (Oftedal 2002).

Non-native plants including filaree (*Erodium cicutarium*), Malta starthistle (*Centaruea melitensis*), Mediterranean grass (*Schismus barbatus*), red brome (*Bromus rubens*), Sahara mustard (*Brassica tournefortii*), and Russian thistle (*Salsola tragus*) have been documented as generally a minor part of the diet, with only red brome and filaree at times reported as a major component (Oftedal 2002, Van Devender and others 2002). Although the nutrient value of some non-native plants that are used by desert tortoise are similar to native plants when compared within the same taxonomic groups and life forms, the presence of non-native plants that are invasive—and in particular alter fire regimes—may have an indirect effect on desert tortoise diet by causing a reduction in the abundance and richness of native forage plants (Van Devender and others 2002 and references therein). Therefore, a concern exists that desert tortoise nutrition and long-term condition may be compromised with shifts in plant communities from predominantly native species to increased abundance of invasive non-native species. For example, the replacement of C_4 grasses by annual non-native C_3 grasses may impact the nutritional status of tortoises given the lower protein and potassium excretion potential content of C_3 desert grasses and the associated rapid decline in such content due to rapid phenological maturation (Oftedal 2002). Livestock grazing has been implicated as a cause of the occurrence and spread of many invasive non-native species (see Chapter 4).

One paper that is frequently cited in the scientific literature is Bostick (1990). Bostick (1990) suggests that not only is cattle grazing beneficial to desert tortoise in the Mojave and Sonoran Deserts, but also that as cattle grazing has been reduced or eliminated on some desert ranges desert tortoise are suffering great population declines. The author claims that severe overgrazing in the early part of the 20th century improved desert tortoise habitat and initiated a population explosion, and that cattle dung supplies desert tortoise with an important food supply and water source. The many unsubstantiated claims made by Bostick (1990) are contested by empirical research conducted by numerous tortoise biologists (Grover and DeFalco 1995). If the trends in desert tortoise populations described by Bostick (1990) are valid, then the error of interpretation is in attributing correlational patterns as causality. During the same period that livestock grazing has declined, tortoise populations may have suffered from disease, drought, high predation rates,

---

[19] An ephemeral grazing system refers to an allotment in which grazing is not authorized unless adequate ephemeral forage is present or a high probablility exists (based on rainfall amounts prior to livestock stocking) that adequate ephemeral forage will be produced (Barrett and Johnson 1990).

habitat fragmentation, or many other possible threats rather than a decline in cattle dung supply with unsubstantiated benefits.

In summary, specific studies that attempted to quantify livestock grazing impacts on populations of the Sonoran Desert tortoise are generally lacking. In the absence of specific impact data, Barrett and Johnson (1990) suggested that livestock (cattle) impacts to tortoises and their habitat may be less than to other wildlife in the Sonoran Desert of Arizona based mainly on habitat factors, such as percent slope and distance to waters, that segregate tortoises and cattle in space. The indirect effects on nutrition and habitat condition caused by the interaction of cattle and invasive non-native plants may be cause for concern as these impacts are not necessarily limited to areas of habitat overlap.

Lizards

The impact of grazing-induced vegetation change on lizards depends on the microhabitat preferences and foraging guild of a particular species. Jones (1981) compared lizard abundance on lightly grazed versus heavily grazed sites in western Arizona in chaparral, desert grassland, mixed riparian scrub, cottonwood-willow riparian, and Sonoran desertscrub plant communities. The author found that changes in lizard species abundance and community composition are affected primarily by structural changes in the vegetation caused by grazing, but the effect of grazing intensity on vegetation structure was less pronounced in Sonoran desertscrub than in the other vegetation communities. Sit-and-wait predators that forage in open spaces between bushes, such as the side-blotched lizard (*Uta stansburiana*), are favored in ungrazed or lightly grazed areas in many habitats including chaparral, mixed riparian scrub, and cottonwood willow riparian forests (Jones 1981, Romero-Schmidt and Ortega-Rubio 1999), but no such pattern was observed in Sonoran desertscrub (Jones 1981). Sit-and-wait predators that forage on rocks, trees, and downed limbs such as the desert spiny lizard (*Sceloporus magister*) and tree lizards (*Urosaurus spp.*) were favored in heavily grazed areas where grazing served to increase the abundance of downed limbs (Jones 1981, Romero-Schmidt and Ortega-Rubio 1999). Again, no such pattern was observed in Sonoran desertscrub (Jones 1981). The strongest effect of grazing in all habitats, including Sonoran desertscrub, was observed for widely foraging species, such as whiptails (*Cnemidophorus spp.*). Widely foraging species had significantly greater relative abundance in lightly grazed or ungrazed areas in comparison to heavily grazed areas (Jones 1981, Romero-Schmidt and Ortega-Rubio 1999). The cause of the decrease in this lizard foraging guild in heavily grazed areas is unknown, but may be due to a reduction in their invertebrate prey (Jones 1981).

Brooks (1999) found that total lizard abundance and species richness was greater in a site protected from sheep grazing and recreational activities (primarily ORV use) for 21 to 23 years (“protected”) than in a site where these activities are ongoing (“unprotected”) in the Mojave Desert. Busack and Bury (1974) also found lower lizard abundance, biomass, and species richness at sites disturbed by ORV use and sheep grazing in the Mojave Desert than undisturbed sites. Brooks’ (1999) and Busack and Bury’s (1974) studies stand in contrast to the results of the studies discussed above that showed that some lizards benefit from livestock-induced vegetation changes. This discrepancy may result because even though some lizards may benefit from the opening of vegetation afforded by grazing, any beneficial effect is offset by the detrimental impacts of human activities (for example, trampling or crushing lizards or their burrows, primarily through ORV use) in the unprotected areas (Brooks 1999). In addition, the degree of vegetation change induced by grazing and recreational uses in the unprotected versus protected sites may have been greater than those found by Jones (1981) and Romero-Schmidt and Ortega-Rubio (1999). Brooks (1999) observed that dead creosotebush branches were more abundant in the protected site than the unprotected site, which likely benefited some lizard foraging guilds that preferred the grazed sites in studies by Jones (1981) and Romero-Schmidt and Ortega-Rubio (1999).

Clearing of mesquite is an activity practiced on some shrub-encroached semidesert rangelands in an effort to increase grass production for cattle. On the Santa Rita Experimental Range in the Apache Highlands Ecoregion southeast of Tucson, Arizona, mesquite clearing was found to decrease the diversity and abundance of lizards in comparison to undisturbed sites or sites with irregularly shaped clearings (Germano and Hungerford 1981). The zebra-tailed lizard (*Callisaurus draconoides*), desert spiny lizard and western whiptail (*Aspidoscelis tigris*) were absent or rarely seen in the mesquite-cleared sites, but the Sonora spotted whiptail (*Cnemidophorus sonorae*) was significantly more abundant at these sites. Although this study took place in the Apache Highlands Ecoregion and mesquite removal is not a common practice in the Sonoran Desert, the results have some relevance for desert grassland sites in the Sonoran Desert, such as the tobosa grassland (*Pleuraphis mutica*) in the Vekol Valley, where mesquite may have increased in abundance and density over the past decades (Morrison and others 2003).

8.2.4 Birds

We evaluated ten papers that addressed livestock grazing impacts on birds. Only one of the studies was conducted in the Sonoran Desert. The remainder of the included papers are relevant insofar as they depict general trends and/or impacts of livestock grazing on species that also occur in the Sonoran Desert. We first consider the literature relevant to the federal endangered cactus ferruginous pygmy-owl (*Glaucidium brasilianum cactorum*) and then other birds.

Cactus Ferruginous Pygmy-Owl

We located only one paper that directly studied the effect of livestock grazing on the cactus ferruginous pygmy-owl in the Sonoran Desert. Flesch (2003) recorded mixed results on the impacts of livestock grazing on habitat suitability for pygmy-owls in Sonora, Mexico. When vegetation volume is high and provided suitable nest substrates, such as large cacti, are common, grazing can create openings and reduce ground cover that enhances the suitability of the habitat for pygmy-owls. As a result, along low elevation valley bottoms with suitable numbers of large cacti, pygmy-owl occupancy increased with grazing intensity. Conversely, Flesch (2003) observed that the density of large columnar cacti tended to be lower in areas with higher grazing intensity with a concomitant impact on pygmy-owl occupancy. Flesch (2003) concluded that livestock grazing could increase habitat suitability for pygmy-owls in the short-term in some habitat situations; however, in the long-term it could adversely affect cacti regeneration and habitat-specific prey diversity and abundance, especially if grazing intensity is high.

In addition, some potential impacts of livestock grazing on the cactus ferruginous pygmy-owl can be inferred from review information provided in a U.S. Forest Service Biological Assessment related to grazing on the Coronado National Forest (USFS 1998). This document states that past and present habitat destruction and modification is the primary threat to the pygmy-owl and that improper livestock grazing practices have contributed to habitat degradation in the Sonoran Desert. Heavy grazing may reduce the availability of nest and roost trees used by the pygmy-owl in riparian areas. Heavy livestock grazing also may negatively impact pygmy-owls by reducing the density of vegetation, thereby reducing pygmy-owl prey availability. This latter finding seems to conflict with the findings of Flesch (2003) above, which seems to imply that the impact may differ with plant community type. The guidance criteria set forth in the Biological Assessment state that livestock grazing "may affect, not likely to adversely affect" if all of the following apply:

- livestock grazing occurs in areas occupied by the pygmy-owls or in unsurveyed suitable habitat during the nesting or breeding period

- livestock grazing is limited to utilization levels that avoid degradation of composition and vigor of understory vegetation or that preclude regeneration of any strata of vegetation and is limited to 30% utilization in desert scrub and xeroriparian areas and no more than 30% utilization of the apical stems of seedlings/saplings (0 to 6 feet) of woody riparian species in riparian areas in a given year

- mature desert scrub vegetation (saguaros, mesquite, ironwood, and so on) below 4,000 feet elevation is maintained with good ground cover for the prey base

- livestock gathering activities do not occur within a quarter mile radius of an occupied site or in unsurveyed suitable habitat, between January 1 and June 30 (USFS 1998).

The occurrence of the pygmy-owl has not been confirmed on the Sonoran Desert National Monument (SDNM), but the monument has suitable habitat and few areas have been surveyed for pygmy-owls up to this point in time (BLM unpublished data).

Other Birds

In addition to lizards, Brooks (1999) also compared bird communities in an area protected from sheep grazing and recreational activities (primarily ORV use) for 21 to 23 years ("protected") with a site where these activities are ongoing ("unprotected") in the Mojave Desert. Bird abundance and species richness was significantly higher in the protected area during the breeding season and years of high rainfall. Species composition was different between the protected and unprotected sites, with six species only found in the protected site (Brewer's sparrow [*Spizella breweri*], orange-crowned warbler [*Vermivora celata*], Townsend's warbler [*Dendroica townsendi*], blue-gray gnatcatcher [*Polioptila caerulea*], Anna's hummingbird [*Calypte anna*], and Costa's hummingbird [*Calypte costae*]) and two species only found in the unprotected area (house finch [*Carpodacus mexicanus*] and greater roadrunner [*Geococcyx californianus*]). Five species had significantly greater abundance in the protected area than in the unprotected area. These species were (with the percent difference in abundance at protected versus unprotected plots noted parenthetically): sage sparrow (*Amphispiza belli*) (163 to 222%), loggerhead shrike (*Lanius ludovicainus*) (367%), LeConte's thrasher (*Toxostoma lecontei*) (317%), verdin (*Auriparus flaviceps*) (200%), and ash-throated flycatcher (*Myiarchus cinerascens*) (700%). Clearly, most birds benefited from the significantly higher plant cover in the protected areas. Brooks (1999) suggests that although some bird species typically prefer more open areas for foraging and predator avoidance, this preference may have been offset by a lack of food resources, such as seeds, that may have been more abundant in the protected areas. Although Brooks (1999) does not quantify uses or impacts on the study sites, they are considered typical of general multiple-use management, such as that which occurs on most BLM land.

Bock and others (1984) found a pattern opposite to that described by Brooks (1999) for bird communities in the semidesert grasslands (Apache Highlands Ecoregion) in southeastern Arizona. The authors found significantly higher bird abundance and species diversity during the summer months on a grazed plot than a plot protected from cattle grazing for 13 to 14 years. They observed no significant difference in bird abundance or species diversity during the winter. The difference in patterns of bird diversity and abundance between the two studies could be due to several factors, aside from the obvious differences in habitats and species between study areas. Unlike Brook's (1999) findings, Bock and others (1984) found that several species of open ground foragers, such as mourning doves (*Zenaida aurita*), horned larks (*Eremophila alpestris*), lark sparrows (*Chondestes grammacus*), and mockingbirds (*Mimus spp*.), were significantly more abundant on the grazed site. The grazed site in the semidesert grasslands likely has adequate quantities of seeds and other forage for these species, in contrast to the unprotected site in the Mojave Desert. Another possibility is that the intensity of the disturbances at the two study areas is different, or that ground foraging birds are negatively impacted by ORV use at the Mojave Desert site. In a Chihuahuan Desert study in New Mexico, Smith and others (1996) observed that mourning dove sightings were greater on ranges in good condition than on ranges in excellent condition (condition based on percentage of climax vegetation remaining with excellent condition range scored at a higher percentage). The good condition range had significantly less grass (and overall ground) cover than the excellent condition range.

As was found by Brooks (1999) in the Mojave Desert, grazed and ungrazed sites in the semidesert grasslands of southeastern Arizona showed shifts in bird species composition (Bock and Webb 1975, Bock and others 1984). Cassin's and grasshopper sparrows (*Aimophila cassinii* and *Ammodramus savannarum*) prefer areas with abundant shrubs and grass cover, typical of ungrazed sites, whereas horned larks and lark sparrows are indicators of grazed sites with few shrubs (Bock and Webb 1975, Bock and others 1984). Some of the more abundant birds in the grazed area are typical of lower elevations and xeric habitats (scaled quail [*Callipepla squamata*] and Brewer's and black-throated sparrows (*Amphispiza quinquestriata*); Bock and others 1984).

Kochert and others (1988) conducted a literature review to determine the effects of livestock grazing on raptors in the Southwest. Although the authors do not focus on Sonoran Desert habitats or studies conducted in the Sonoran Desert, many of the raptor species discussed occur in the Sonoran Desert. Vegetation changes induced by livestock grazing can potentially affect raptors by altering nest substrate availability, prey abundance, or prey vulnerability (Kochert and others 1988). Based on the results of their literature review and to the extent that grazing causes vegetation changes at the particular habitat, Kochert and others (1988) found that grazing generally has a negative impact on raptors that nest in riparian areas and on the ground. In contrast, shrub and tree encroachment caused in part by livestock grazing in southwestern grasslands benefits Harris' hawks (*Parabuteo unicinctus*), black-shouldered kites (*Elanus Caeruleus*), Coopers hawks (*Accipiter cooperii*), and crested caracaras (*Polyborus plancus*) (Kochert and others 1988). Raptor prey communities (such as birds and small mammals) show shifts in species composition due to grazing, with some species increasing in abundance and others decreasing, depending on the individual species' foraging and vegetation cover preferences. Livestock grazing activities that reduce vegetation cover may enhance foraging habitat for great horned owls (*Bubo virginianus*), burrowing owls (*Athene cunicularia*), prairie falcons (*Falco mexicanus*), and Swainson's hawks (*Buteo swainsoni*) (Kochert and others 1988).

Fencing associated with grazed rangelands can benefit raptors by affording them with perch sites for foraging (Kochert and others 1988). On the other hand, numerous birds, including barn owls (*Tyto alba*), short-eared owls (*Asio flammeus*), and great horned owls, have died by becoming entangled in barbed wire fences (Fitzner 1975, Anderson 1977, Knight and others 1980). The overall frequency of harmful interactions between birds and fencing is unknown. Transient bald eagles (*Haliaeetus leucocephalus*) and osprey (*Pandion haliaetus*) have been found foraging at rangeland water developments in western Arizona (Kochert and others 1988), but some raptors, including burrowing owls, have been found drowned in livestock watering tanks (Craig and Powers 1976).

8.2.5 Mammals

Mammals are broken down for review purposes into rodents and lagomorphs, bats, Sonoran pronghorn (*Antilocapra americana sonoriensis*), mule deer (*Odocoileus hemionus*), and bighorn sheep (*Ovis canadensis*).

Rodents and Lagomorphs

In this section we use the term "small mammals" to refer collectively to both rodents and lagomorphs (rabbits and hares). The effect of livestock grazing on small mammal populations and communities can be direct, such as by trampling burrows, or indirect, such as by compacting soil used by burrowing mammals, reducing seed set on grasses or other food plants, or changing vegetation structure by reducing plant cover. Bock and others (1984) and Brooks (1995) both found significantly greater total nocturnal rodent abundance and species richness at ungrazed compared with grazed sites in the Apache Highlands Ecoregion and Mojave Desert, respectively. The measurable effect of livestock grazing, however, may depend on the spatial scale under consideration. On the Colorado Plateau, Rosenstock (1996) found that at the macrohabitat scale (greater than 100 hectares [247 acres]) small mammal abundance and species richness was greater on ungrazed sites, but no difference in these attributes was apparent between grazed and ungrazed sites at a microhabitat scale (less than a hectare [2.47 acres]). Furthermore, the effect of livestock grazing on small mammals largely appears to require changes in vegetation structure, with variable effects depending on the species under consideration.

Only one paper reviewing the effect of livestock grazing on small mammals was conducted in the Sonoran Desert. The majority of the studies were conducted in other habitats, in particular, the semidesert grasslands of the Apache Highlands Ecoregion. One particular study conducted a meta-analysis of various data sets from various grazing impact studies across the arid and semi-arid portions of the western U.S. (Jones 2000). This author found that rodent species richness and diversity were significantly lower in grazed sites versus nearby ungrazed controls. Not all individual studies included within the analyses showed the same directional trend and stocking rates, grazing systems, and grazing intensity were not necessarily consistent between studies. As a result, Jones' (2000) findings do not have specific applicability to the Sonoran Desert but instead imply a more general effect of livestock grazing in arid and semi-arid ecosystems. With respect to studies conducted in other ecosystems, we focused on species that are also distributed within the Sonoran Desert.

Warren and Anderson (1992) studied differences in rodent abundance and diversity at Organ Pipe Cactus National Monument, Arizona in two periods of time: before cattle and wild burros were removed from the park and nine years after grazing exclusion. The authors found that independent of patterns of vegetation change, many species experienced marked and unexpected decreases in abundance after livestock exclusion. The natural patterns and cycles of rodent communities (such as in response to climate) are not well understood at the site, so the authors suggested that additional research and sampling effort was required to better comprehend the potential effects of livestock grazing (Warren and Anderson 1992). Although the overall trend of decreased abundance in rodents at Organ Pipe was not as expected, Warren and Anderson (1992) found some interesting patterns at the individual species level. Merriam kangaroo rats decreased in abundance in habitats where they were dominant prior to livestock removal and where vegetation cover increased after the cessation of grazing (creosotebush-bursage and saltbush habitats). At plots within saltbush habitats, Warren and Anderson (1992) observed a shift in abundance and dominance from Merriam kangaroo rats to desert pocket mice (*Perognathus penicillatus*) associated with the increase in vegetation cover after livestock removal. Desert pocket mice populations, however, did not show similar changes in abundance or dominance in other habitats, as evidenced by an unexplained decreased abundance in creosotebush-bursage and limberbush habitats (Warren and Anderson 1992).

Studies conducted in other ecoregions also showed that grazing-induced changes in perennial plant cover may cause shifts in small mammal species composition and abundance. Concordant with Warren and Anderson's (1992) findings, Jones and others (2003) also observed shifts in kangaroo rat and pocket mice dominance in the semidesert grasslands and shrublands of Sonoita Valley, Arizona (Apache Highlands Ecoregion); however, the pattern for this study was further complicated by the presence of murid rodents and, for one of the paired grazed-ungrazed (since 1968) sites for which temporal data 17 years apart was available, increases in vegetative cover between sample times at both the grazed and ungrazed plots. At this latter paired site, Merriam's kangaroo rat, which was present in both plots in 1983 (though less abundant in the ungrazed plot) disappeared from both the grazed and ungrazed plots in 2000. Cover, as well vegetative height, increases on the ungrazed plot were attributed to invasion by the relatively tall non-native Lehmann lovegrass (*Eragrostis lehmanniana*). Pocket mice (*Chaetodipus hispidus and Perognathus flavus*) increased on the grazed plot, but declined on the ungrazed plot. Four species of Muridae in general increased between sample times on both plots and across all eight paired sites were significantly more common on ungrazed versus grazed plots (across all eight sites, mean vegetative height and cover were greater on the ungrazed plots). Based on their findings the authors postulated that in relatively mesic grasslands livestock grazing and fire promote a shift in the rodent community to one dominated by heteromyids instead of murids and that in more arid landscapes, grazing and fire favor kangaroo rats over pocket mice. Their ground cover-based model for depicting how these rodent taxa may segregate in ecological space also suggested that kangaroo rats will decline if ground cover is reduced beyond some minimum level.

Merriam kangaroo rats avoid areas with high density and cover of perennial grasses and associate with open areas with annual grasses and woody plants (Fagerstone and Ramey 1996). In a semidesert grassland site in the Apache Highlands Ecoregion, Merriam kangaroo rats are more abundant in grazed sites and benefit from grazing-induced decreases in grass cover and mesquite invasion (Reynolds 1950, Reynolds 1958, Bock and others 1984, Fagerstone and Ramey 1996). When grazing is moderate and vegetation cover is not reduced, however, populations of Merriam kangaroo rats have been significantly greater in ungrazed areas (Heske and Campbell 1991). Brooks (1995) similarly found that Merriam kangaroo rats were significantly greater inside an area protected from sheep grazing and ORV use in the Mojave Desert, even though annual plant and forb biomass was greater in the protected area. One possible explanation for the different findings among these studies is that cattle grazing may decrease seed abundance (Brooks 1995) or alter plant species composition (Heske and Campbell 1991) resulting in an observed association with ungrazed sites, despite perhaps a suboptimal level of plant cover at these sites.

Pocket mice also are affected by grazing because of changes in plant cover. Most pocket mice prefer heavy protective cover from shrubs and grasses (Fagerstone and Ramey 1996), though the Arizona pocket mouse (*Perognathus amplus*) has been associated with open habitat and increased grazing pressure (Fagerstone and Ramey 1996). The effects of grazing on pocket mice seem to depend to some degree on the species under consideration (Fagerstone and Ramey 1996). In general, however, within the heteromyids kangaroo rats are associated with microhabitats that have sparse perennial vegetation and enable foraging in associated open spaces, whereas pocket mice are associated with more dense perennial vegetation on rocky areas and forage in structurally complex areas under the canopies of shrubs or trees (Price and Brown 1983, Reichman and Price 1993).

Black-tailed jackrabbits (*Lepus californicus*) and desert cottontails (*Sylvilagus audubonii*) also seem to respond differently to grazing-induced changes in vegetation cover. Jackrabbits rely on their acute vision for predator avoidance and vigilance and prefer open areas for rapid escape. In contrast, cottontails prefer areas with greater vegetation cover where they forage and hide. As a result (and to the extent that livestock grazing reduces vegetation cover), cottontails are most abundant at ungrazed sites (Taylor and others 1935). Most studies show a higher abundance of jackrabbits on grazed sites than on ungrazed sites (Taylor and others 1935, Brooks 1999), with a greater increase in abundance observed at sites grazed during the growing season compared to continuously grazed sites (Taylor and others 1935). In addition to benefiting from visibility on grazed sites, jackrabbits also may benefit from grazing-induced changes in forage species composition and/or texture of grazed plants (Taylor and others 1935). In two different studies from the Chihuahuan Desert in New Mexico, black-tailed jackrabbits were sighted significantly more often on ranges that were considered in lower ecological condition (less grass and more shrubs) compared to better condition ranges (Smith and others 1996, Nelson and others 1997). Some authors, however, have found negative effects of livestock grazing on jackrabbits (reviewed by Fagerstone and Ramey 1996), which may be caused by higher grazing intensities to the point that range condition becomes poor and jackrabbits have greater competition from livestock for forage (Taylor and others 1935, Fagerstone and Ramey 1996).

The effect of grazing on the burrowing pocket gopher (*Thomomys bottae*) is mixed, with some studies showing increased abundance on grazed ranges versus ungrazed or lightly grazed ranges (reviewed by Fagerstone and Ramey 1996) and others showing decreases (Hunter 1991, Fagerstone and Ramey 1996) or neutral effects (Fagerstone and Ramey 1996). The differences in results may be due to many possible factors, including differences in study area characteristics (such as climate, vegetation, and soils) and seasonality of grazing with differential effects on preferred pocket gopher forage species (Fagerstone and Ramey 1996).

Bats

As discussed in section 8.2.1, Hovorka (1996) compared vegetation, insects, and insectivorous bats in grazed and ungrazed plots in the Sonoran Desert and did not find any significant difference in insect order composition or abundance at the different sites. Perhaps because no significant difference existed in the availability of their food source, insectivorous bat activity and abundance also was not significantly different between grazed and ungrazed sites. Also, bat abundance is more likely to be dependent upon the availability of roost sites and water than insect composition or abundance.

The U.S. Forest Service reviewed the potential effects of livestock grazing on the federal endangered lesser long-nosed bat on grazing allotments within Coronado National Forest in southern Arizona (USFS 1998). The primary way in which livestock grazing could impact the lesser long-nosed bat in this region is by altering the abundance and flower production of their food sources, namely paniculate agaves and saguaros. In the Sonoran Desert, the lesser long-nosed bat is reliant upon nectar and pollen of columnar cacti flowers as a food source, including saguaros. As described in Chapter 5, heavy livestock grazing has the potential to adversely affect saguaro recruitment. As a result, vegetation changes caused by livestock grazing near lesser long-nosed bat roost sites and within their foraging areas can negatively impact the bats by reducing food availability. Lesser long-nosed bats have been documented to fly up to 31 miles from roosts to feeding areas (USFS 1998), so livestock grazing relatively far from roost sites may still incur negative impacts on the bats.

Sonoran Pronghorn

The literature on Sonoran pronghorn interactions with domestic livestock is scant. The recovery plan for the Sonoran pronghorn (USFWS 1998) speculates that livestock grazing may have competed with or excluded Sonoran pronghorn from portions of their range based mostly on inference from a few studies on grazing impacts not strictly related to the Sonoran pronghorn, Arizona Game and Fish Department reports, and personal observations reported to the recovery team. For example, habitat degradation, attributed in large measure to livestock grazing, was presumed to be the leading cause in the decline of Sonoran pronghorn numbers through the 1980s (Wright and deVos 1986).

Other subspecies of pronghorn have been studied in regard to interactions with livestock. The findings from these studies may provide some insights relative to potential livestock interactions with Sonoran pronghorn. Interactions between livestock (and associated management practices) and pronghorn can include agonistic encounters, competition for forage, impacts on general habitat condition, disease transmission, and impacts associated with range improvements. Aggressive or avoidance behavior between pronghorn and cattle seems limited (see below), but the observations related to domestic sheep are more mixed (Yoakum and O'Gara 1990, Yoakum and others 1996). McNay and O'Gara (1982), however, reported a tendency for pre- and post-parturient does to avoid cattle in northwestern Nevada and, as a result, select less favorable fawn bedsites. They also suggested and reported other citings that cattle can sometimes act aggressively toward and trample fawns, as well as flush them from their bedsites and thus make them more vulnerable to predators.

Diet studies seem to indicate minimal dietary overlap between pronghorn and cattle when grassland and shrub-steppe rangelands are in good condition, whereas the overlap between pronghorn and domestic sheep can be significant as they both readily consume forbs and shrubs (Yoakum and O'Gara 1990, Yoakum and others 1996). Competition for forage in these ecosystems, even between pronghorn and cattle, potentially can occur on a seasonal basis or during drought conditions (Yoakum and others 1996). Because grasses are less prevalent in the Sonoran Desert and cattle tend to browse more compared to their foraging behavior in grasslands, significant dietary overlap between Sonoran pronghorn and cattle is more of a possibility.

Based on a sample of pronghorn from Idaho, Stauber and others (1980) found that pronghorn have antibodies against a variety of livestock pathogens. They cautioned, however, that evidence of exposure does not provide evidence that the microbial agent is pathogenic to the pronghorn or that transmission of the pathogen occurred between pronghorn and livestock. Bluetongue can be a serious disease in pronghorn and cattle are carriers of this disease (Yoakum and others 1996). The actual transfer of disease or parasite from livestock to pronghorn seems limited to occurrences of internal parasite transfer from domestic sheep to pronghorn on ranges in deteriorated condition (Yoakum 1975).

Yoakum and O'Gara (1990) and Yoakum and others (1996) summarized information regarding pronghorn interactions with range improvements such as water developments and fencing. Pronghorn will use water developments associated with livestock; however, appropriate water quality would need to be maintained within appropriate limits. Fences can represent a significant obstacle to pronghorn that restricts their mobility and limits their access to food, water, or escape routes. Fence designs associated with cattle have been developed that pronghorn will crawl under; however, "sheep tight" or woven wire fences pose a barrier to pronghorn movement.

Mule deer

Little information was available on mule deer and livestock interactions in the Sonoran Desert, but a review article by Peek and Krausman (1996) offered numerous insights into how livestock grazing may positively or negatively impact mule deer throughout the species' range. The majority of the studies on mule deer-livestock interactions focus on dietary overlap and forage competition between the species. It is thought that diet selectivity is higher for mule deer than cattle because cattle are capable of digesting lower quality forage. Some studies suggest that grazing and browsing by cattle may stimulate growth of young plant tissue that is favored by and more palatable to mule deer. In contrast, cattle grazing can exert a negative impact on mule deer due to competition for forage, water, or cover, particularly when grazing intensity is high and during drought.

Generally, mule deer are opportunistic foragers, with dietary shifts based on the particular habitat and the composition and abundance of seasonably available forage at a site. For example, in central Arizona 106 species of plants were identified as food sources for the desert mule deer (*O. h. eremicus*). Moreover, the species diet differed significantly from year to year and season to season based on the relative availability of forage (Peek and Krausman 1996). Krausman and others (1997) analyzed 14 different diet studies and found that across the range of desert mule deer, the species diet included 92 browse species (shrubs, vines, and trees), 14 succulents, six grasses, and 69 forbs (to be recorded the species had to constitute ≥ 1% of the diet for ≥ one season). Overlap in species use between studies was generally low. Browse species and secondarily forbs were the most important diet constituents. Krausman and others (1997) also provided separate data on three diet studies within the Sonoran Desert. Species use (≥ 1% of the diet) ranged from 14 to 29 species at the three sites and again differed between seasons. Browse was the dominant forage consumed during all seasons with forbs constituting a significant portion of the diet during the winter and spring.

Peek and Krausman (1996; citing G.F. Cole. 1958. Montana Wildlife. April:24–30) emphasize that four conditions must be met to determine if forage competition occurs between mule deer and livestock: (1) overlap in use of the same area and habitat, (2) overlap in diet, (3) more than one item in the diet has to be important to both species, (4) items of common importance have to be declining in productivity or as part of the plant community due to combined use. These four conditions appear to have been met in the Sonoran Desert on the Kofa National Wildlife Refuge (NWR) prior to removal of cattle and wild burros from the range (USFWS 1981). Fecal analysis revealed that the diet of mule deer and cattle overlapped by 70% in an area used by both species. Jojoba (*Simmondsia chinensis*) was the largest component of both species' diet (comprising 22% of cattle diet and 66% of deer diet), and the condition of jojoba was declining in these areas (USFWS 1981). The USFWS (1981) suggested that mule deer would derive the greatest benefits (reduction of competition for food, water, cover, and space) on the Kofa NWR with elimination of cattle grazing, but could also benefit from seasonal cattle grazing (in the winter-spring season) such that competition would be reduced during the summer when it is typically most intense. Other studies suggest the evidence is inconclusive that forage competition between livestock and mule deer exists, with the exception of areas with high intensity grazing that reduces plant productivity or species richness or during conditions of drought (Kie and others 1991, Loft and others 1991, Peek and Krausman 1996).

The most widely used and preferred habitat by mule deer in the Southwest are xeroriparian areas (Krausman and others 1985, Peek and Krausman 1996). Krausman and others (1985) suggested that desert mule deer in the Sonoran Desert of Arizona may associate with xeroriparian washes because they provide more food, cover, and travel lanes than the surrounding areas. These areas are also highly sought out by cattle because of their shade and productivity. Yet we found no papers that looked at habitat or forage competition in xeroriparian areas in the Sonoran Desert.

In the semidesert grasslands in southeastern Arizona, Ragotzkie and Bailey (1991) found that radio-collared mule deer used ungrazed dry wash (xeroriparian) habitats significantly more than expected based on available habitat, and they used grazed upland (mesquite grass-shrubland) habitat significantly less than expected. These habitat associations were greatest for female mule deer during the pre-monsoon drought. It is unclear if mule deer are actively avoiding areas where cattle are present or if their habitat associations are based on differences in forage or other habitat features at the grazed site (Ragotzkie and Bailey 1991).

Range developments such as livestock waters and fencing can have mixed effects on mule deer, depending on livestock concentration and dispersion (Peek and Krausman 1996). Mule deer will drink from livestock waters, particularly during seasonal or extended periods of drought, but they may avoid foraging in areas surrounding waters due to compromised range at those sites (USFWS 1981, Peek and Krausman 1996). The timing of livestock grazing should be such that it offsets the timing of production of plants important for deer seasonal forage and dietary needs (Peek and Krausman 1996).

Bighorn Sheep

Bighorn sheep populations have declined throughout the southwestern United States, including Arizona, since the latter half of the 19th century in correspondence to the period of time when livestock numbers were at their peak (Monson and Sumner 1980, Krausman and others 1996). It is not known, however, if livestock are the primary cause of regional declines in bighorn sheep populations because other negative impacts were likely inflicted upon bighorn sheep during this period of time, including urban expansion; construction of dams, canals, and highways; and unregulated hunting (Monson and Sumner 1980, Krausman and others 1996). Some ways in which bighorn sheep may be impacted by livestock is by forage competition, habitat fragmentation, and disease. Numerous subspecies of bighorn sheep are recognized throughout its range in western North America (Monson and Sumner 1980). We focus our review on the impact of cattle grazing and its effects on the subspecies of bighorn found in the desert Southwest, *Ovis canadensis mexicana*.

In Arizona, bighorn sheep feed almost equally on grass, forbs, and browse (including cacti) (Monson and Sumner 1980). Grasses, including big galleta (*Pleuraphis rigida*), are important in the northern and eastern part of the range of the desert bighorn sheep and are favored when available. Browse becomes more important in the fall and winter (between growing seasons) and in the southern and western portions of the desert bighorn sheep’s range. Jojoba (*Simmondsia chinensis*), where it occurs, is one of the most important year-round forage plants for desert bighorn sheep (Monson and Sumner 1980). Because successful reproduction of bighorn sheep is dependent upon the quality of food and the resultant condition of ewes during and after pregnancy (Monson and Sumner 1980), competition with livestock for forage could negatively impact bighorn populations.

Competition between bighorn sheep and livestock for forage depends on the species of domestic livestock and may depend on many characteristics of the grazing system, including the stocking rate and seasonality of grazing. Monson and Sumner (1980) state that competition for forage with domestic sheep has been implicated in reducing bighorn numbers in some areas throughout the Southwest (including the Harcuvar Mountains in the Sonoran Desert of Arizona). Domestic goats also can compete directly with desert bighorn sheep for forage because they graze in rugged habitat preferred by sheep and have a propensity for overgrazing the range (Monson and Sumner 1980).

In contrast to what is concluded for domestic sheep and goats, evidence that cattle and bighorn sheep directly compete for forage is mixed (Monson and Sumner 1980, USFWS 1981, Krausman and others 1996). If one were to look only at the diet of bighorn sheep and cattle, it might seem that a potential exists for forage competition. For example, in Aravaipa Canyon, Arizona (a transition area between the Sonoran Desert and Apache Highlands Ecoregions), the average percentage yearly dietary overlap between cattle and bighorn sheep was 35% (Dodd and Brady 1986). Cattle, however, are generally unable to negotiate the steep rocky habitat where bighorn spend the majority of their time, implying some degree of habitat partitioning and minimizing the potential for forage competition (Monson and Sumner 1980, Dodd and Brady 1986). Conversely, some overlap in habitat use is possible. On the Kofa NWR before cattle were removed in 1980, USFWS (1981) concluded competition between bighorn sheep and cattle was potentially greatest in the narrow mountain canyons during summer. To the degree that habitat partitioning occurs, how much may be attributed to the unique habitat associations of the species involved and how much to avoidance of cattle by bighorn sheep?

In Idaho, Bissonette and Steinkamp (1996) showed that California bighorn sheep reduced their home range size and decreased their distance to escape terrain as cattle were moved to pastures that were closer and more visible to the bighorn. The bighorn sheep fled the area when cattle approached to within about 2,600 feet (800 meters) (Bissonette and Steinkamp 1996). Bissonette and Steinkamp's (1996) results suggest that the "social intolerance" exhibited by bighorn sheep toward cattle may impose greater limitations on their distribution and habitat use than competition for forage. On the Kofa NWR, year-round presence of cattle and burros for the 30 to 40 years prior to 1980 prevented desert bighorn sheep from using all available habitat (USFWS 1981). In 1980, 77% of all bighorn sightings occurred in the ungrazed areas of the Kofa Mountains, where population increases also were observed (USFWS 1981). As a result, bighorn sheep were crowded into ungrazed portions of their habitat where they are more vulnerable to disease and competition for food, water, cover, and space in lambing or bedding areas (USFWS 1981). Crowding can compromise bighorn sheep health, possibly because of a resultant deficient diet or stress (Monson and Sumner 1980). In contrast to the preceding findings, the Arizona Game and Fish Department "has evidence of bighorn sheep mingling with cattle and crossing valleys where cattle are grazing" (R. Engel, personal communication).

Rangeland developments (artificial waters and fencing) seem to have an overall negative effect on desert bighorn sheep. Bighorn sheep prefer open areas with high visibility. These conditions enable them to be vigilant for predators or other threats. Although livestock grazing around water sources may be beneficial to bighorn sheep because it clears away dense vegetation (Monson and Sumner 1980), the benefits of livestock watering points to bighorn sheep is minimized because cattle tend to congregate around water sources and sheep may avoid areas where livestock are present (Monson and Sumner 1980, USFWS 1981).[20] As previously mentioned, fences associated with grazing management can limit bighorn sheep movement and contribute to habitat fragmentation. Furthermore, bighorn sheep can become injured or die by becoming entangled in barbed wire fencing or could become trapped in areas with inadequate forage or water (USFWS 1981).

In summary, the presence of livestock and livestock-associated rangeland developments may fragment bighorn sheep habitat and crowd a population into only a portion of its available or suitable habitat; however, fragmentation through avoidance behavior may not always occur. Bighorn sheep are an area-dependent species that require unimpeded intermountain corridors for gene flow and to maintain genetic variability (Bleich and others 1990). Much of the desert bighorn sheep's habitat is already fragmented by urban and agricultural development, canals, and roads. The presence of livestock and associated rangeland developments within bighorn sheep habitat or movement corridors are additional factors that may serve to isolate bighorn populations. Such isolation potentially can lead to a loss of genetic diversity within bighorn sheep populations.

Disease transmission to bighorn sheep is a serious negative impact of livestock grazing. In terms of disease transmission, domestic sheep pose the greatest threat to bighorn sheep as they can transmit diseases such as acute bronchopneumonia and scabies that result in high death rates (Krausman and others 1996). The potential for disease transmission, especially from domestic sheep, also seems to represent the limiting factor that determines whether bighorn sheep translocations will be successful (see Krausman 2000 for an overview). As witnessed recently in the Silver Bell Mountains near Tucson, Arizona, domestic goats also can be effective at rapidly spreading disease to bighorn sheep. Domestic goats likely transmitted bacterial-caused keratoconjunctivitis to the desert bighorn sheep population in this area, which resulted in a significant impact to the population including mortalities (Krausman and others 2004). If domestic livestock graze intermountain corridors, they may pass diseases to bighorn during their movements between mountain ranges (Bleich and others 1990). The role of cattle in the spread of disease to bighorn sheep is poorly documented and not well understood (Krausman and others 1996).

8.3 CONCLUSIONS

Whether livestock grazing has a positive or negative effect on wildlife depends on the species under consideration—including their preferred forage and foraging habitat, the season of grazing and its intensity, and other site-specific factors. In general, most of the studies showed that

---

[20] It is beyond the scope of this project to review the controversial topic of bighorn sheep's water needs or their reliance (or lack thereof) on water sources developed for wildlife usage. Here we only mention bighorn sheep's use of water sources that are developed specifically for livestock.

livestock grazing impacts wildlife to the extent that vegetation structure and/or composition is altered by grazing activities. The degree to which vegetation is changed by livestock and the resultant effects on wildlife depends on grazing intensity, season of use, and the habitat under consideration. Although some level of grazing may "improve" habitat structurally for certain species that are associated more with open habitats (such as kangaroo rats and jackrabbits), excessive grazing may eventually negatively impact these species when forage becomes limiting. Because many wildlife species are highly responsive to and dependent upon the seasonal pulses of productivity characteristic of the Sonoran Desert, heavy livestock grazing during these times reduces the total available forage or cover that native wildlife rely on, with potential detrimental effects on survival and/or reproduction.

Artificial water developments, in regard to whether they are beneficial or harmful to wildlife populations in the Southwest, are controversial. Livestock water developments also may be used by wildlife species, but as they were installed with other purposes in mind their impacts should be assessed separately from those water developments specifically designed to meet the needs of a particular target wildlife species or species. Some species clearly may benefit from livestock water developments. In certain situations, such as in the Upper Vekol Valley of the SDNM, artificial waters (some of which result from erosion control projects) provide breeding and larval habitat for several species of relatively uncommon amphibians that otherwise may not be present. In general, however, livestock water developments can negatively impact wildlife, at least on a local scale, if one takes into consideration the impacts on vegetation and soils and increases in invasive non-native plants around such waters. Moreover, water developments that interrupt flows along dry desert washes also can adversely impact downgradient xeroriparian vegetation, which is a habitat disproportionately important for wildlife in the Sonoran Desert (for example, see Johnson and Haight 1985, Morrison and others 1997). Fences installed to support grazing operations can fragment the habitat and limit the movements of large mammalian species.

Information on the impacts of livestock grazing to particular high profile species of concern is limited. No Sonoran Desert-specific empirical studies exist relative to the lesser long-nosed bat and Sonoran pronghorn and only one study addressed the cactus ferruginous pygmy-owl. Habitat degradation, attributed in large measure to livestock grazing, was presumed to be the leading cause in the decline of Sonoran pronghorn numbers through the 1980s. The recent drought has exacerbated the population decline. Habitat alterations induced by livestock grazing could potentially adversely impact the lesser long-nosed bat and pygmy-owl as well; however, under certain circumstances of high vegetation density, moderate or less intensive grazing may enhance pygmy-owl habitat at least in the short-term. Impacts to desert tortoise by cattle may be mostly limited in the Sonoran Desert because of habitat segregation between cattle and the tortoise.

In addition to the few studies we reviewed that took place within the Sonoran Desert, studies conducted in the Mojave Desert may be the most applicable to the Sonoran Desert (particularly the Lower Colorado River Valley subdivision) due to similarity in habitats and wildlife species composition. Brooks' (1995, 1999) and Busack and Bury's (1974) studies are of interest because their "unprotected" sites included not only livestock grazing, but also recreational activities that included vehicular use. Although we were unable to disentangle the impacts of recreational uses and grazing in these studies, these two activities potentially have cumulative impacts on wildlife. Management decisions should take into account this potential.

The one species that stands out from the others in that livestock grazing clearly causes negative impacts is the bighorn sheep. Although there are mixed findings on whether livestock and bighorn compete for forage, there is no question that livestock and livestock management activities can have serious negative impacts on bighorn sheep populations by spreading disease and causing habitat fragmentation. Domestic sheep and goats harbor the major diseases that can spread to bighorn. Habitat fragmentation can be caused by other factors besides the fencing associated with grazing. In some, but not all, cases the behavioral avoidance that bighorn sheep show toward the presence of livestock also has been implicated. Bighorn sheep is an area-dependent species that requires periodic movement between mountain ranges and across valleys to access areas for foraging and reproduction and to maintain gene flow between populations. Already bighorn sheep habitat has been fragmented by freeways, railroads, canals, urban and exurban development, and agriculture. Livestock grazing on remaining “open space” rangelands may serve to isolate bighorn populations even more if fencing does not enable bighorn sheep movement, possible disease transmission necessitates separation, or behavioral avoidance actually occurs.

Because each wildlife species has to some degree its own unique habitat needs, differential responses to livestock grazing would be expected at a local scale. At this scale, some species may do poorly and others may increase their numbers provided in part that grazing leaves sufficient residual forage or other habitat requirements. But land managers would be wise to evaluate multiple scales when assessing the negative or positive effects of grazing on wildlife habitat. Under pre-livestock conditions, natural disturbance regimes likely resulted in a patch mosaic of different habitats that fluctuated over time and space (though the timeline for these ecological processes likely was relatively long in the Sonoran Desert compared to semiarid or mesic ecosystems). Wildlife populations likely similarly fluctuated over time and space in response depending on whether the species was a generalist or habitat specialist. In the absence of excessive grazing that would be detrimental to all wildlife species, the issue for livestock management at broader spatial scales is to avoid overly homogenizing the landscape so that the appropriate degree of habitat and wildlife diversity is maintained and ecological processes are allowed to occur.

CHAPTER 9 CULTURAL SITES

Literature on the impacts of livestock grazing on cultural sites is limited. As a result, in this chapter we provide only a limited discussion of the topic.

9.1 IMPACTS OF LIVESTOCK GRAZING ON CULTURAL SITES

Livestock grazing could potentially impact cultural sites by directly trampling artifacts or other features that are located on the soil surface. Livestock grazing has the potential to indirectly impact cultural sites by inducing changes in vegetation structure or soil characteristics that lead to accelerated erosion, gullying, or increased runoff and flooding.

We found one source that discussed the impact of cattle and wild burro grazing on archeological sites in the Sonoran Desert: the Final Environmental Impact Statement (EIS) and Proposal to Eliminate Cattle Grazing and Wild Burro Populations on Kofa National Wildlife Refuge (NWR; USFWS 1981). The main archeological resources on the Kofa NWR are surface sites that are located in the mountainous areas near water sources. At the time when the EIS was prepared, 55 archeological sites had been recorded and mapped, including pot sherds, petroglyphs, sleeping circles, metates, mescal pits, and grinding stones (USFWS 1981).

The EIS suggested that cattle and burros cause trampling and trailing, which destroys and disturbs surface archeological sites. It evaluated six alternative actions for their potential impacts to archeological sites on the Kofa NWR. The USFWS (1981) determined that the two alternatives that proposed to remove cattle and burros from the refuge would eliminate damage to archeological sites (the two alternatives differed from each other only in the date by which grazing would be terminated). Two other alternatives, one of which reduced the stocking level of cattle and burros and the other of which proposed seasonal cattle grazing and elimination of burros, were determined to reduce, but not eliminate damage to surface sites. In contrast, the implementation of a deferred-rotation grazing system (and elimination of wild burros) was determined to increase the damage to surface sites from trampling, because cattle would be concentrated in the grazed pasture. As new waters were developed and new areas opened to grazing, surface sites in those areas would become vulnerable to disturbance. Under the “no action” alternative (year-round grazing by 350 cattle in a portion of the refuge), it was determined that disturbances to archeological sites would continue (USFWS 1981).

Although the EIS was useful in that it evaluated the impacts under numerous management scenarios, the information presented on the archeological resources and impacts from grazing was superficial and a lack of evidence was presented that cattle and burro grazing were damaging the sites. For example, the report lacked information on if or how cattle and/or burro grazing had already impacted any of the sites and lacked comparisons between archeological sites in grazed and ungrazed areas. Furthermore, the current condition of the archeological sites was not known. Finally, the purported impacts of grazing management alternatives were not considered in terms of the spatial distribution of the archeological sites. Although cattle and burro grazing may indeed have negative impacts on surface archeological sites, the USFWS EIS (1981) does not offer enough information to support that impacts to such sites have occurred or could occur on the Kofa NWR under each alternative.

Despite our thorough literature search methods described in Chapter 2, the EIS (USFWS 1981) was the only source that we found that discussed grazing impacts on archeological sites. This report turned up in the searches because of a variety of other topics it addressed, not because it reported impacts to cultural or archeological sites. We may not have used the appropriate indices or key words to access the appropriate literature. We also tried searching the internet (using Google) and found information on the National Resources Defense Council (NRDC) website (http://www.nrdc.org/land/parks/roh/chaco.asp) that suggests that grazing-induced erosion and flooding threatens the long-term integrity of several archeological sites at the Chaco Culture National Historical Park on the Colorado Plateau in northwestern New Mexico. The NRDC website states that “the loss of vegetation and erosion of land caused by grazing outside the park have contributed to numerous destructive flash floods through the park’s Chaco Wash. Erosion triggered by such flooding threatens several archeological sites, including the popular Pueblo del Arroyo.”

9.2 CONCLUSIONS

Limited information is available on the impact of livestock grazing on cultural sites and evidence of impacts is mostly anecdotal. Additional research on this subject is needed. Literature searches in additional databases and the use of other key words might turn up other relevant research on direct or indirect impacts of livestock grazing on cultural sites.

Despite the lack of information on this topic, some general conclusions can be inferred from the literature. The first step in protecting cultural sites from any disturbance, including livestock grazing, is to conduct a thorough inventory of the distribution and condition of cultural sites in the area of interest. Additional information on the distribution and condition of cultural sites on the Kofa NWR would have enhanced our ability to determine if grazing was responsible for damage to the sites, as implied in the EIS (USFWS 1981). Once the locations of cultural sites are mapped and their condition assessed, one can predict where or under what circumstances livestock grazing may have direct or indirect impacts on cultural sites. As noted on the Kofa NWR (USFWS 1981), some changes in livestock management that might benefit the plant communities (such as a deferred rotation grazing system) could increase concentration of livestock in sensitive areas with increased probability of trampling and damage to surface cultural sites. Cultural sites located within several miles of livestock watering areas are more likely to be trampled or subject to indirect impacts from livestock because of more intense use at these areas.

CHAPTER 10 LIVESTOCK GRAZING MANAGEMENT STRATEGIES

Chapters 4 through 9 assessed both the literature on livestock impacts to various categories of abiotic and biotic resources and, where appropriate, the ecological context for assessing those impacts appropriate to the Sonoran Desert. In this chapter we focus on an evaluation of livestock grazing strategies in the broad sense and their applicability to livestock grazing in the Sonoran Desert. As part of our literature review relating to grazing strategy development and implementation, we briefly assess the current state of range ecology theory with respect to equilibrium and non-equilibrium paradigms of vegetation dynamics and their management model associates, range and state-and-transition models, respectively. Theory often leads to practice. As a result, we conclude it is important to understand how ecological theory may affect the development and implementation of appropriate grazing strategies.

10.1 GRAZING MANAGEMENT STRATEGIES: AN OVERVIEW

In the latest edition of *Range Management: Principles and Practices*, Holechek and others (2004b) summarize the four basic components of grazing management as: proper stocking rate, proper timing of use, proper distribution, and proper grazing system. One can argue that these four components are not mutually exclusive and overlap in numerous ways. For example, imposition of a particular grazing system will of necessity affect timing of use. As a result, we have organized this section using in part grazing systems as an organizing principle, but we also comment when appropriate on the other aspects of grazing management. No matter what the grazing system used, any advantage gained by use of a particular system can be undermined by improper stocking (Holechek and others 2004b).

Below we briefly describe some of the most common grazing systems in use in the western United States. The primary sources of information for this section are Holechek (1983), SRM (1989), Howery and others (2000), and Holechek and others (2004b), the latter of which provides the references for the underlying studies that compare the performances of the different grazing management strategies under different ecosystem conditions. Reference often is made to growing and dormant seasons. In much of the western U.S., summer is the growing season and winter is the dormant season. This is not necessarily the case, however, in the Sonoran Desert where there can be multiple dormant and growing seasons or, more generally across large expanses of the region, a significant reliance on winter rain for forage production. We try to cover the most salient points of each grazing system that can provide some insight in terms of its applicability to grazing in the Sonoran Desert. We focus our discussion on the ecological aspects of these grazing systems and not on their relative economic considerations or ease of implementation. Because in this report we do not evaluate livestock grazing associated with perennial or intermittent stream-associated riparian habitats occurring within the Sonoran Desert, we do not include their presence in considering the applicability of the various grazing systems to the Sonoran Desert. Their presence within a grazing allotment potentially could alter some of our assessment and conclusions regarding the applicability of a particular grazing system.

We note right at the beginning that the use of ephemeral, perennial, and perennial-ephemeral allotment strategies, as currently practiced on public lands in the Sonoran Desert, have not been explicitly evaluated in the literature. We also note that an underlying, but generally unstated, assumption of the various grazing systems in terms of how they have been studied and are implemented seems to be almost exclusively situations in which herbaceous species, usually grasses, are the primary forage base. Riparian ecosystems also seem to have received considerable attention. Although some studies exist relative to evaluating use of shrub species (see Holechek and others [2004b] for a review), what is disappointingly missing are studies that evaluate the ecological consequences of shifting from a herbaceous-based grazing system to one in which shrub (and even tree) species are a significant portion of livestock diet. Across most of the Sonoran Desert, shrub and tree species may be at least a seasonally significant portion of the diet (see section 4.1.5) on at least perennial allotments; however, on these same allotments some components of the herbaceous vegetation may be exposed to the direct and indirect effects of livestock grazing yearlong.

10.1.1 Continuous Grazing

A grazing system is defined as “a specialization of grazing management which defines the periods of grazing and non-grazing” (SRM 1989). In continuous grazing a specific range unit is grazed throughout the year or for that portion of the year during which grazing is feasible. As a result, under the preceding definition continuous grazing, as well as season-long grazing (section 10.1.2), are technically not grazing systems because they presumably do not build in a non-grazing component (Howery and others 2000). Under continuous grazing, a pasture is grazed during both the dormant and growing seasons year after year. Because of the need to leave adequate forage to carry livestock during the dormant season, continuous grazing must be accompanied by appropriate stocking densities that are lower than what may be used under a grazing system. In practice, livestock may not use a range unit uniformly and may show preferences for particular plants and areas. These areas generally occur where water, forage, and cover are in close proximity and which may receive excessive use even under light stocking densities.

The above problems with continuous grazing can be mitigated to some extent, at least in relatively flat terrain situations, by controlling livestock access to watering points. Appropriately distributed waters also may reduce the tendency for livestock to linger in the same places. In addition to flat terrain and close proximity of waters, continuous grazing also seems to work best (compared to specialized grazing systems) within ecosystems in which most plants have similar grazing values, or a high resistance to grazing, and relatively uniform precipitation patterns enable opportunities for plant regrowth after defoliation. Ecosystems such as the shortgrass prairie (or shortgrass steppe) in the Great Plains, in which the grasses evolved under heavy grazing by bison, and California annual grasslands, in which annual grasses of similar palatability predominate, have been cited as tolerant of continuous grazing. In the case of annual grasses, they only need to set sufficient seed year after year to maintain themselves. As stated above, whether an ecosystem possesses those attributes that enable it to tolerate continuous grazing is moot if appropriate stocking densities are not established.

None of the studies reviewed by Holechek and others (2004b) that show the relative advantage of continuous grazing over a grazing system took place in the Sonoran Desert. In addition, studies that supposedly demonstrate that particular plant groups, such as grasses, will not be overgrazed under continuous grazing were not conducted in the Sonoran Desert. The general abiotic and biotic attributes, described above, that indicate the kinds of ecosystems that would best tolerate continuous grazing do not indicate a close congruence with the Sonoran Desert ecosystem. The temporally and spatially variable and unpredictable precipitation pattern characteristic of the Sonoran Desert makes it a poor candidate for a continuous grazing management approach. In addition, although individual plant species may show some degree of tolerance to grazing, Sonoran Desert plant and animal communities as a whole do not have a long evolutionary relationship with grazing by large, hooved mammalian herbivores. Livestock usage patterns also are potentially even more uneven in the Sonoran Desert given the patchy nature of forage distribution in most areas. Finally, frequent drought can more easily lead to conditions in which a stocking density appropriate to average precipitation and productivity results in frequent situations of overstocking and a hindered capacity to recover from drought. Rapid destocking in response to drought would be expected to be difficult under a continuous grazing management approach.

10.1.2 Season-Long Grazing

Season-long grazing is similar to continuous grazing in that both lack a rotation component. Season-long grazing can be distinguished from continuous grazing in that livestock are grazed on a particular range unit for only part of the year. Some authors limit the definition of season-long grazing to grazing that occurs throughout the entire growing season (Howery and others 2000), whereas other authors define it simply as grazing restricted to a particular season (SRM 1989, Holechek and others 2004b).

Within the Sonoran Desert, season-long grazing may be analogous to the use of ephemeral allotments in the absence of an underlying perennial component to the allotment permit. The complete analogy also depends on whether livestock are kept on the allotment the entire growing season or are delayed from grazing on the allotment a period of time at the beginning of the growing season (deferment; see below) to enable seed set, recruitment, and restoration of plant vigor.

10.1.3 Grazing Systems

The remaining sections below will briefly describe various grazing systems. Holechek and others (2004b) list six factors that characterize when specialized approaches to grazing management have been the most useful. These factors include rugged terrain, temporally and spatially variable precipitation, and vegetation with a low resistance to grazing. In addition, specialized systems may be appropriate when other resource values are of concern. We begin our descriptions with deferred-rotation grazing.

Deferred-Rotation Grazing

Deferred-rotation was the first specialized grazing system developed in the U.S. Initial research occurred in the Blue Mountains of northeastern Oregon in the early 20th century. In a deferred-rotation grazing system, the range is divided into two or more pastures and livestock are rotated through on a schedule so that a delay of grazing occurs on particular pastures in some years (usually every two to four years depending on the number of pastures). The deferment is to enable time for plant reproduction, establishment of new plants, and restoration of vigor of existing plants. Deferred rotation tends to work best in areas where relatively large differences exist between the palatability of plants and convenience of areas for grazing. For example, meadows and riparian zones within mesic mountain ranges often receive excessive use by cattle even under light stocking densities while surrounding uplands receive light or no use. Deferment enables heavily impacted areas or particular palatable species to regain vigor and set seed periodically. Variable seasonal deferments also may enable plants with different phenologies in the same grazing area to benefit from deferred-rotation. For ecosystems in which perennial grasses are the primary forage base, deferment of grazing until after seed set may enable higher stocking rates that can compensate to some extent for the reduced grazing period (Howery and others 2000). In arid and semiarid ecosystems in which biological soil crusts are an important ecological component, livestock may need to be removed before the end of the growing (wet) season to enable regrowth of crust biota before extended periods of drought (Belnap and others 2001b).

Within the Sonoran Desert, deferred-rotation, or at least the principle of deferment, may have some applicability to the management of ephemeral allotments. (We indicated above where use of a continuous grazing management approach, in which the perennial allotment is the analogous management approach, may have limited applicability within the Sonoran Desert.) Its application, even for ephemeral allotments, would be complicated by the availability of multiple allotments/pastures within which rotation can occur and whether the overall management area is under the effects of drought. As a result, its application would have to be modified to the extent that other factors may dictate deviations from a strict deferred-rotation schedule.

Rest-Rotation Grazing

Rest-rotation grazing approaches were first implemented by the U.S. Forest Service in the 1950s and 1960s. In a rest-rotation grazing system, the range is divided into multiple pastures (usually three to five) as in deferred-rotation grazing. In rest-rotation grazing, however, one or two of the pastures are rested (ungrazed) the entire year while the remaining pastures absorb the grazing load. Various sorts of rotation/deferment schemes are used on the remaining pastures. If accompanied by conservative stocking rates (see below for a description), rest-rotation grazing is considered an appropriate system for both vegetation condition and livestock performance in rugged, mountainous terrain where livestock distribution is an issue. Most of the failures of this system are associated with heavy stocking rates. As a result, the benefits of rest (even for multiple years) can be easily offset if previously rested pastures are overgrazed, especially in arid regions where frequent drought can impede recovery. On flat desert areas, Holechek and others (2004b) suggested the rest-rotation grazing system was not an improvement over other grazing management approaches when the goal was primarily livestock production; however, they felt it may have some advantages in multiple-use contexts.

The Santa Rita grazing system is a specific application of a rest-rotation grazing system that was developed for semidesert grasslands with predominantly mid-summer rainfall in southeastern Arizona. The Santa Rita grazing system involves one herd, three pastures, and a three-year rotation period. The rest-grazing sequence for one pasture is: (1) rest 12 months (November to October), (2) graze four months (November to February), (3) rest 12 months (March to February), and (4) graze eight months (March to October) to complete the three-year cycle. Under this cycle, each pasture is rested during the spring and summer growing seasons for two out of three years but each year's forage is utilized within one of the pastures. A full year of rest occurs before livestock graze during a spring growing season. This provides old herbage that protects early growth from repeated close grazing. Stocking rates are kept at moderate levels (30 to 40% utilization). Benefits are greatest where animals tend to congregate, such as around livestock waters. The Santa Rita system is reported to have accelerated the recovery of semidesert grasslands in poor condition, but seemed to provide little advantage over continuous grazing at moderate levels on similar rangelands in good condition (Martin and Severson 1988).

Within the Sonoran Desert, rest-rotation may have some applicability to the management of ephemeral allotments similar to what we described above for deferred-rotation. Again its application would be complicated by the availability of multiple allotments/pastures within which rotation can occur and whether the overall management area is under the effects of drought. As a result, its application would have to be modified to the extent that other factors may dictate deviations from a strict rest-rotation schedule. The specific timing of the Santa Rita system would not be applicable over most of the Sonoran Desert because of the shift to a predominantly winter rainfall pattern. Two other deviations from this specific system are likely. First, because rest-rotation likely could only be applied within an ephemeral allotment context in the Sonoran Desert, forage utilization when measured across all allotments/pastures included in the rotation would not occur across the whole year. Second, the utilization level used to determine appropriate stocking rates for semidesert grasslands likely is non-conservative with respect to the Sonoran Desert (see below).

Seasonal-Suitability Grazing and Best Pasture

In the seasonal-suitability grazing system the range is partitioned into pastures based on vegetation type. Generally fencing is used to segregate the pastures, but in some cases controlling access to water can be used to manipulate livestock use of particular areas. Seeded pastures are often but not always used as part of the system. To have any advantage as a grazing system, productivity of individual vegetation types must be sufficient enough to enable fencing or water control to be practical.

The best-pasture grazing system is best described as a variant of the seasonal-suitability grazing system that was first proposed for use in the semidesert ranges of south-central New Mexico. In the Southwest local rainfall patterns, especially during the summer, can cause considerable and unpredictable differences in forage availability between pastures. As a result, the best-pasture grazing system differs from the traditional seasonal-suitability grazing system in that the "best" pasture, as determined by nutritional and forage availability standpoints, is grazed each season rather than a strict adherence to different vegetation types or rigid rotation cycles. Range condition then also can influence which pasture is grazed.

The best-pasture grazing system may offer advantages in areas that have localized rainstorms and high variation in forage production over short distances. In regard to its applicability within the Sonoran Desert, its underlying conceptual basis may best be applied on a within-allotment basis through control of access to water if significant differences exist in range condition throughout the allotment. Except for the small remnant tobosa (*Pleuraphis mutica*) grasslands that exist in limited areas of the Sonoran Desert, little segregation by vegetation type may be achievable as the major forage availability differences will be between xeroriparian and matrix communities (Creosotebush-Bursage Desert Scrub and Paloverde-Mixed Cacti-Mixed Scrub on Bajadas).

Short-Duration Grazing

Short-duration grazing was first developed in Zimbabwe by Allan Savory and later introduced to the U.S. This type of system also has been referred to as rapid-rotation, time-control, and cell grazing. Savory's subsequent modifications of the basic approach have been called the Savory grazing method or holistic management. Short-duration grazing differs from other grazing systems in that a range unit is typically divided into several small pastures (also called paddocks or cells), each of which may receive more than one period of non-use and grazing during a single growing season. Five to 12 pasture units commonly may be involved in which the grazing periods last from three to 14 days followed by a non-grazing period of up to 60 days to enable forage regrowth (ideally the grazing period should be five days or less followed by at least four weeks of non-use [Holechek and others 2004b]; however, pasture rotations and non-use periods are dependent on growing conditions). Livestock may be moved less frequently if the system is applied when the vegetation is dormant. Pasture layout is variable, but typically may involve a wagon-wheel arrangement of fences with water and livestock-handling facilities located in the center of the range unit. Stocking rates supposedly can be increased substantially (even doubled or tripled) compared to continuous and other grazing systems. The increase in stocking rates achieved presumably results from better livestock distribution—the confinement of a large number of animals to a small area for a short period improves uniformity of use and forces the use of areas and plants that would not otherwise be used.

The proponents of short-duration grazing maintain that when properly implemented the system results in numerous benefits to rangeland resources, including inproved water infiltration as a result of hoof action, increased mineral cycling, and reduced forage selectivity so that more plants are grazed and the range is grazed more evenly. The purported benefits of this system, however, often go unrealized (Bryant and others 1989, Brown 1994b, Howery and others 2000, Sayre 2001, Holechek and others 2000, 2004b; see also Chapter 7). From a theoretical standpoint, short-duration grazing should work best in flat, humid grasslands with more than three months of plant growth and over roughly 20 inches (50 cm) of average annual precipitation (Holechek and others 2004b).

Short-duration grazing is generally less feasible in the arid and semiarid regions of the western U.S. in which growing seasons are relatively short, productivity is low, plant growth rates are more often than not slower than the rotation rate (D. Milchunas, personal communication), and drought is frequent. Especially in arid regions, the limited and highly variable production of forage does not support high stocking rates, and concentration of livestock early in the short growing season can cause severe trampling and soil compaction, heavy defoliation, and erosion, with little opportunity for recovery (Holechek 1983, Warren and others 1986, Bryant and others 1989, Brown 1994b, Howery and others 2000, Holechek and others 2000, 2004a, b). Desert grasses as a group, in particular, may be detrimentally affected by short-duration grazing because their regrowth occurs over a short period of time, they show low resistance to grazing compared to prairie grasses, and they are susceptible to long-term damage if overgrazed during drought (Holechek 1983, Howery and others 2000, Holechek and others 2004b). Furthermore, in areas where large differences exist between the palatability of plants (such as in many plant communities of the Sonoran Desert), attempts to encourage cattle to eat less preferred forage can be unsuccessful and result in depletion of preferred species.

10.1.4 General Grazing Management Considerations

As mentioned near the beginning of this chapter, grazing management consists of four basic components: proper stocking rate, proper timing of use, proper distribution, and proper grazing system (Holechek and others 2004b). In the preceding sections we discussed a number of these components in the context of assessing the applicability of different grazing systems to the Sonoran Desert. Here we address a few additional considerations primarily related to establishing proper stocking rates and drought management.

Stocking Rate Considerations

At the conclusion of their review of grazing management strategies, Holechek and others (2004b) concluded that no grazing system will be effective biologically (or financially) if accompanied by an excessive stocking rate. We conclude from our assessment of the different grazing strategies we considered that an inherent tension exists between the mix of management objectives that may accompany selection of a particular grazing strategy. The tension is principally between whether any particular grazing system, as compared to continuous grazing, can enable both improvement in resource condition and increased stocking rates. To a large extent increases in stocking rates, while resource condition is maintained or improved, presumably are accomplished through implementation of a grazing system that results in better distribution of livestock, and hence more complete utilization of available forage, and better timing of livestock use. Timing is important because forage plants can withstand higher utilization levels during certain times of the year as compared to others (Caldwell 1984). These assumptions need to be critically tested, especially in hot deserts such as the Sonoran and Mojave Deserts, where forage availability is patchy, unpredictable, and often reduced substantially by frequent drought, and plant palatability and grazing resistance are variable.

A particular stocking rate presumably leads to a particular level of grazing intensity (defined as the cumulative effects grazing animals have on rangelands during a particular time period [see Holechek and others 2004b]). Various approaches can be used to measure grazing intensity, including percent utilization of forage, plant stubble heights, and so on. The important point here is that measures of grazing intensity can be considered from the standpoint of individual plant species or from an ecosystem perspective. At the ecosystem level various empirical data have been analyzed across a number of rangeland types that relate percent utilization of forage to different qualitative categories of grazing intensity: light, conservative, moderate, and heavy (Holechek and others 2004a, b).[21] Holechek and others (2004a) contend that grazing at moderate to light intensities represents controlled or managed grazing. Based on a review of 18 studies, these authors concluded that managed grazing compared to grazing exclusion can enhance rangeland vegetation by accelerating plant succession, increasing plant diversity and productivity, and reducing plant mortality, with positive effects most likely when grazing intensities are light to conservative. Our purpose here is not to critically evaluate the conclusions of Holechek and others (2004a); instead, we highlight that of the studies assessed to determine the impacts/benefits of managed grazing, none of them occurred within the Sonoran Desert

Holecheck and others (2004b) summarized utilization data from various studies across North America to derive average utilization values that correspond to the various qualitative grazing intensity categories: 57% (heavy), 43% (moderate), and 32% (light). These authors also suggested that conservative grazing generally involves about 35% utilization. Two key points need to be kept in mind: (1) these rates are averages across a number of different vegetation types and (2) for any particular study site they also represent average utilization rates across multiple years. In regard to the latter point, this means that grazing intensity may exceed the average at times. If we use the definition of moderate grazing as a guide, Holechek and others (2004b:table 8.8) also provide data on utilization guidelines for different range types in the U.S. that if followed presumably would maintain forage production. A range of values is provided for each range type: the higher utilization level is for ranges in good condition and/or that are grazed in the dormant season, whereas the lower utilization level is for ranges in poor condition or ranges that are grazed during the growing season. For moderate intensity grazing the utilization range is as high as 50 to 60% for range types receiving over 50 inches of rain per year to 25 to 35% for deserts such as the Mojave receiving less than eight inches of rain per year.

The above Mojave data are based on a study by Hughes (1982). The data are indicative of the problem with averages. Although average utilization of perennial forage was around 30 to 35%, in some years utilization exceeded 50%. Hughes (1982) concluded that these occasionally high rates harmed the desert grasses even when they occurred following rest from grazing. He suggested that utilization levels should never exceed 50% in any year.

The guidelines included in Holechek and others (2004b) do not include the Sonoran Desert. A first level estimate would suggest they may be similar to the Mojave Desert if establishing moderate grazing intensities is the goal; however, a few caveats are in order. First, in general,

---

[21] Klipple and Bement (1961) provided definitions for heavy, moderate, and light grazing intensities. *Heavy grazing* means a degree of herbage utilization that does not permit the desirable forage species to maintain themselves. Its continued application leads to deterioration of range vegetation. *Moderate grazing* means a degree of herbage utilization that enables palatable species to maintain themselves but usually does not permit them to improve in herbage-producing ability. Moderate grazing leads to stabilization of existing range conditions. *Light grazing* means a degree of herbage utilization that [enables palatable species to maximize their herbage-producing ability]. Light grazing (according to Klipple and Bement 1961) leads to improvement of deteriorated range condition up to site capacity.

utilization values for managed grazing have been developed based on range types in which herbaceous vegetation is the primary forage base. Although we noted above that some guidance may be available to set shrub utilization levels, this does not account for how to set utilization levels for herbaceous vegetation exposed to the yearlong presence of livestock. In addition, it seems the necessary studies have not been done to estimate appropriate utilization levels of vegetation that respond to variable participation on time scales that may at times exceed a few years (for example, winter annuals). Second, range condition affects what utilization level corresponds to a particular grazing intensity, which in turn will affect the corresponding stocking rate. Third, a stocking rate established to achieve a certain grazing intensity under average meteorlogical or forage conditions will result in a higher grazing intensity under drought conditions. If rapid destocking is problematic, overgrazing can easily occur during drought. Clearly, researched-informed utilization levels (or other measures of grazing intensity) that may reflect the desired objectives of managed grazing are yet to be empirically determined for Sonoran Desert plant communities.

Drought Management Considerations

In section 4.1.2 we discussed various definitions for and aspects of drought that may be important to consider in a livestock grazing management context. We concluded that definitions of, metrics for, and livestock management responses to drought in the Sonoran Desert needed to account for the three periods of drought: onset, during, and exiting. Some general guidance for drought management in the southwestern U.S. has been developed that accounts for these three periods (Howery 1999). We also identified at least one empirical study from southeastern Arizona that provides a strong basis for appropriately managing stocking rates during the various periods of drought. We discuss the findings from the empirical study first and then offer some general findings related to the implications for drought management in the Sonoran Desert.

Robinett (1992) assessed drought recovery on areas grazed by cattle within a transition zone between the Sonoran Desert and the semidesert grasslands of southeastern Arizona. He compared perennial grass density and vigor at three key areas[22] during and after a severe drought. Drought was defined as first a prolonged dry period in the winter-spring of 1988 to 1989 in which precipitation was less than half of the mean amount for the period. Summer rainfall in 1989 and subsequent winter-spring rainfall stayed below approximately 60% of the mean. The drought ended with the onset of slightly above average summer rains in July 1990. All three key areas were in the Altar Valley in southern Arizona on sandy loam upland ecological sites where the dominant forage species are Arizona cottontop (*Digitaria californica*) and Santa Rita three-awn (*Aristida californica* var. *glabrata*). The description of the overall area implies it may represent degraded semidesert grassland.

The key areas were all grazed by cattle under a rest-rotation grazing system, but differed in their utilization levels of the above two species and duration and timing of rest. Key area (KA) 1 had approximately 40 to 60% utilization during 1989 with a year of rest in 1988 and in 1990, whereas KA 3 had approximately 30 to 60% utilization during 1988 and 1990 with rest in 1987 and 1989. Conversely, KA 2 did not receive any yearlong rest but had lower utilization levels

---

[22] A key area is a relatively small portion or a pasture of a management unit selected because of its location, use, or grazing value as a monitoring point for grazing use (SRM 1989).

(approximately 10 to 40%) throughout 1987 to 1990. All key areas showed significant declines in percent frequency of Arizona cottontop and Santa Rita three-awn during the drought, with more than 50% mortality of both grazed and ungrazed plants regardless of grazing rotation schedules or utilization rates.

Once the drought ended, surviving perennial grasses regained vigor at all sites, but only at KA 2 did the grass density of both species return to near pre-drought conditions. Robinett (1992) attributed the better recovery of KA 2 to two key features: (1) it entered the drought with a denser stand of grasses than the other two key areas and (2) light grazing use (low utilization levels) before, during, and after the drought left more grass to become litter on the soil surface. By June 1990 virtually no litter was left at KAs 1 and 3. The first hard summer rains in July 1990 removed the remaining organic debris. The denser stand of grasses at KA 2 during the drought contributed to increased litter at the soil surface. The presence and abundance of litter provided suitable habitat for grass germination and survival once the summer rains arrived. Robinett (1992) suggested that ranchers need to use a flexible stocking rate to deal with natural climatic fluctuations, including drought, that are characteristic of the region. Utilization (and hence stocking rates) should be reduced during and immediately following drought to prevent declines in forage production and to maintain herbaceous material and litter. For the area in question, Robinett (1992) also suggested that reductions in winter precipitation can be used as guide to predict grass mortality. The appropriate management response would be a concordant reduction in stocking rate to help conserve litter and enable more rapid recovery if dry conditions persisted. In sum, this particular study provides some useful insights in how to approach livestock grazing management during the three periods of drought.

Most of the Sonoran Desert receives less mean annual rainfall and is subject to more frequent and severe drought conditions than the area studied by Robinett (1992). As a result, the principles of drought management potentially have even more severe consequences for the Sonoran Desert ecosystem if not addressed. The ability to implement flexible stocking rates that can in a timely manner respond to all three periods of drought likely is the most important aspect of drought management in the Sonoran Desert; however, achieving this flexibility may be highly problematic under a continous grazing (perennial allotment) scenario. The setting of stocking rates as a percentage of what is considered to be the average long-term stocking rate may be a reasonable approach for some rangeland types (Howery 1999); however, the more variable the precipitation and productivity, and the more frequent the likelihood and severity of drought, the more likely this approach may still result in resource degradation (Westoby and others 1989, Brown 1994). Productivity has a non-linear relationship with precipitation; as a result, in a “dry” year production drops off proportionally more than the decline in precipitation (see section 4.1.2). Drought management may best be approached in the Sonoran Desert on the basis of setting proper stocking rates for ephemeral allotments.

10.2 REVIEW OF THE LITERATURE THAT EVALUATED GRAZING MANAGEMENT STRATEGIES IN THE SONORAN DESERT

Only two documents attempted to analyze the ecological trade-offs of grazing management strategies as applied in the Sonoran Desert. One document was an Environmental Impact Statement (EIS) prepared by the U.S. Fish and Wildlife Service (USFWS 1981) to evaluate the potential impacts of different livestock grazing systems on Sonoran Desert ecosystems on the Kofa National Wildlife Refuge (NWR) in southwestern Arizona. The other document evaluated grazing management alternatives on the Sif-Oidak District of the Tohono O'odham Nation (Hayes 2004).

The USFWS (1981) evaluated the impacts of six cattle and wild burro management alternatives on a 187,000-acre (75,000 ha) portion of the Kofa NWR. The management objectives of the Kofa NWR are to "provide high-quality habitat representative of the lower Sonoran Desert, and manage for optimum populations of native plants and animals" and to conserve a "large, healthy desert bighorn sheep population while also maintaining sufficient high-quality habitat to provide a maximum diversity of mammal, bird, reptile, and amphibian species" (USFWS 1981:5). Two of the alternatives (including the preferred alternative) involved complete elimination of cattle and wild burros from the refuge, but differed in the timing of removal. Three alternatives involved livestock management and one alternative was the "no action" alternative. The cattle and burro management alternatives that were evaluated included: (1) reduced stocking level of cattle and reduced number of burros, (2) seasonal cattle grazing and elimination of burros, and (3) deferred-rotation grazing system and elimination of burros. The implementation of any of the three grazing management strategies was dependent upon inventories of range suitability and carrying capacity.

Under the reduced stocking rate alternative the number of cattle permitted was to be determined based upon inventories and was likely to be reduced by 40 to 50% of the pre-EIS permitted 4,200 animal-unit-months (AUMs) or up to 350 cattle. Livestock was to be permitted to graze continuously year round. Although some heavily grazed species such as jojoba (*Simmondsia chinensis*) might benefit from reduced stocking rates, the USFWS predicted that little overall improvement in vegetation would occur because palatable and accessible plants would continue to be grazed and be subject to gradual loss of vigor or elimination.

In the seasonal grazing alternative the stocking rates and season of use were to be established by annual rainfall, in which grazing would be precluded in drought years and permitted for up to six months during wet years. The USFWS (1981) determined that seasonal grazing might have some potential for habitat improvement at heavily used sites such as around livestock waters, but it was predicted to have negative impacts on the many species of forbs, grasses, and shrubs, such as jojoba and big galleta (*Pleuraphis rigida*), that have their critical growth period in the winter and spring. Grazing during the new shoot growth period prohibits development of adequate food reserves and root systems, with subsequent reduction in flower production (USFWS 1981). Furthermore, seasonal cattle grazing was predicted to have negative impacts on desert bighorn sheep (*Ovis canadensis mexicana*) because it is during the winter and spring that the habitat overlap between cattle and bighorn sheep is greatest and when the sheep are most evenly distributed in available habitat.

In the deferred-rotation grazing alternative the study area was to be divided into pastures that would be grazed and rested systematically such that some portion of the range would have cattle and rest each year but none would have a full year of grazing rest. The stocking rate and timing of grazing was to be determined by the productivity of key forage species on each portion of the range to be grazed. The deferred-rotation grazing system is dependent upon consistent and adequate rainfall, and it requires flexibility and deviation from the grazing schedule and stocking rate to wait for forage species to reach a state in which they can withstand some degree of grazing. The USFWS (1981) determined that this alternative would not be feasible on the refuge because rainfall is highly variable and prolonged droughts are common, so deviation from the grazing schedule would be the norm.

The USFWS (1981) determined that the grazing management alternative most compatible with the wildlife objectives that established the Kofa NWR was complete elimination of cattle and wild burros. Elimination of grazing was predicted to result in significant long-term improvement in grass, shrub, and forb density, cover, vigor, and recruitment, especially within one to three miles (1.6 to 4.8 km) of livestock waters. Improvement in vegetation was also predicted to increase plant litter and to help improve soil characteristics including soil stability. The USFWS eventually chose and implemented this last alternative.

Hayes (2004) conducted a case study of historical and current livestock management institutions for the 480,200 acre (194,400 ha) Sif-Oidak District of the Tohono O'odham Nation. Current livestock management strategies in the Sif-Oidak District reflect a communal livestock management approach. Subdivided fenced pastures do not exist and livestock (cattle and horses) are allowed a high degree of mobility to track forage and water as it becomes available across a variable, heterogeneous landscape in which rainfall itself is low and highly variable. Some local interest existed to create a system of fenced pastures to enable a rotational grazing system as a way to increase perennial grass production. Hayes (2004) evaluated the two alternatives and concluded that the existing management approach had the greater potential for effectively raising livestock within the Sif-Oidak District. Based on his study of current grazing dynamics on the Sif-Oidak District in relation to the effect on perennial grass production (previously reviewed in section 4.2.2), Hayes (2004) concluded the creation of fenced pastures and implementation of a rest-rotation grazing system would not result in improved perennial grass production.

10.3 RANGE ECOLOGY THEORY AND APPLICATION: EQUILIBRIUM AND NON-EQUILIBRIUM PARADIGMS AND MODELS OF VEGETATION DYNAMICS

The approaches to evaluating vegetation dynamics on rangelands are tied to underlying assumptions of ecological theory. Two paradigms of ecology that attempt to describe how plant and animal communities and ecosystems respond to disturbance are the equilibrium and non-equilibrium paradigms. As pointed out by Ellis and Swift (1988), our perception of how particular ecosystems function determines the models and methods we advocate when attempting to modify or otherwise manipulate those ecosystems. Within the narrow context of vegetation dynamics on rangelands, the equilibrium paradigm assumes continous and reversible vegetation dynamics, whereas the non-equilibrium paradigm can accommodate discontinous and non-reversible vegetation change (Briske and others 2003). Their specific applications to livestock grazing in terms of conceptual models for rangeland management, including range condition and trend analysis, are referred to as the range succession (Westoby and others 1989), range condition (Laycock 1991), ecological condition (Bartolome 1993), or range (Briske and others 2003) model (hereafter range model) and the state-and-transition model (Westoby and others 1989), respectively. In this section, we briefly describe the history of the paradigms, and associated vegetation dynamics models, and their use in guiding rangeland management. The appropriate ecological conditions and metrics under which each paradigm is applicable and can be distinguished, how they relate (for example, whether they are mutually exclusive), and how the impacts of livestock grazing should be interpreted and measured under each paradigm have at times been controversial. As a result, we include as part of our overview a discussion of the preceding issues, as elucidating such issues are important to our understanding of how either paradigm may be applied to livestock grazing in the Sonoran Desert.

10.3.1 History of the Paradigms and Associated Conceptual Vegetation Models

The equilibrium paradigm is based on the assumption that communities/ecosystems (hereafter referred to as ecological systems when both are implied) possess the capacity for internal regulation through negative feedback mechanisms (Briske and others 2003). This capacity is assumed to contribute to vegetation dynamics that are predictable and directional in the absence of a disturbance. If a disturbance occurs, equilibrium systems are assumed to return to their pre-disturbance state or to their pre-disturbance trajectory once the disturbance has ended. These attributes as related to plant communities are in concordance with a Clementsian view of plant community succession. Moreover, this concept of equilibrium and the associated Clementsian ideas of plant ecology are the underlying theoretical basis for the range model (Westoby and others 1989, Briske and others 2003), which has been the prevailing guide for range condition and trend analysis for most of the last century.

Early range ecologists assumed that selective grazing by livestock changed the relative fitness of plants, which led to changes in plant community structure and composition (Bartolome 1993). If deterioration of the range occurred because of overgrazing, as reflected by the inability of preferred plants to out-compete less palatable species, recovery through improved management (for example, destocking) was assumed to parallel the changes that occur during secondary succession (Bartolome 1993). As a result, the range model assumes a given plant community will achieve a single persistent state (climax) in the absence of livestock grazing (Westoby and others 1989). In addition, as described by Westoby and others (1989), the range model assumes that livestock grazing produces progressive, directional community change that is in the direction opposite to the successional tendency. As a result, presumably livestock grazing intensity can be manipulated through stocking rate adjustments to achieve an equilibrium, as measured by vegetation condition, between the opposing tendencies. All possible states of the vegetation can be arrayed along a continuum from heavily grazed, early-successional, poor condition to ungrazed, climax, excellent condition. Condition then is a relative term that corresponds to the vegetation's position along the successional continuum, whereas trend describes the trajectory of the vegetation along the continuum. Dyksterhuis (1949) provided a quantitative approach to determining vegetation condition in accordance with the range model—that is still considered applicable in many western U.S. rangeland contexts today (Holecheck and others 2004b)—in which the responses of different plant groups (decreasers, increasers, and invaders) to grazing, as determined by changes in relative cover values, provide a quantitative basis for determing an extant plant community's departure from the climax state. In sum, the objective of management under the range model is to use a stocking rate that establishes a long-term balance between the effects of livestock grazing and the successional tendency. The model also can accommodate variability in precipitation and its effect on vegetation. It presumes that drought affects vegetation in a similar way to grazing and that above average rainfall can be viewed as accelerating the successional tendency. To maintain equilibrium, stocking rates would have to be varied in a manner that offsets changes in rainfall.

Dissatisfaction with the ability of the equilibrium paradigm to adequately describe observed responses of bird communities in grassland and shrub-steppe habitats led Wiens (1984) to propose that communities should be viewed as existing along a gradient of states ranging from non-equilibrium to equilibrium. In contrast to equilibrium communities, he suggested that non-equilibrium communities should be characterized by a general decoupling of biotic interactions (that is, a limited capacity for internal regulation) and a larger dependence, in terms of community structuring and dynamics, on species-specific reactions to environmental variation. Weins (1984) and subsequently others in regard to specifically grazing systems (Ellis and Swift 1988, Briske and others 2003) provided attribute values that characterize ecological systems at either extreme of the equilibrium-non-equilibrium continuum. In Table 10.1 we have summarized a few of the characteristics described by these authors, with a focus on those attributes related to abiotic processes, plant-herbivore interactions, population patterns, and community/ ecosystem characteristics. The attribute values tabulated in each column in Table 10.1 may overlap to some degree. Although non-equilibrium systems are primarily structured by external drivers, such as climatic events, this does not imply that their behavior is unconstrained by other factors, such as evolutionary limits (Briske and others 2003).

TABLE 10.1 Characteristics of Equilibrium and Non-Equilibrium Systems[1]

Attribute	Equilibrium	Non-Equilibrium
Abiotic Processes	Predictable in occurrence and relatively constant in expression Plant growing conditions relatively constant (and response can be optimal) Few stochastic effects	Dynamic in occurrence and highly variable in expression Plant growing conditions variable (and response must be opportunistic) Large stochastic effects (event driven)
Plant-Herbivore Interactions	Biotic regulation of plant biomass through negative feedback Tight biotic coupling	Abiotic control of plant biomass Weak biotic coupling (or decoupling)
Population Patterns	Density dependence Populations track carrying capacity	Density independence Dynamic carrying capacity limits population tracking (abiotic factors drive population cycles)
Community/Ecosystem Characteristics	Competitive structuring of communities Internal regulation	Competition not expressed External drivers (disturbance regimes) critical to system dynamics

[1] Modified from Weins (1984), Ellis and Swift (1988), and Briske and others (2003).

Some attempts have been made to use specific climatic criteria to distinguish equilibrium from non-equilibrium systems (reviewed by Illius and O'Connor 1999). Frequency of drought and degree of aridity have been suggested as possible criteria; however, the one quantitative, though arbitrary, criterion described by Illius and O'Connor (1999) involves using the coefficient of variation (CV) associated with annual rainfall: that is, environments in which the CV for interannual rainfall is greater than 33% are considered to behave in accordance with the non-equilibrium paradigm. A quick inspection of Table 3.2 indicates that only the Tucson weather station (at 28.2%) has a CV less than 33% for interannual precipitation. The above cut-off value was used to distinguish arid environments. Semiarid environments also have been considered to operate under non-equilibrium dynamics. Illius and O'Connor (2000) suggested that semiarid environments typically have CVs greater than 25%.

Criticism of the range model as an ineffective, over-simplification of vegetation dynamics on many rangelands led to the development of state-and-transition models (Westoby and others 1989) as a means to overcome the limitations of the range model as applied to variable environments. The focus on model limitations, however, obscured the fact that the rangeland debate was itself layered over a broader ecological evaluation of the appropriate paradigm for interpreting ecosystem behavior in response to disturbance (Briske and others 2003). In their critique of the equilibrium and non-equilibrium paradigms, Briske and others (2003) concluded that the methodological dichotomy that developed between the range and state-and-transition models fostered the perception that the two underlying paradigms were mutually exclusive. In their analysis of the literature, they further concluded that: (1) equilibrium and non-equilibrium systems are not distinguished on the basis of unique ecological processes or functions, but instead by an evaluation of system dynamics at various temporal and spatial scales; (2) ecological systems may express both equilibrium and non-equilibrium dynamics; (3) empirical evidence that could demonstrate the occurrence of both equilibrium and non-equilibrium dynamics in numerous systems is frequently confounded by a number of methodological and system response factors; and (4) focus should shift to paradigm integration. Because state-and-transition models can accommodate both equilibrium and non-equilibrium vegetation dynamics (Bestelmeyer and others 2003), they can support paradigm integration (Briske and others 2003).

In a later section we address some issues associated with the application and interpretation of the equilibrium and non-equilibrium paradigms with a focus on the implications for livestock grazing management within the Sonoran Desert. But first we briefly describe state-and-transition models and two other non-equilibrium models that have been developed.

10.3.2 State-and-Transition Models (and Other Related Models)

In addition to the state-and-transition model, Briske and others (2003) describe two other models that were developed to accommodate discontinuous vegetation dynamics: the threshold and persistent non-equilibrium models. We describe these two latter models first and then the state-and-transition model.

Threshold Model

The threshold model is based on contemporary ecological theory and a recognition that rangelands may exist in multiple stable states (contrary to the assumptions of the range model) and that transition between these states occurs when particular thresholds of change are passed (Friedel 1999, Laycock 1999). Once a threshold is passed, the transition may be irreversible in the sense that removing the causal factor (for example, livestock grazing [Laycock 1991]) will not enable a return to the previous stable state. Moreover, drivers may act synergistically. For example, drought may exacerbate the impacts of livestock grazing and cause a threshold to be passed (Friedel 1999). Friedel (1999) suggested that two thresholds are readily apparent in arid and semiarid rangelands: (1) change from grassland to shrubland and (2) change from stable to degraded soil. Laycock (1991) further suggested that in North America in addition to livestock grazing, fire and the introduction of non-native species often are involved in the transitions to other stable states. Briske and others (2003) noted that thresholds may ultimately be more appropriately distinguished by changes in the natural disturbance regime than by changes in the dominant growth forms (see also Brown 1994). Although the threshold model was meant to replace the range model in situations in which the range model did not seem to apply, Laycock's (1991) application retained a connection to the Clementsian ideas of plant ecology by referring to the alternate stable states as if they were in a lower successional state. And although transitioning from one stable state to another defines a non-equilibrium system, it does not mean that the individual states operate under non-equilibrium dynamics (Briske and others 2003). Ultimately, the inherent flexibility of state-and-transition models enable them to accommodate the concept of thresholds (Bestelmeyer and others 2003; see below), which seemingly obviates the need to consider the threshold model as a competing model.

Persistent Non-Equilibrium Model

Briske and others (2003) attributed the persistent non-equilibrium model to Ellis and Swift (1988). The model itself seems to be a special application to an Africa pastoral grazing system that potentially mimics the behavior of free-roaming herbivores within a variable precipitation environment. During sequences of good (wet) years, livestock populations expand at moderate rates. Single-year droughts affect this pattern only slightly; however, the consequences of multi-year droughts are collapses in livestock numbers. Because of the relatively high return frequency of multi-year droughts, livestock populations supposedly never reach the carrying capacity of the vegetation and as a result strong negative feedback relationships between plants and livestock never develop. Livestock populations approach but never reach extinction because droughts do not last long enough to completely eliminate the population. Ellis and Swift (1988) concluded the system is persistent because it operates within a limited range of variation, though populations are unstable over time. An important component of the system's success is the ability of the pastoralists to increase the spatial scale of exploitation during stress (drought) periods (Ellis and Swift 1988).[23] The model does not explicitly define the pattern of vegetation

---

[23] Although similarities exist between the pastoralists approach to livestock grazing management and the communal livestock management approach described by Hayes (2004) for the Sif-Oidak District of the Tohono O'odham Nation, significant differences likely also exist such as the inability to increase the spatial scale of exploitation on the Sif-Oidak District in the same manner as the pastoralists.

dynamics involved (Briske and others 2003). Alternative interpretations of the level of impact of livestock grazing to vegetation in this system are discussed in section 10.3.3.

State-and-Transition Model: Overview

The state-and-transition model was developed to accommodate some observed problems of application with the range model, whose most apparent weakness was in regard to its applicability in arid and semiarid rangelands. For these rangelands presumably episodic (climatic) events are important and the influence of grazing and intrinsic (self-regulating) vegetation change act only intermittently (Westoby and others 1989). Its original architects (Westoby and others 1989) proposed their formulation as a practical way to organize information for management and not because it followed from theoretical models about vegetation dynamics. The state-and-transition model was not meant as a complete replacement to the range model in all rangeland situations but rather as a complementary model that can accommodate both equilibrium and non-equilibrium vegetation dynamics (Westoby and others 1989, Bestelmeyer and others 2003, Briske and others 2003).

In the original formulation of the state-and-transition model, rangeland vegetation dynamics were described by a set of discrete vegetation states that could occur on a particular piece of ground and a set of transitions—triggered by natural events such as weather or fire or management actions such as changes in stocking rate—between states (Westoby and others 1989). Westoby and others (1989) viewed states as an abstraction that encompassed a certain amount of variation in space and time. As a result, states do not necessarily have to be clearly demarcated from each other, which enables some flexibility in how states are used to distinguish between threshold-dependent and progressive changes in vegetation and other ecological conditions. This flexibility has been more recently distinguished in model development as changes among plant communities within states (pathways) that are reversible versus changes among states (transitions) that are either non-reversible or reversible only with considerable management effort (Bestelmeyer and others 2003). Reversible changes could occur through changes in climate or changes in management referred to as facilitating practices by Bestelmeyer and others (2003). The range model can be applied to pathways and as a result is incorporated into the state-and-transition model. Bestelmeyer and others (2003) referred to the management actions needed to reverse transitions as accelerating practices. In addition to states and transitions, Westoby and others (1989) also recommended cataloging opportunities—climatic circumstances under which management actions such as fire or different grazing strategies could be used to produce a favorable transition—and hazards—climatic circumstances under which particular management actions could produce an unfavorable transition.

In general, to develop a state-and-transition model requires compilation of various pieces of information about a site, ecosystem, or plant community of interest. Four main characterization steps are involved in developing state-and-transition model(s) for a particular site or sites: (1) classify and describe the sites of interest based on landforms, soils, and climate; (2) describe the existing vegetation at the sites of interest; (3) interpret differences in existing vegetation at different sites based on biotic or abiotic factors and land-use history; (4) describe the ecological processes of the sites of interest to hypothesize how and under what conditions the vegetation and abiotic conditions are likely to change (B. Bestelmeyer, personal communication).

State-and-Transition Model: Current Application and Future Plans

The Bureau of Land Management (BLM) in Arizona has had some experience with the development and use of state-and-transition models. For example, a state-and-transition model that was developed initially by The Nature Conservancy was subsequently modified by the BLM and others (1998) to explain some of the significant ecological processes and changes that occured within the semidesert grasslands of southeastern Arizona. The modified model was applicable to the Muleshoe Ecosystem located in the Galiuro Mountains of northern Cochise and southern Graham County. Five vegetation states, applicable to three different ecological sites, were defined that differed in their relative composition of shrubs and annual and perennial grasses. The catalog of transitions between states included alterations in two types of transitions: livestock grazing intensity during the growing season and fire frequency. The BLM, U.S. Forest Service, Arizona Game and Fish Department, and The Nature Conservancy set ecological objectives for the Muleshoe Ecosystem based on the state-and-transition model (BLM and others 1998). At present, the state-and-transition model is used to guide management actions, such as prescribed burning and grazing rest, to make progress towards meeting the ecological objectives.

State-and-transition models have not yet been developed to accommodate vegetation dynamics and appropriate livestock management practices for the Sonoran Desert. A challenge to developing state-and-transition models for Sonoran Desert plant communities will be incorporating natural and anthropogenic disturbance regimes—that in combination affect transitions and thresholds—that occur at different spatial and temporal frequencies and with differing degrees of predictability. If such models are developed within an adaptive management framework, then appropriate multi-scale data collection and long time periods will be required to understand how plant communities change in response to climatic and particular anthropogenic disturbance factors and how grazing management strategies may be used to avoid undesirable transitions. The Natural Resources Conservation Service and other collaborators are currently updating the Ecological Site Descriptions (ESDs) across the Southwest, which describe potential vegetation communities of a site based on climate and soil characteristics. The ESDs for the Sonoran Desert were first developed in the late 1980s and early 1990s and will be revised beginning in 2006 to incorporate new information that reflects the current state of knowledge of these ecosystems (D. Robinett, personal communication). When appropriate and feasible, state-and-transition models are intended to be incorporated into the updated ESDs. As a result, the planned updating of the ESDs for the Sonoran Desert provides an opportunity to incorporate contemporary ecological knowledge about Sonoran Desert ecosystem dynamics and potential grazing management strategies designed specifically for applicability to the Sonoran Desert within a testable framework.

We suggest that the information contained in this report provides a good starting point for identifying the types of information that may need to be considered when constructing state-and-transition models for Sonoran Desert plant communities. Clearly, information about climatic patterns, especially precipitation patterns and extreme temperatures, will need to be incorporated. This information should include estimates of the probabilities that particular precipitation or temperature events will occur at different temporal scales (Westoby and others 1989), their effect on vegetation dynamics, and how the probabilities can be used to inform appropriate grazing management responses. This will be especially important in the context of drought management. Cataloging states and transitions that reflect the role and intersection with grazing of the three periods of drought in causing vegetation change may be of value in this regard. An understanding of the preceding and the pulse-dynamic nature of plant and animal responses in the Sonoran Desert can facilitate setting appropriate stocking rates in response to ephemeral production that are flexible and reflect past, current, and projected moisture conditions. Other factors that should be incorporated into state-and-transition models for the Sonoran Desert are soil-related differences that affect susceptibility to accelerated erosion and significant differences in moisture holding capacity, presence and abundance of invasive non-native species, biological soil crusts, and other land-uses that may act synergistically with livestock grazing to cause undesirable transitions.

10.3.3 Issues Associated with the Application and Interpretation of the Equilibrium and Non-Equilibrium Paradigms

At the beginning of section 10.3 we pointed out the observation by Ellis and Swift (1988) that our perception of how particular ecosystems function determines the models and methods we advocate when attempting to modify or otherwise manipulate those ecosystems. Briske and others' (2003) critique of the current paradigms—equilibrium and non-equilibrium—that provide the conceptual framework for understanding vegetation dynamics on rangelands challenged the perception that the two paradigms were mutually exclusive and that particular ecosystems could operate under only one or the other dynamic. They concluded that ecosystems may express both equilibrium and non-equilibrium dynamics and that the rangeland debate should be redirected from a paradigm shift or dichotomy to paradigm integration. As a result, they further concluded that both event-driven (non-equilibrium) and continuous (equilibrium) vegetation dynamics must be incorporated into vegetation management on rangelands.

In this section we briefly address some of the conceptual issues that have hampered our understanding of whether equilibrium or non-equilibrium vegetation dynamics apply in any particular situation. In addition, we also address the misconception that livestock grazing has less impact on vegetation dynamics in non-equilibrium systems than in equilibrium systems. At the extreme are those that argue that stocking rates are completely irrelevant in non-equilibrium systems with extreme interannual climatic variability (Fernandez-Gimenez and Allen-Diaz 1999). We begin first with the question of whether domestic livestock grazing operates as an internal regulation factor even in equilibrium systems.

Domestic Livestock Grazing as an Internal Regulator Versus External System Driver

Within the context of the equilibrium paradigm, Briske and others (2003:603) stated that "grazing represents a biotic process that internally regulates system behaviour by imposing negative feedbacks on vegetative processes, rather than a disturbance that externally influences system behaviour (e.g., fire or climatic variability)." At the same time, however, the range model, which relies on the equilibrium paradigm for its underlying theoretical basis, assumes that livestock grazing produces progressive, directional community change that is in the direction opposite to the successional tendency (Westoby and others 1989). Except when grazing intensity is more or less in balance with other factors that may be controlling vegetation within an equilibrium dynamic and can be adjusted quickly to track closely any changes attributable to external drivers, it would seem that contemporary approaches to managing domestic livestock on rangelands would more often than not result in a situation that grazing acts as a disturbance or external driver no matter what the prevailing vegetation dynamics of the system. One of the range model's primary assumptions is that vegetation change caused by grazing is reversible. Of seemingly less consequence to the model's assumptions is whether grazing acts as an internal regulator or external driver of vegetation change. External drivers, depending on the magnitude of the force they exert on ecological system change, do not have to result in irreversible changes. The situations in which a contemporary grazing management strategy can operate as an internal regulator of system change would seem to be quite limited and rely on a broader set of criteria—such as the evolutionary history of a plant community or ecosystem with large native herbivores and its productivity—than simply whether the system is governed by primarily equilibrium or non-equilibrium dynamics. Managerial involvement of any significance would seem to reduce the likelihood that livestock grazing can be integrated sufficiently to become an integral component of a self-regulated ecological system. The preceding discussion could be an example of a situation in which theory is not perfectly aligned with its implementing management model.

In sum, the question whether under contemporary grazing management strategies, which as described in section 4.1.5 tend to result in on average herbivore biomass amounts an order of magnitude greater than natural grazing systems, livestock can ever act even within an equilibrium paradigm as a component of an ecological system's overall capacity for self regulation seems rather moot. Instead, except under perhaps quite limited circumstances, livestock grazing more likely routinely operates as an external disturbance agent in what would otherwise be characterized as either equilibrium or non-equilibrium systems. As a result, we suggest the more pertinent questions are: (1) how livestock grazing at various intensities impacts ecological systems of either type (or more generally along any part of the equilibrium-non-equilibrium continuum); (2) how should impacts be measured, including at what spatial and temporal scales; (3) and how should management adjustments be made when management objectives, such as avoiding undesirable transitions, are not being met?

Impacts of Livestock Grazing in Relation to Non-Equilibrium Systems

The acceptance of the non-equilibrium paradigm as a basis for describing rangeland vegetation dynamics seems to have led to the assumption that because plant production in highly variable climates is largely dependent on rainfall then the impacts of livestock grazing must be limited (Illius and O'Connor 1999). The occurrence of climatic variability, however, does not justify this assumption (Illius and O'Connor 1999, 2000, Briske and others 2003). We briefly review some studies that reach the conclusion that grazing has a non-negligible impact on vegetation dynamics in supposedly non-equilibrium systems; however, we first note that in environments characterized by relatively low and variable precipitation, relatively long periods of time may be needed to tease out the effects of grazing and climate (Briske and others 2003). So even though none of the studies described below took place in the Sonoran Desert, it is reasonable to conclude that similar studies may need to be conducted over relatively long periods of time to disentangle the effects of climate from livestock grazing in the Sonoran Desert before assuming that grazing has a negligible effect on vegetation because of the strong effects of climate variability.

Illius and O'Connor (1999, 2000) modeled spatially explicit plant-herbivore interactions and precipitation variability associated with African rangelands. They argued that despite the apparent lack of equilibrium, given the climatic variability, herbivore numbers are regulated in a density-dependent manner by the limited forage available in key resource areas. These resource areas are utilized in the dry season. During the wet season additional range can be used; however, here the system is generally non-equilibrium (except perhaps during drought) because the animal population is in long-term equilibrium with only the dry-season resources. Both spatially and temporally, the whole system is heterogenous with respect to whether it tends towards equilibrium, with equilibrium dynamics diminshing with distance from water and key resource areas and during the wet season. Illius and O'Connor (1999) argued that the wet-season range is more heavily used by animal poulations sustained by key resource areas than would occur in the absence of key resources. Uncoupling the animal population from the vegetation carries an increased risk of range degradation (that is, impaired primary and secondary production [Illius and O'Connor 1999]), especially during drought. The more key resource areas that are present relative to wet-season range the larger the animal population that can be sustained and the greater the risk of range degradation. Moreover, management interventions, such as increasing the number of watering points, have the effect of shifting a system with a low ratio of key resource areas to wet-season range toward a higher ratio, which again increases the risk of degradation. Additional explicit modeling by Illius and O'Connor (2000) confirmed many of the predictions made by Illius and O'Connor (1999). Moreover, the model predicted that under variable precipitation, animal numbers could build up such that they impose much higher defoliation intensities than under a constant precipitation regime. As a result, the model supported their prediction that grazing systems prone to climatic variability are more likely to be at risk of extreme herbivore impacts, because droughts may impose more intense and localized defoliation on vegetation than would occur in a system at or near equilibrium.

The lack of tight coupling between herbivores and vegetation in non-equilibrium systems is often used to support the hypothesis that free-roaming herbivores have less of an impact on vegetation in non-equilibrium systems than they do in equilibrium systems (Briske and others 2003). Even in ecological systems without high production zones (key resource areas) such as that studied by Ellis and Swift (1988), Briske and others (2003) offered an alternative interpretation that grazing impacts may be greater in such non-equilibrium systems because grazing intensity increases prior to herbivore mortality during periodic multi-year droughts.

The above studies demonstrate conditions under which livestock grazing may have greater ecological impacts in non-equilibrium than in equilibrium systems. To be concerned about livestock grazing impacts in non-equilibrium systems is not dependent on demonstrating that impacts are greater than in equilibrium systems. Current misconceptions about non-equilibrium dynamics imply that grazing-induced changes in vegetation are swamped by climatic events so that grazing impacts are negligible. A number of studies, however, argue against this point of view.

Fuhlendorf and others (2001) assessed the relative contribution of grazing intensity and climatic variability to rangeland vegetation change over a 44-year record within a semiarid savanna on the Edwards Plateau in Texas. Although the average annual precipitation is about 24 inches (600 mm), the interannual CV for precipitation was 33% (which as mentioned above is a proposed criterion to distinguish equilibrium from non-equilibrium systems). Fuhlendorf and others (2001) analyzed three contrasting grazing regimes and found that grazing intensity had a significant, directional effect on the relative composition of short- and mid-grass response groups as compositional shifts were significantly correlated with time since the grazing regimes were established. Interannual precipitation was not significantly correlated with response group composition; however, it was significantly correlated with total plant basal area, whereas time since imposition of grazing regimes was not. Both grazing regime and interannual precipitation were significantly correlated with total plant density. Fuhlendorf and others (2001) concluded that both grazing and climatic variability were important agents of change in the particular semiarid rangeland under study, but that they seemingly affect vegetation change on different temporal scales. For example, recovery of the mid-grass response group required about 25 years following the elimination of grazing, but the period of recovery and its pace was affected by climatic variability operating on a shorter time scale. As a result, grazing intensity established the long-term directional change in response group composition, but episodic climatic events defined the short-term rate and trajectory of the change while also determining the upper limit on total basal area.

Chase and others (2000) compiled data from published studies on the relationship between precipitation (proxy for primary productivity), plant and herbivore standing biomass (21 studies world-wide), and the results of large-herbivore exclosure experiments (54 studies extracted from Milchunas and Lauenroth [1993]) on plant abundance and composition in grasslands. Although the grassland sites considered within the two data sets included more than just semiarid grasslands, the patterns discerned may further elucidate the involvement of both grazing and climate on vegetation dynamics in grazed systems. Chase and others (2000) found that: (1) both producer and herbivore biomass increase across a precipitation gradient; (2) based on exclosure studies, the relative effect of large herbivores on plant biomass increases as precipitation decreases; and (3) the effect of herbivores on plant composition increases with precipitation. The data illustrate that though the intensity of the interaction may differ, herbivores can affect vegetation over a broad range of primary productivity (see also Briske and others 2003). Second, the nature of the interaction differs across the precipitation/productivity gradient. In their meta-analysis Milchunas and Lauenroth (1993) found only a loose relationship between changes in species composition along a productivity gradient with grazing. They suggested that the use of species composition criteria may lead to erroneous conclusions regarding the long-term ability of an ecological system to sustain productivity. The different nature of the plant-herbivore interaction at various points along the precipitation/productivity gradient may explain the different interpretations of similar data. For arid and semiarid rangelands the effect of herbivore selectivity on species composition may be negligible and the level of grazing intensity effect on plant biomass becomes a more important management concern (Bartolome 1993), whereas in more productive rangelands an increased expression of selective herbivory affects species composition with little effect on plant biomass (Chase and others 2000, Briske and others 2003).

A final caution is in order to the assumption that the impacts of livestock grazing can be ignored in ecological systems that experience extreme interannual variability in climate, especially precipitation. Watson and others (1996) suggested that an overemphasis on event-driven (non-equilibrium) dynamics at the expense of continuous ecological processes (equilibrium dynamics) may shift the responsibility for managing rangeland resources and processes from the manager to the vagaries of nature, with the implication that management is of little consequence. Instead, they argued that by paying attention to those components of systems that behave in a equilibrium manner, the manager can "condition" the resource to enhance the probability of desirable transitions or to increase its resilience to undesirable transitions. In the vernacular of Bestelmeyer and others' (2003) description of state-and-transition models, this can be thought of as managing the pathways within states.

Determining whether an Ecological System is Equilibrium or Non-Equilibrium or Both

As we mentioned in section 10.3.1, empirical evidence to support Briske and others' (2003) claim that both equilibrium and non-equilibrium dynamics occur in numerous ecological systems is frequently confounded by a number of methodological and system response issues. We discuss a few of these issues here. We already have indicated that long-term studies may be needed in ecosystems such as the Sonoran Desert to distinguish equilibrium versus non-equilibrium dynamics, so the issue of a lack of long-term studies in general may be obvious. We do not discuss this issue any further but conclude that it is an important consideration as exemplified by the study of Fuhlendorf and others (2001).

We discussed above the disproportionate responses among vegetation attributes to climate and grazing that can occur. These responses may not only indicate that individual ecological systems may express both equilibrum and non-equilibrium dynamics (Fuhlendorf and others 2001), but also supports the thesis of Fernandez-Gimenez and Allen-Diaz (1999) that our interpretation of whether a system is behaving in accordance with equilibrium or non-equilibrium dynamics depends on which variables we measure. These latter authors assessed the extent to which a non-equilibrium model (non-equilibrium persistent model of Ellis and Swift [1988]) as compared to the range model applied to three distinct Mongolian rangeland ecosystems: desert-steppe, steppe, and mountain-steppe. They concluded that ecosystem responses were more complicated than predicted by either model across all three ecosystems. The desert-steppe largely conformed to the non-equilibrium model but not in all variables measured. For the other two ecosystems, some variables showed concordance with the range model (grazing influence), others showed concordance with the non-equilibrium model (precipitation influenced), and still others were influenced by both grazing and precipitation. Fernandez-Gimenez and Allen-Diaz (1999) concluded that their results prevented clear acceptance or rejection of the non-equilibrium model for any of the three ecosystems.

Briske and others (2003) proposed that equilibrium dynamics may not represent a fundamental property of ecological systems. Instead, equilibrium dynamics may emerge as a characteristic of increasing spatial (and presumably temporal) scale. As a result, our ability to distinguish between either dynamic may depend on the spatial and temporal scale of our observations rather than recognition of processes or functions unique to each dynamic. Ecological patterns and processes are often scale-dependent. Few studies, however, have examined the relationship of livestock grazing as an ecological process to spatial scale (Fuhlendorf and Smeins 1999, Briske and others 2003). Fuhlendorf and Smeins (1999) determined that grazing can have a positive, a negative, or no influence on vegetation heterogeneity between sample units depending on the scale of observation. Similarly, Ryerson and Parmenter (2001) observed different vegetation responses to the removal of livestock and prairie dogs (*Cynomys* spp.) over a 20-year period that depended on the spatial scale of observation. They evaluated 30 sites within and adjacent to the Sevilleta National Wildlife Refuge in central New Mexico. At the site scale, vegetation exhibited species-specific and site-specific responses. The responses were not uniform in direction and the causative agents, removal of herbivores and climate dynamics, were not consistent between sites. The non-uniform, multi-directional changes of the vegetation at the site scale obscured detection of overall changes in perennial vegetation at the landscape scale (refuge plus surroundings), though annual forbs and plant litter did show increases at the landscape scale. They concluded that vegetation responses were clearly scale-dependent and that an analysis of both site and landscape scales is required to identify the underlying causes of observed vegetation change.

Briske and others (2003) also postulated that because the range model was developed explicitly to evaluate vegetation dynamics at the site scale, the continued and extensive use of individual sites as management units today for vegetation evaluation (Bestelmeyer and others 2003) has probably contributed to the perception that non-equilibrium vegetation dynamics occur more frequently than equilibrium dynamics. The implication is that if larger land areas were considered the existence of equilibrium dynamics may be more apparent (Briske and others 2003). One of Brown's (1994) performance criteria for models for rangeland management was their ability to detect change at both the community (site) and landscape scales. Explicitly incorporating scale considerations into model development and implementation could eliminate much of the confusion associated with the rangeland debate (Briske and others 2003).

10.4 CONCLUSIONS

No particular grazing management strategy can be expected to perform well in all ecosystems, whether the desired management objectives relate to vegetation condition or livestock performance. Approaches that are developed and tested in one ecosystem may not necessarily work in other ecosystems, especially if important environmental variables such as precipitation patterns are not congruent with strategy assumptions. Studies that evaluate grazing management strategies as practiced in the Sonoran Desert are extremely limited and none appear in the primary literature. An understanding of equilibrium and non-equilibrium dynamics and their appropriate incorporation into management models can assist in appropriately managing rangelands. Below we briefly summarize our conclusions relative to these two topics.

10.4.1 Grazing Management Strategies

Based on our review of the literature on grazing management strategies, we conclude that no currently described approach, including continuous grazing and each of the specialized grazing systems, is completely applicable to or appropriate for the Sonoran Desert ecosystem—inclusive of the Arizona Upland and Lower Colorado River Valley subdivisions—within their current formulations. Furthermore, in conjunction with our review of stocking rate and drought management considerations, we conclude that continuous grazing in which livestock are maintained within fenced allotments yearlong is not a feasible grazing management strategy on Sonoran Desert public lands. As a reminder, our assessment and conclusion does not address situations in which access to perennial or intermittent, stream-associated riparian habitats are involved.

We base the above conclusion on a number of factors evaluated in this report. First, the highly variable and overall low precipitation, which contributes to variable soil moisture conditions and overall low, highly variable, and patchy primary productivity, makes the Sonoran Desert marginal rangeland. Second, frequent and often extended drought makes Sonoran Desert plant communities and other natural resources susceptible to overgrazing even under relatively low stocking rates. Extended droughts can themselves represent a significant disturbance event even in the absence of anthropogenic impacts that only exacerbate the situation. As a result, BLM perennial allotments, which reflect implementation of a continuous grazing approach, may be problematic with respect to the capacity to destock them in a timely manner in response to drought. Seasonal drought each year also represents a period of stress for Sonoran Desert plant and animal communities. With reduced availability of forage during these times, livestock rely heavily on shrub and tree species within xeroriparian communities at a time when wildlife may be reliant on these same key resource areas. Third, the constant presence of livestock may not provide sensitive resources, such as biological soil crusts, time for recovery and growth. The lack of a long evolutionary history with large, hooved mammalian herbivores cautions against maintaining domestic livestock on a continuing basis at overall biomass levels that likely exceed the smaller biomass levels of the smaller, more nomadic native ungulates. Fourth, because we: (1) lack managed grazing studies specific to the Sonoran Desert ecosystem in general, (2) lack studies that evaluate livestock-plant community interactions associated with xeroriparian communities in particular, and (3) have a poor understanding of the consequences of continuous livestock presence on herbaceous vegetation and biological soil crusts within the Sonoran Desert, the literature does not support a finding that we know enough to set appropriate stocking densities that would permit continuous grazing and accomplish managed grazing objectives.

The conclusion that continuous grazing is not feasible does not imply that seasonal grazing or any particular specialized grazing system, as these approaches are currently described in the literature, is appropriate. A grazing management strategy should be tailored to the specific ecological realities of the Sonoran Desert. As such, our conclusion that continuous grazing is not feasible in the Sonoran Desert should not be construed to indicate that seasonal grazing or a particular grazing system should be implemented in its place without significant modification from what is described in the literature. Grazing systems involve adding rotation as a component of grazing management. The ability to rotate among allotments may or may not be an option open to BLM for management purposes. Furthermore, grazing systems have been used in the past on the basis of whether they can result in improved (or at least similar) livestock performance, as well as meet other needs. They tend to result in the use of higher stocking densities than continuous grazing to compensate for the inability to graze an area yearlong. Full compensation for the inability to continuously graze through use of higher stocking densities is not necessarily an achievable management objective within the Sonoran Desert.

The BLM’s use of ephemeral allotments could be an appropriate starting point for a Sonoran Desert-specific livestock grazing management strategy. For most of the Sonoran Desert, as described in this report, only grazing in response to winter rains may be feasible. The eastern margin of the Sonoran Desert, because it receives more reliable summer rains as well as winter rains, also may be amenable to manage for the monsoon pulse of vegetation. In both cases, the ability to set flexible stocking rates and to remove livestock quickly in response to changing conditions will be paramount. Drought conditions—cumulative and during the season of intended use—are the best guide to setting stocking rates in accordance with the three periods of drought: onset, during, and exiting. To enable time for plant reproduction, establishment of new plants, and restoration of vigor of existing plants, a period of deferment would be appropriate when drought conditions do not otherwise preclude grazing. If approached as an experiment, the establishment of appropriate stocking rates commensurate with soil moisture conditions and recovery from drought would enable the eventual setting of research-informed stocking rates that achieve managed grazing objectives. Sensitive resource areas, such as areas susceptible to accelerated soil erosion, are appropriate to protect from livestock grazing and, as a result, would be eliminated from the calculation of stocking rates. Appropriate measures of grazing intensity would provide the necessary benchmark to determine when livestock should be removed from the range, unless removal in response to the onset of seasonal drought occurs first.

10.4.2 Range Ecology Theory and Application

Our review of the rangeland debate also provides some insights applicable to livestock grazing management in the Sonoran Desert. Ecological theory often leads to specific management models and practices. The rangeland debate has involved both theory—equilibrium versus non-equilibrium dynamics—and the management implications of theory. The range model, based on equilibrium dynamics and a Clementsian view of plant ecology, is still widely used today. Non-equilibrium dynamics, and its management model associates, was meant to address the short comings of equilibrium theory and the range model, especially for arid and semiarid rangelands that are characterized by highly variable climatic patterns. Recent arguments have suggested that ecological systems my express both equilibrium and non-equilibrium dynamics. Because of their conceptual flexibility, state-and-transition models can accommodate both equilibrium and non-equilibrium dynamics.

Livestock grazing does not necessarily have negligible impacts in non-equilibrium systems, and in some cases the impacts may be greater than if a system operated under strictly equilibrium dynamics. Observations at appropriate spatial and temporal scales will be needed to indicate whether ecological systems combine both equilibrium and non-equilibrium dynamics. For ecosystems such as the Sonoran Desert, relatively long periods of time may be needed to disentangle the effects of grazing and climatic variability. Frequent drought makes the Sonoran Desert susceptible to the impacts of overgrazing, even when stocking rates are appropriate for what are considered average conditions. Sonoran Desert xeroriparian habitats may function as key resource areas (as used by Illius and O'Connor 1999, 2000) that provide forage during the dry season (seasonal drought); however, their presence along with water developments may increase the risk of range degradation if their role in ecosystem dynamics and grazing management is not appropriately considered.

CHAPTER 11 GENERAL CONCLUSIONS

In this chapter we draw three sets of general conclusions. First, we synthesize our findings from the literature to characterize those aspects of Sonoran Desert ecosystem dynamics that provide the ecological context for livestock grazing in the Sonoran Desert. Second, we broadly summarize our findings from the livestock grazing impact literature and its limitations. Third, based on our review of the literature on grazing management strategies, as well as the current status of range ecology theory, we draw conclusions regarding a framework for a grazing management strategy appropriate to the Sonoran Desert. Our conclusions are broadly applicable to the Arizona Upland and Lower Colorado River Valley subdivisions of the Sonoran Desert. Because we did not consider perennial or intermittent stream-associated riparian habitats that occur within the Sonoran Desert, our conclusions do not apply to those habitats.

11.1 ECOLOGICAL CONTEXT OF LIVESTOCK GRAZING IN THE SONORAN DESERT

The Sonoran Desert can be characterized in general terms as a species rich, structurally diverse, and low productivity, hot desert ecosystem in which individual species are adapted to extreme variability in the driving ecological processes. Precipitation—its quantity, timing, and variability—is the main environmental factor that in conjunction with local soil conditions determines vegetation production and species recruitment in Sonoran Desert plant communities. As a result, these events, as well as mortality, are episodic and can manifest as pulses of recruitment, production, and death. Annual plants in particular are highly dependent on adequate amounts of rainfall, which may only occur periodically and in an unpredictable fashion, for their recruitment, survival, and reproduction. In turn, ephemeral pulses of biomass are important events in the population cycles of native wildlife. Animals may time or scale their reproduction to these ephemeral pulses or otherwise use increases in available forage to restore depleted nutritional reserves in preparation for the next period of low productivity.

Biological soil crusts are under-appreciated for their role in maintaining ecological processes in the Sonoran Desert. In many ecosystems they are primary sources of fixed nitrogen, help maintain soil stability, and recover slowly (on the order of decades or more) from disturbance. Even though the literature specific to Sonoran Desert biological soil crusts is limited, the findings are consistent with what we know from other hot deserts. A reasonable hypothesis then, that remains to be fully tested, is that intact biological soil crusts play an important role in Sonoran Desert ecosystem dynamics.

As indicated above, rainfall is the primary driver of vegetation dynamics in the Sonoran Desert. It is characteristically low in quantity, unpredictable in the timing of its occurrence, and highly variable both spatially and temporally. Periods of drought, seasonal and long-term, are not uncommon. The native vegetation and wildlife of the Sonoran Desert have evolved in response to these characteristics. Our analysis of historic rainfall data across the region (along a west to east gradient) also indicates that the less overall rainfall an area receives, the more variable it is on an interannual basis. This pattern extends to the year-to-year variation in seasonal rainfall:

for example, the interannual coefficient of variation in summer monsoon rainfall is greater at the dry end of the gradient than at the wet end. Finally, the literature also suggests that vegetation does not necessarily respond immediately (adequately recover) to the return of average or above average rainfall following a period of drought.

Our assessment of the ecosystem dynamics of the Sonoran Desert in comparison to semiarid or non-desert ecosystems, such as semidesert grasslands, suggests that grazing strategies developed for the latter may have limited applicability to the Sonoran Desert. The unique ecological characteristics of the Sonoran Desert deserve specific attention when considering development and implementation of a grazing management strategy. We have detailed throughout this report the ecological characteristics of Sonoran Desert abiotic and biotic components that have relevence to livestock grazing management. In addition, we have addressed a number of controversial or contemporary topics, such as the herbivore optimization hypothesis, equilibrium and non-equilibrium dynamics, and pulse dynamics, that may bear on the development and implemention of appropriate grazing management strategies for the Sonoran Desert.

11.2 GENERAL CONCLUSIONS: GRAZING IMPACT LITERATURE

The literature on grazing impacts in the Sonoran Desert is both limited in its number and scope and sometimes mixed in its observations and conclusions. Unfortunately, the weakest aspect of the livestock impact literature we reviewed was that most of the individual studies were not conceived from the standpoint of assessing grazing management alternatives within the Sonoran Desert.

The literature on plant community impacts is illustrative of the general coverage of the literature. Most studies assessed the effects of release from historic grazing, few studies compared grazed and ungrazed sites simultaneously (the latter of which typically had experienced historic grazing), and only one study supposedly compared grazed sites with sites that had never been grazed. For all of these studies, detailed knowledge of historic or current stocking densities, timing and duration of grazing if not year-round, and how often grazing occurred generally were lacking. In some cases associated climatic information and site conditions were considered that enabled a more robust interpretation of a study’s findings. Finally, investigations involving Sonoran Desert xeroriparian plant communities and domestic livestock interactions, despite the relative importance of these communities for wildlife and livestock, have not been reported in the literature.

Despite the limitations of the impact studies described above, in combination they do indicate that livestock grazing can adversely impact soils, biological soil crusts, and plant community composition, structure, and function at the sites that were studied. Plant community impacts can manifest as decreased overall vegetation cover and density, reduced cover and density of palatable woody perennials and grasses, reduced species richness of annual plants, and increased species richness, cover, and density of non-native plants. Biological soil crusts deserve additional management attention, as they are susceptible to damage from various disturbance sources including livestock grazing.

Whether livestock grazing has a positive or negative effect on wildlife depends on the species under consideration—including their preferred forage and foraging habitat, the season of grazing and its intensity, and other site-specific factors. In general, most of the studies we reviewed showed that livestock grazing impacts wildlife indirectly by altering vegetation structure and/or composition. Of the species considered, the evidence for adverse impacts is most prevalent for bighorn sheep.

Specific cause and effect—historic grazing versus current grazing versus cyclical weather patterns—were not always possible to tease out in the various studies. As a result, uncertainty may exist relative to the applicability of findings to specific current grazing practices (which typically were not quantified) and the small breadth of the studies considered in terms of locales and plant communities; however, this uncertainty should not be viewed as evidence that livestock grazing, as currently practiced in the Sonoran Desert, does not have clear, demonstrated significant impacts within the Sonoran Desert ecosystem. The lack of studies and confounding factors that can obscure clear study results can cut both ways depending on the decision-making context. Most importantly, we did not find, based on the available literature, evidence to support what appropriate managed livestock grazing may look like in the Sonoran Desert because apparently such studies have not been conducted.

11.3 GENERAL CONCLUSIONS: GRAZING MANAGEMENT STRATEGY LITERATURE

No particular grazing management strategy can be expected to perform well in all ecosystems, whether the desired management objectives relate to vegetation condition or livestock performance. Approaches that are developed and tested in one ecosystem may not necessarily work in other ecosystems, especially if important environmental variables such as precipitation patterns are not congruent with strategy assumptions. Studies that evaluate grazing management strategies in the Sonoran Desert are extremely limited and none appear in the primary literature.

Based on our review of the literature on grazing management strategies, we conclude that no currently described approach, including continuous grazing and each of the specialized grazing systems, is completely applicable to or appropriate for the Sonoran Desert ecosystem within their current formulations. Furthermore, in conjunction with our review of stocking rate and drought management considerations, we conclude that continuous grazing in which livestock are maintained within fenced allotments yearlong is not a feasible grazing management strategy on Sonoran Desert public lands.

The conclusion that continuous grazing is not feasible does not imply that seasonal grazing or any particular specialized grazing system, as these approaches are currently described in the literature, is appropriate. A grazing management strategy should be tailored to the specific ecological realities of the Sonoran Desert.

The BLM's use of ephemeral allotments could be an appropriate starting point for a Sonoran Desert-specific livestock grazing management strategy. For most of the Sonoran Desert, as described in this report, only grazing in response to winter rains may be feasible. The eastern margin of the Sonoran Desert, because it receives more reliable summer rains as well as winter rains, also may be amenable to manage for the monsoon pulse of vegetation. In both cases, the ability to set flexible stocking rates and to remove livestock quickly in response to changing conditions will be paramount. Drought conditions—cumulative and during the season of intended use—are the best guide to setting stocking rates in accordance with the three periods of drought: onset, during, and exiting. To enable time for plant reproduction, establishment of new plants, and restoration of vigor of existing plants, a period of deferment would be appropriate when drought conditions do not otherwise preclude grazing. If approached as an experiment, the establishment of appropriate stocking rates commensurate with soil moisture conditions and recovery from drought would enable the eventual setting of research-informed stocking rates that achieve managed grazing objectives. Sensitive resource areas, such as areas susceptible to accelerated soil erosion, are appropriate to protect from livestock grazing and, as a result, would be eliminated from the calculation of stocking rates. Appropriate measures of grazing intensity would provide the necessary benchmark to determine when livestock should be removed from the range, unless removal in response to the onset of seasonal drought occurs first.

CHAPTER 12 LITERATURE CITED

Abou-Haidar, F. 1989. Influence of Livestock Grazing on Saguaro Seedling Establishment. Unpublished master's thesis. Arizona State University, Tempe. 50 p.

Abou-Haidar, F. 1992. Influence of livestock on saguaro seedling establishment. Pages 57–61 in C.P. Stone and E.S. Bellatoni (eds.), Proceedings of the Symposium on Research in Saguaro National Monument. 23–24 January 1991, Tucson, Arizona. National Park Service, Rincon Institute, and Southwest Parks and Monument Association, Tucson, Arizona.

[AIDTT] Arizona Interagency Desert Tortoise Team. 2000. Status of the Sonoran Population of the Desert Tortoise in Arizona: An Update. R.C. Averill-Murray (ed.). Arizona Interagency Desert Tortoise Team and Arizona Game and Fish Department, Phoenix.

Anderson, H.L. 1977. Barbed wire impales another Great Horned Owl. Raptor Research 11:71–72.

Andrew, M.H. 1988. Grazing impact in relation to livestock watering points. Trends in Evolutionary Ecology 3:336–339.

Austin, A.T., L. Yahdjian, J.M. Stark, J. Belnap, A. Porporato, U. Norton, D.A. Ravetta, and S.M. Schaeffer. 2004. Water pulses and biogeochemical cycles in arid and semiarid ecosystems. Oecologia 141:221–235.

Averill-Murray, A., and R.C. Averill-Murray. 2002. Distribution and Density of Desert Tortoises at Ironwood Forest National Monument, with Notes on Other Vertebrates. Nongame and Endangered Wildlife Program Technical Report 193. Arizona Game and Fish Department, Phoenix.

Averill-Murray, R.C. 2002. Reproduction of *Gopherus agassizii* in the Sonoran Desert, Arizona. Chelonian Conservation and Biology 4:295–301.

Bahre, C.J. 1991. Livestock grazing. Pages 108–123 in C.J. Bahre, A Legacy of Change. University of Arizona Press, Tucson.

Balling, R.C., Jr. 1988. The climatic impact of a Sonoran vegetation discontinuity. Climatic Change 13:99–109.

Balling, R.C., Jr., J.M. Klopatek, M.L. Hildebrandt, C.K. Moritz, and C.J. Watts. 1998. Impacts of land degradation on historical temperature records from the Sonoran Desert. Climatic Change 40:669–681.

Barrett, S.L., and T.B. Johnson. 1990. Status Summary for the Desert Tortoise in the Sonoran Desert. Report to the U.S. Fish and Wildlife Service, Albuquerque, New Mexico. 115 p.

Barth, R.C., and J.O. Klemmedson. 1982. Amount and distribution of dry matter, nitrogen, and organic carbon in soil-plant systems of mesquite and palo verde. Journal of Range Management 35:412–418.

Bartolome, J.W. 1993. Application of herbivore optimization theory to rangelands of the western United States. Ecological Applications 3:27–29.

Belnap, J. 1992. Characteristics of cyanobacterial-lichen soil crusts in long-term saguaro monitoring plots. Pages 259–262 in C.P. Stone and E.S. Bellantoni (eds.), Proceedings of the Symposium on Research in Saguaro National Monument. 24–24 January 1991, Tucson, Arizona. National Park Service, Rincon Institute and Southwesst Parks and Monument Association, Tucson, Arizona.

Belnap, J. 1995. Surface disturbances: their role in accelerating desertification. Environmental Monitoring and Assessment 37:39–57.

Belnap, J. 2001a. Comparative structure of physical and biological soil crusts. Pages 177–191 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Belnap, J. 2001b. Factors influencing nitrogen fixation and nitrogen release in biological soil crusts. Pages 241–262 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Belnap, J. 2001c. Biological soil crusts and wind erosion. Pages 339–347 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Belnap, J. 2002. Impacts of off-road vehicles on nitrogen cycles in biological soil crusts: resistance in different U.S. deserts. Journal of Arid Environments 52:155–165.

Belnap, J., and D. Eldridge. 2001. Disturbance and recovery of biological soil crusts. Pages 363–383 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Belnap, J., and O.L. Lange. 2001. Structure and functioning of biological soil crusts: a synthesis. Pages 471–479 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Belnap, J., R. Prasse, and K.T. Harper. 2001a. Influence of biological soil crusts on soil environments and vascular plants. Pages 281–300 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Belnap, J., J.H. Kaltenecker, R. Rosentreter, J. Williams, S. Leonard, and D. Eldridge. 2001b. Biological Soil Crusts: Ecology and Management. Technical Reference 1730–2. U.S. Department of the Interior, Bureau of Land Management, National Science and Technology Center, Denver, Colorado. 110 + v p.

Belsky, A.J. 1986. Does herbivory benefit plants? A review of the evidence. The American Naturalist 127:870–892.

Belsky, A.J., W.P. Carson, C.L. Jensen, and G.A. Fox. 1993. Overcompensation by plants: herbivore optimization or red herring? Evolutionary Ecology 7:109–121.

Bestelmeyer, B.T., and J.A. Wiens. 2001. Ant biodiversity in semiarid landscape mosaics: The consequences of grazing vs. natural heterogenity. Ecological Applications 11:1123–1140.

Bestelmeyer, B.T., J.R. Brown, K.M. Havstad, R. Alexander, G. Chavez, and J.E. Herrick. 2003. Development and use of state-and-transition models for rangelands. Journal of Range Management 56:114–126.

Bissonette, J.A., and M.J. Steinkamp. 1996. Bighorn sheep response to ephemeral habitat fragmentation by cattle. Great Basin Naturalist 56:319–325.

Bleich, V.C, J.D. Wehausen, and S.A. Holl. 1990. Desert-dwelling mountain sheep: conservation implications of a naturally fragmented distribution. Conservation Biology 4:383–390.

[BLM] Bureau of Land Management, Coronado National Forest, Arizona Game and Fish Department, and The Nature Conservancy. 1998. Final Muleshoe Ecosystem Management Plan and Environmental Assessment. U.S. Department of the Interior, Bureau of Land Management, Tucson Field Office, Arizona. 206 p.

Blydenstein, J. 1966. Root systems of four desert grassland species on grazed and protected sites. Journal of Range Management 19:93–95.

Blydenstein, J., C.R. Hungerford, G.I. Day, and R.R. Humphrey. 1957. Effect of domestic livestock exclusion on vegetation in the Sonoran Desert. Ecology 38:522–526.

Bock, C.E., and B. Webb. 1975. Birds as grazing indicator species in southeastern Arizona. Journal of Wildlife Management 48:1045–1049.

Bock, C.E., J.H. Bock, W.R. Kenney, and V.M. Hawthorne. 1984. Responses of birds, rodents, and vegetation to livestock exclosure in a semidesert grassland site. Journal of Range Management 37:239–242.

Bostick, V. 1990. The desert tortoise in relation to cattle grazing. Rangelands 12:149–151.

Bowers, J.E. 1981. Catastrophic freezes in the Sonoran Desert. Desert Plants 2:232–236.

Bowers, J.E. 2002. Regeneration of triangle-leaf bursage (*Ambrosia deltoidea:* Asteracea): germination behavior and persistent seed bank. Southwestern Naturalist 47:449–453.

Bowers, J.E., and R.M. Turner. 2002. The influence of climatic variability on local population dynamics of *Cercidium microphyllum* (foothill paloverde). Oecologia 130:105–113.

Bowers, J.E., R.M. Turner, and T.L. Burgess. 2004. Temporal and spatial patterns in emergence and early survival of perennial plants in the Sonoran Desert. Plant Ecology 172:107–119.

Briske, D.D. 1993. Grazing optimization: a plea for a balanced perspective. Ecological Applications 3:24–26.

Briske, D.D., and J.H. Richards. 1995. Plant responses to defoliation: a physiological, morphological and demographic evaluation. Pages 635–710 in D.J. Bedunah and R.E. Sosebee (eds.), Wildland Plants: Physiological Ecology and Developmental Morphology. Society for Range Management, Denver, Colorado.

Briske, D.D., S.D. Fuhlendorf, and F.E. Smeins. 2003. Vegetation dynamics on rangelands: a critique of the current paradigms. Journal of Applied Ecology 40:601–614.

Brooks, M.L. 1995. Benefits of protective fencing to plant and rodent communities of the western Mojave Desert, California. Environmental Management 19:65–74.

Brooks, M.L. 1999. Effects of protective fencing on birds, lizards, and black-tailed hares in the western Mojave Desert. Environmental Management 23:387–400.

Brooks, M.L., and T.C. Esque. 2002. Alien plants and fire in desert tortoise (*Gopherus agassizii*) habitat of the Mojave and Colorado Deserts. Chelonian Conservation and Biology 4:330–340.

Brooks, M.L., and D.A. Pyke. 2001. Invasive plants and fire in the deserts of North America. Pages 1–14 in K.E.K. Galley and T.P. Wilson (eds.), Proceedings of the Invasive Species Workshop: the Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: the First National Congress on Fire Ecology, Prevention, and Management. Miscellaneous Publication No. 11. Tall Timbers Research Station, Tallahassee, Florida.

Brooks, M.L., J.R. Matchett, and K.H. Berry. In Press. Effects of livestock watering sites on plant communities in the Mojave Desert, USA. Journal of Arid Environments.

Brooks, M.L., C.M. D'Antonio, D.M. Richardson, J.B. Grace, J.E. Keeley, J.M. DiTomaso, R.J. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of invasive alien plants on fire regimes. BioScience 54:677–688.

Brotherson, J.D., S.R. Rushforth, and J.R. Johansen. 1983. Effects of long-term grazing on cryptogram crust cover in Navajo National Monument, AZ. Journal of Range Management 36:579–581.

Brown, D.E. 1978. The vegetation and occurrence of chaparral and woodland flora on isolated mountains within the Sonoran and Mojave Deserts in Arizona. Journal of the Arizona-Nevada Academy of Science 13:7–12.

Brown, D.E. (ed.). 1994a. Biotic Communities: Southwestern United States and Northwestern Mexico. University of Utah Press, Salt Lake City.

Brown, D.E. 1994b. Out of Africa. Wilderness Winter:24–31.

Brown, D.E., and Lowe C.D. 1980. Biotic Communities of the Southwest (Map at Scale 1:1,000,000). General Technical Report RM-78. U.S. Department of Agriculture, Forest Service, Ogden, Utah.

Brown, J.H., and B.A. Harney. 1993. Population and community ecology of hereromyid rodents in temperate habitats. Pages 618–651 in H.H. Genoways and J.H. Brown (eds.), Biology of the Heteromyidae. American Society Mammalogists, Special Publication No. 10. Provo, Utah.

Brown, J.R. 1994. State and transition models for rangelands. 2. Ecology as a basis for rangeland management: performance criteria for testing models. Tropical Grasslands 28:206–213.

Bryant, F.C., B.E. Dahl, R.D. Pettit, and C.M. Britton. 1989. Does short-duration grazing work in arid and semiarid regions? Journal of Soil and Water Conservation July-August:290–296.

Bryant, N.A., L.F. Johnson, A.J. Brazel, R.C. Balling, and C.F. Hutchingson. 1990. Measuring the effect of overgrazing in the Sonoran Desert. Climatic Change 17:243–264.

Burgess, T.L. 1995. Desert grassland, mixed shrub savanna, shrub steppe, or semidesert scrub? The dilemma of coexisting growth forms. Pages 31–67 in M.P. McClaran and T.R. Van Devender (eds.), The Desert Grassland. The University of Arizona Press, Tucson.

Burgess, T.L., J.E. Bowers, and R.M. Turner. 1991. Exotic plants at the Desert Laboratory, Tucson, Arizona. Madroño 38:96–114.

Búrquez, A., A. Martínez-Yrízar, R.S. Felger, and D. Yetman. 1999. Vegetation and habitat diversity at the southern edge of the Sonoran Desert. Pages 36–67 in R.H. Robichaux (ed.), Ecology of Sonoran Desert Plants and Plant Communities. The University of Arizona Press, Tucson.

Bury B.R., and J.A.Whelan. 1984. Ecology and management of the bullfrog. Resource Publication 155. U.S. Department of the Interior, Fish and Wildlife Service. Washington, D.C. 23 p.

Busack, S.D., and R.B. Bury. 1974. Some effects of off-road vehicles and sheep grazing on lizard populations in the Mojave Desert. Biological Conservation 6:179−183.

Cable, J.M., and T.E. Huxman. 2004. Precipitation pulse size effects on Sonoran Desert soil microbial crusts. Oecologia 141:317−324.

Caldwell, M.M. 1984. Plant requirements for prudent grazing. Pages 117–152 in Developing Strategies for Rangeland Management: A report Prepared by the Committee on Developing Strategies for Rangeland Management. National Research Council/National Academy of Sciences. Westview Press, Boulder, Colorado.

Cameron, R.E. 1960. Communities of soil algae occurring in the Sonoran Desert in Arizona. Journal of Arizona Academy of Science 1:85–88.

Cameron, R.E., and W.H. Fuller. 1960. Nitrogen fixation by some algae in Arizona soils. Soil Science Society Proceedings 24:353–356.

Chase, J.M., M.A. Leibold, A.L. Downing, and J.B. Shurin. 2000. The effects of productivity, herbivory, and plant species turnover in grassland food webs. Ecology 81:2485–2497.

Chesson, P., R.L.E. Gebauer, S. Schwinning, N. Huntly, K. Wiegand, M.S.K. Ernest, A. Sher, A. Novoplansky, and J.F. Weltzin. 2004. Resource pulses, species interactions, and diversity maintenance in arid and semi-arid environments. Oecologia 141:236–253.

Chew, R.M. 1982. Changes in herbaceous and suffrutescent perennials in grazed and ungrazed desertified grassland in southeastern Arizona, 1958–1978. American Midland Naturalist 108:159–169.

Clemensen, A.B. 1987. Cattle, Copper, and Cactus: The History of Saguaro National Monument, Arizona. National Park Service, Denver Service Center.

Comrie, A.C., and E.C. Glenn. 1998. Principal components-based regionalization of precipitation regimes across the southwest United States and northern Mexico, with an application to monsoon precipitation variability. Climate Research 10:201–215.

Cooke, R.U., and R.W. Reeves. 1976. Arroyos and Environmental Change in the American South-West. Oxford University Press, London.

Craig, T.H., and L.R. Powers. 1976. Raptor mortality due to drowning in a livestock watering tank. Condor 78:412.

D'Antonio, C.M., and P.M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics 23:63–87.

Davenport, D.W., D.D. Breshears, B.P. Wilcox, and C.D. Allen. 1998. Viewpoint: sustainability of piñon-juniper ecosystems—a unifying perspective of soil erosion thresholds. Journal of Range Management 51:231–240.

Dickinson, V.M., J.L. Jarchow, M.H. Trueblood, and J.C. deVos. 2002. Are free-ranging Sonoran Desert tortoises healthy? Pages 242–264 in T.R. Van Devender (ed.), The Sonoran Desert Tortoise: Natural History, Biology, and Conservation. The University of Arizona Press and Arizona-Sonora Desert Museum. Tucson.

Dimmit, M. 2000. *Cactaceae* (cactus family). Pages 183–218 in S.J. Phillips and P. Wentworth Comus (eds.), A Natural History of the Sonoran Desert. Arizona-Sonora Desert Museum Press, Tucson, Arizona.

Dodd N.L., and W.W. Brady. 1986. Cattle grazing influences on vegetation of a sympatric desert bighorn range in Arizona. Desert Bighorn Council Transactions 30:8–13.

Durfee, J.A. 1988. Response of Mohave Desert Communities to Release from Grazing Pressure. Unpublished master's thesis. Brigham Young University, Provo, Utah. 28 p.

Dyer, M.I., C.L. Turner, and T.R. Seastedt. 1993. Herbivory and its consequences. Ecological Applications 31:10–16.

Dyksterhuis, E.J. 1949. Condition and management of range land based on quantitative ecology. Journal of Range Management 2:104–115.

East, R. 1984. Rainfall, soil nutrient status and biomass of large African savanna mammals. African Journal of Ecology 22:245–270.

Elderidge, D.J. 2001. Biological soil crusts and water relations in Australian deserts. Pages 315–326 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Ellis, J.E., and D.M. Swift. 1988. Stability of African pastoral ecosystems: alternate paradigms and implications for development. Journal of Range Management 41:450–459.

Evans, R.D., and J.R. Johansen. 1999. Microbiotic crusts and ecosystem processes. Critical Reviews in Plant Sciences 18:183–225.

Evans, R.D., and O.L. Lange. 2001. Biological soil crusts and ecosystem nitrogen and carbon dynamics. Pages 263–279 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Fagerstone, K.A., and C.A. Ramey. 1996. Rodents and lagomorphs. Pages 83-132 in P.R. Krausman (ed.), Rangeland Wildlife. 1st edition. The Society for Range Management, Denver, Colorado.

Farnsworth, R.B., E.M. Romney, and A. Wallace. 1978. Nitrogen fixation by microfloral-higher plant associations in arid to semiarid environments. Pages 17–19 in N.E. West and J. Skujiņš (eds.), Nitrogen in Desert Ecosystems. US/IBP Synthesis Series 9. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Faust, W.F. 1970. The Effect of Algal-Mold Crusts on the Hydrologic Processes of Infiltration, Runoff, and Soil Erosion under Simulated Conditions. Unpublished master's thesis. University of Arizona, Tucson.

Felker, P., and P.R. Clark. 1980. Nitrogen fixation (acetylene reduction) and cross inoculation in 12 *Prosopis* (mesquite) species. Plant and Soil 57:177–186.

Felker, P., and P.R. Clark. 1981. Nodulation and nitrogen fixation (acetylene reduction) in desert ironwood (*Olneya tesota*). Oecologia 48:292–293.

Fernandez-Gimenez, M.E., and B. Allen-Diaz. 1999. Testing a non-equilibrium model of rangeland variation dynamics in Mongolia. Journal of Applied Ecology 36:871–885.

[FWIE] Fish and Wildlife Information Exchange. 1996. Species Globe-berry, Tumamoc. Species ID ESIS702036. Last updated July 16, 2003. Available http://fwie.fw.vt.edu/WWW/esis/lists/e702036.htm. (Accessed June 2004).

Fitzner, R.E. 1975. Owl mortality on fences and utility lines. Raptor Research 9:55–57.

Fleischner, T.L. 1994. Ecological costs of livestock grazing in western North America. Conservation Biology 8:629–644.

Flesch, A.D. 2003. Distribution, Abundance, and Habitat of Cactus Ferruginous Pygmy-Owls in Sonora, Mexico. Unpublished master's thesis. University of Arizona, Tucson. 161 p.

Fletcher, J.E. 1960. Some effects of plant growth on infiltration in the Southwest. Pages 51–63 in B.H. Warnock and J.L. Gardner (eds.), Symposium on Water Yield in Relation to Environment in the Southwestern United States. Southwest Rocky Mountain Division, American Association for the Advancement of Science, Washington D.C.

Fletcher, J.E., and W.P. Martin. 1948. Some effects of algae and molds in the rain-crust of desert soils. Ecology 29:95–100.

Fletcher, J.E., D.L. Sorensen, and D.B. Porcella. 1978. Erosional transfer of nitrogen in desert ecosystems. Pages 171–181 in N.E. West and J. Skujiņš (eds.), Nitrogen in Desert Ecosystems. US/IBP Synthesis Series 9. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Friedel, M.H. 1991. Range condition assessment and the concept of thresholds: a viewpoint. Journal of Range Management 44:422–426.

Fuhlendorf, S.D., and F.E. Smeins. 1999. Scaling effects of grazing in a semi-arid grassland. Journal of Vegetation Science 10:731–738.

Fuhlendorf, S.D., D.D. Briske, and F.E. Smeins. 2001. Herbaceous vegetation change in variable rangeland environments: the relative contribution of grazing and climatic variability. Applied Vegetation Science 4:177–188.

Fuller, W.H., R.E. Cameron, and N.R. Raica, Jr. 1960. Fixation of nitrogen in desert soils by algae. Transactions 7th International Congress of Soil Science 2:617–624.

[GAO] U.S. General Accounting Office. 1991. Rangeland Management: BLM's Hot Desert Grazing Program Merits Reconsideration. GAO/RECD–92–12. United States General Accounting Office, Washington, D.C. 68 p.

Gardner, J.L. 1951. Vegetation of the creosotebush area of the Rio Grande Valley in New Mexico. Ecological Monographs 21:379–403.

Geraghty and Miller, Inc and SWCA, Inc. 1997. Acuña cactus survey report on portions of the Barry M. Goldwater Range. Prepared for Luke Air Force Base. Geraghty and Miller, Phoenix, Arizona.

Germano, D.J., and C.R. Hungerford. 1981. Reptile population changes with manipulation of Sonoran Desert scrub. Great Basin Naturalist 41:129–138.

Glinski, R.L., and D.E. Brown. 1982. Mesquite (*Prosopis juliflora*) response to severe freezing in southeastern Arizona. Journal of the Arizona-Nevada Academy of Science 17:15–18.

Gold, W.G., and M.M. Caldwell. 1989. The effects of the spatial pattern of defoliation on regrowth of a tussock grass. I. Growth responses. Oecologia 80:289–296.

Goldberg, D.E., and R.M. Turner. 1986. Vegetation change and plant demography in permanent plots in the Sonoran Desert. Ecology 67:695–712.

Grover, M.C., and L.A. DeFalco. Desert tortoise (*Gopherus agassizii*): status-of-knowledge outline with references. General Technical Report INT-316. U.S. Department of the Agriculture, Forest Service, Ogden, Utah. 134 p.

Hadley, N.F., and S.R. Szarek. 1981. Productivity of desert ecosystems. BioScience 31:747–753.

Halvorson, W.L., and D.T. Patten. 1975. Productivity and flowering of winter ephemerals in relation to Sonoran Desert shrubs. American Midland Naturalist 93:311–319.

Hanley, T.A., and W.W. Brady. 1977. Feral burro impact on a Sonoran Desert range. Journal of Range Management 30:374–377.

Hayes Jr., J.U. 2004. Perennial Grass Abundance and Livestock Management in the Arid Rangelands of the Sif-Oidak-Oidak District, Tohono O'Odham Nation. Unpublished master's thesis. University of Arizona, Tucson. 165 p.

Helbsing, T., and N. Fisher. 1992. Demographic patterns of saguaro and fish-hook barrel cactus populations in the cactus forest of Saguaro National Monument. Pages 13–22 in C.P. Stone and E.S.

Bellantoni (eds.), Proceedings of the Symposium on Research in Saguaro National Monument. 23–24 January 1991, Tucson, Arizona. National Park Service, Rincon Institute and Southwewst Parks and Monument Association, Tucson, Arizona.
Heske, E.J., and M. Campbell. 1991. Effects of an 11-year livestock exclosure on rodent and ant numbers in the Chihuahuan Desert, southeastern Arizona. Southwestern Naturalist 36:89–93.

Holechek, J.L. 1983. Considerations concerning grazing systems. Rangelands 5:208–211.

Holechek, J.L., T.T. Baker, and J.C. Boren. 2004a. Impacts of Controlled Grazing versus Grazing Exclusion on Rangeland Ecosystems: What We Have Learned. Range Improvement Task Force Report 57. New Mexico State University, Las Cruces. 42 p.

Holechek, J.L., R.D. Pieper, and C.H. Herbel. 2004b. Range Management: Principles and Practices. 5th edition. Pearson Prentice Hall, New Jersey. 607 p.

Holechek, J.L., H. Gomes, F. Molinar, D. Galt, and R. Valdex. 2000. Short-duration grazing: the facts in 1999. Rangelands 22:18-22.

Hovorka, M.D. 1996. The Impacts of Livestock Grazing on Sonoran Desertscrub Vegetation, Insect and Insectivorous Bat Communities. Unpublished master's thesis. York University, Toronto, Ontario. 84 p.

Howery, L. 1999. Rangeland Management Before, During, and After Drought. Arizona Cooperative Extension Bulletin AZ1136. University of Arizona, Tucson.

Howery, L.D., J.E. Sprinkle, and J.E. Bowns. 2000. A Summary of Livestock Grazing Systems Used on Rangelands in the Western United States and Canada. Arizona Cooperative Extension Bulletin AZ1184. University of Arizona, Tucson.

Howland, J.M., and J.C. Rorabaugh. 2002. Conservation and protection of the desert tortoise in Arizona. Pages 334–354 in T.R. Van Devender (ed.), The Sonoran Desert Tortoise: Natural History, Biology, and Conservation. The University of Arizona Press and Arizona-Sonora Desert Museum. Tucson.

Hughes, L.E. 1982. A grazing system in the Mohave Desert. Rangelands 4:256–257.

Humphrey, R.R. 1963. The role of fire in the desert and desert grassland areas of Arizona. Proceedings of the Tall Timbers Fire Ecology Conference 2:45–61.

Humphrey, R.R. 1974. Fire in the deserts and desert grassland of North America. Pages 365–401 in T.T. Koslowski and C.E. Ahlgren (eds.), Fire and Ecosystems. Academic Press, New York.

Hunter, J.E. 1991. Grazing and pocket gopher abundance in a California annual grassland. Southwestern Naturalist 36:117–118.

Huxman, T.E., K.A. Snyder, D. Tissue, A.J. Leffler, K. Ogle, W.T. Pockman, D.R. Sandquist, D.L. Potts, and S. Schwinning. 2004. Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. Oecologia 141:254–268.

Illius, A.W., and T.G. O'Connor. 1999. On the relevance on nonequilibrium concepts to arid and semiarid grazing systems. Ecological Applications 9:788–813.

Illius, A.W., and T.G. O'Connor. 2000. Resource heterogenity and ungulate population dynamics. Oikos 89:283–294.

Johansen, J.R., and L.L. St. Clair. 1986. Cryptogamic soil crusts: recovery from grazing near Camp Floyd State Park, Utah. Great Basin Naturalist 46:632–640.

Johnson, R.R., and L.T. Haight. 1985. Avian use of xeroriparian ecosystems in the North American warm deserts. Pages 156–160 in R.R. Johnson, C.D. Ziebell, D.R. Patton, P.F. Ffolliott, and R.H. Hamre (tech. coords.), Riparian Ecosystems and their Management: Reconciling Conflicting Uses. First North American Riparian Conference, April 16–18, Tucson, Arizona. General Technical Report RM-120. Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Fort Collins, Colorado.

Jones, A. 2000. Effects of cattle grazing on North American arid ecosystems: a quantitative review. Western North American Naturalist 60:155–164.

Jones, A. 2001. Review and Analysis of Cattle Grazing Effects in the Arid West, With Implications for BLM Grazing Management in Southern Utah. The Wild Utah Project, Utah.

Jones, K.B. 1981. Effects of grazing on lizard abundance and diversity in western Arizona. Southwestern Naturalist 26:107–115.

Jones, Z.F., C.E. Bock, and J.H. Bock. 2003. Rodent communities in a grazed and ungrazed Arizona grassland, and a model of habitat relationships among rodents in southwestern grass/shrublands. American Midland Naturalist 149:384–394.

Kade, A., and S.D. Warren. 2002. Soil and plant recovery after historic military disturbance in the Sonoran Desert, USA. Arid Land Research and Management 16:231–243.

Kie, J.G., C.J. Evans, E.R. Loft, and J.W. Menke. 1991. Foraging behavior by mule deer: the influence of cattle grazing. Journal of Wildlife Management 55:665–674.

Klipple, G.E., and R.E. Bement. 1961. Light grazing—is it economically feasible as a range-improvement practice. Journal of Range Management 14:57–62.

Knight, R.L., J. Skriletz, and D.C. Ryan. 1980. Four additional cases of bird mortality on barbed-wire fences. Western Birds 11:202.

Kochert, M., B.A. Millsap, and K. Steenhof. 1988. Effects of livestock grazing on raptors with emphasis on the southwestern U.S. Pages 325–334 in Glinski R.L., B.G. Pendleton, Moss. M.B., M.N. LeFranc, B.A. Millsap Jr., and S.W. Hoffman (eds.), Proceedings of the Southwest Raptor Management Symposium and Workshop. 21–24 May 1986, Tucson, Arizona. National Wildlife Federation, Washington, D.C.

Krausman, P.R. 2000. An introduction to the restoration of bighorn sheep. Restoration Ecology 8(4S):3–5.

Krausman, P.R., B.D. Jansen, J.R. Heffelfinger, C.R. Anderson, J.C. DeVos Jr., and T.D. Noon. In Press. Desert bighorn sheep, disease, and urbanization. In Proceedings of the Sixth International Game Ranching Symposium. In Press, Paris, France.

Krausman, P.R., A.J. Kuenzi, R.C. Etchberger, K.R. Rautenstrauch, L.L. Ordway, and J.J. Hervert. 1997. Diets of desert mule deer. Journal of Range Management 50:513–522.

Krausman, P.R., K.R. Rautenstrauch, and B.D. Leopold. 1985. Xeroriparian systems used by desert mule deer in Texas and Arizona. Pages 144–149 in R.R. Johnson, C.D. Ziebell, D.R. Patton, P.F. Ffolliott, and R. H. Hamre (tech. coords.), Riparian Ecosystems and their Management: Reconciling Conflicting Uses. First North American Riparian Conference, April 16–18, 1985, Tucson, Arizona. General Technical Report RM-120. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Krausman, P.R., A.V. Sandoval, and R.C. Etchberger. 1999. Natural history of desert bighorn sheep. Pages 139–191 in R. Valdez and P.R. Krausman (eds.), Mountain Sheep of North America. The University of Arizona Press, Tucson.

Krausman, P.R., R. Valdez, and J.A. Bissonette. 1996. Bighorn sheep and livestock. Pages 237–243 in P.R. Krausman (ed.), Rangeland Wildlife. 1st edition. The Society for Range Management, Denver, Colorado.

Lange, R.T. 1969. The piosphere: sheep track and dung patterns. Journal of Range Management 22:396–400.

Laycock, W.A. 1991. Stable state and thresholds of range condition on North American rangelands: a viewpoint. Journal of Range Management 44:427–433.

Le Houérou, H.N., R.L. Bingham, and W. Skerbeck. 1988. Relationship between the variability of primary production and the variability of annual precipitation in world arid lands. Journal of Arid Environments 15:1–18.

Loft E.R., J.W. Menke, and J.G. Kie. 1991. Habitat shifts by mule deer: the influence of cattle grazing. Journal of Wildlife Management 55:16–26.

Loik, M.E., D.D. Breshears, W.K. Laurenroth, and J. Belnap. 2004. A multi-scale perspective of water pulses in dryland ecosystems: climatology and ecohydrology of the western USA. Oecologia 141:269–281.

Lundholm, J.T., and D.W. Larson. 2004. Experimental separation of resource quantity from temporal variability: seedling responses to water pulses. Oecologia 141:346–352.

MacGregor, A.N., and D.E. Johnson. 1971. Capacity of desert algal crusts to fix atmospheric nitrogen. Soil Science of America Proceedings 35:843–844.

Mack, R.N. 1981. Invasion of *Bromus tectorum* L. into western North America: an ecological chronicle. Agro-Ecosystems 7:145–165.

MacMahon, J.A., and F.H. Wagner. 1985. The Mojave, Sonoran and Chihuahuan Deserts of North America. Pages 105–202 in M. Evenari, I. Noy-Meir, and D.W. Goodall (eds.), Ecosystem of the World 12A: Hot Deserts and Arid Shrublands, A. Elsevier, Amsterdam, The Netherlands.

Marble, J.R., and K.T. Harper. 1989. Effect of timing of grazing on soil-surface cryptogamic communities in a Great Basin low-shrub desert: a preliminary report. Great Basin Naturalist 49:105–107.

Marshall, R.M., S. Anderson, M. Batcher, P. Comer, S. Cornelius, R. Cox, A. Gondor, D. Gori, J. Humke, R. Paredes Aguilar, I.E. Parra, S. Schwartz. 2000. An Ecological Analysis of Conservation Priorities in the Sonoran Desert Ecoregion. Prepared by The Nature Conservancy Arizona Chapter, Sonoran Institute, and Instituto del Medio Ambiente y el Desarollo Sustentable del Estado de Sonora with support from the Department of Defense Legacy Program and agency and institutional partners, Tucson. 146 p.

Martin, P.S. 1999. Deep history and a wilder West. Pages 255–290 in R.H. Robichaux (ed.), Ecology of Sonoran Desert Plants and Plant Communities. The University of Arizona Press, Tucson.

Martin, S.C., and K.E. Severson. 1988. Vegetation response to the Santa Rita grazing system. Journal of Range Management 41:291–295.

Martin, S.C., and R.M. Turner. 1977. Vegetation change in the Sonoran Desert region, Arizona and Sonora. Journal of the Arizona Academy of Science 12:59–69.

Martínez-Yrízar, A., S. Núñez, and A. Búrquez. 1993. Producción de hojarasca en tres communidades del Desierto Sonorense. In Resumenes del XII Congreso Mexicano de Botánica. Sociedad Botánica de México, Mérida.

Mayland, H.F., and T.H. McIntosh. 1966. Availability of biologically fixed atmospheric nitrogen-15 to higher plants. Nature 209:422–423.

Mayland, H.F., T.H. McIntosh, and W.H. Fuller. 1966. Fixation of isotopic nitrogen on a semiarid soil by algal crust organisms. Soil Science Society of America Proceedings 30:56–60.

McAuliffe, J.R. 1984. Prey refugia and the distributions of two Sonoran Desert cacti. Oecologia 65:82–85.

McAuliffe, J.R. 1986. Herbivore-limited establishment of a Sonoran Desert tree, *Cercidium microphyllum*. Ecology 67:276–280.

McAuliffe, J.R. 1991. Demographic shifts and plant succession along a late Holocene soil chronosequence in the Sonoran Desert of Baja California. Journal of Arid Environments 20:165–178.

McAuliffe, J.R. 1993. Case Study of Research, Monitoring Programs Associated with the Saguaro Cactus (*Carnegiea gigantea*) at Saguaro National Monument, Arizona. Technical Report NPS/WRUA/NRTR-93/01. U.S. Department of the Interior, National Park Service, Washington D.C.

McAuliffe, J.R. 1995. Landscape evolution, soil formation, and Arizona's desert grasslands. Pages 100–129 in M.P. McClaran and T.R. Van Devender (eds.), The Desert Grassland. The University of Arizona Press, Tucson.

McAuliffe, J.R. 1996. Saguaro cactus dynamics. Pages 96–131 in W.L. Halvorson and G.E. Davis (eds.), Science and Ecosystem Management in the National Parks. The University of Arizona Press, Tucson.

McAuliffe, J. 1997. Burning Issues in the Sonoran Desert. Bajada 5(2):12–13.

McAuliffe J.R. 1998. Rangeland water developments: conservation solution or illusion? Pages 310-359 in Proceedings of a Symposium on Environmental, Economic, And Legal Issues Related to Rangeland Water Developments. 13–15November 1997, Tempe, Arizona. Center for the Study of Law, Science, and Technology, Arizona State University, Tempe.

McAuliffe, J.R. 1999. Landscape complexity and ecological diversity. Pages 68–114 in R.H. Robichaux (ed.), Ecology of Sonoran Desert Plants and Plant Communities. The University of Arizona Press, Tucson.

McAuliffe, J.R. 2003. The interface between precipitation and vegetation: the importanced of soils in arid and semiarid environments. Pages 9–27 in J.F. Weltzin and G.R. McPherson (eds.), Changing Precipitation Regimes and Terrestrial Ecosystems: a North American Perspective. The University of Arizona Press, Tucson.

McClaran, M.P. 1995. Desert grasslands and grasses. Pages 1–30 in M.P. McClaran and T.R. Van Devender (eds.), The Desert Grassland. The University of Arizona Press, Tucson.

McIlvanie, S.K. 1942. Grass seedling establishment, and productivity—overgrazed vs. protected range soils. Ecology 23:228–231.

McLaughlin, S.P., and J.E. Bowers. 1982. Effects of wildfire on a Sonoran Desert plant community. Ecology 63:246–248.

McNaughton, S.J. 1993. Grasses and grazers, science and management. Ecological Applications 3:17–20.

McNaughton, S.J. 1986. On plants and herbivores. The American Naturalist 128:765–770.

McNay, M.E., and B.W. O’Gara. 1982. Cattle-pronghorn interactions during the fawning season in northwestern Nevada. Pages 593–606 in Proceedings of the Wildlife-Livestock Relationships Symposium. 20–22 April 1981, Coeur d’Alene, Idaho. Forest, Wildlife, and Range Experiment Station, University of Idaho, Moscow.

Milchunas, D.G. In Press. Responses of Plant Communities to Grazing in the Southwestern United States. General Technical Report. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Milchunas, D.G., and W.K. Lauenroth. 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. Ecological Monographs 63:327–366.

Milchunas, D.G., and I. Noy-Meir. 2002. Grazing refuges, external avoidance of herbivory and plant diversity. Oikos 99:113–130.

Milchunas, D.G., O.E. Sala, and W.K. Lauenroth. 1988. A generalized model of the effects of grazing by large herbivores on grassland community structure. American Naturalist 132:87–106.

Monson, G., and L. Sumner. 1990. The Desert Bighorn. 4th edition. The University of Arizona Press, Tucson. 370 p.

Morrison, M.L., P.C. Hardy, D.J. Griffin, and A.J. Kuenzi. 1997. Neotropical Migratory Bird Monitoring Program: Barry M. Goldwater Range Arizona. Unpublished report prepared for the U.S. Department of the Air Force, Range Management Office, Luke Air Force Base, Arizona by the School of Renewable Resources, University of Arizona, Tucson.

Morrison, P.H., H.M. Smith IV, and S.D. Snetsinger. 2003. The Natural Communities and Ecological Condition of the Sonoran Desert National Monument and Adjacent Areas. Pacific Biodiversity Institute, Winthrop, Washington. 395 p.

Mulroy, T.W., and P.W. Rundel. 1977. Annual plants: adaptations to desert environments. BioScience 27:109–114.

Murray, A.V. 1959. An Analysis of Changes in Sonoran Desert Vegetation for the Years 1928–1957. Unpublished master's thesis. University of Arizona, Tucson. 146 p.

Nash, M.S., D.F. Bradford, S.E. Franson, A.C. Neale, W.G. Whitford, and D.T. Heggem. 2004. Livestock grazing effects on ant communities in the eastern Mojave Desert, USA. Ecological Indicators 4:199–213.

Nash, M.S., W.G. Whitford, D.F. Bradford, S.E. Franson, A.C. Neale, and D.T. Heggem. 2001. Ant communities and livestock grazing in the Great Basin, U.S.A. Journal of Arid Environments 49:695–710.

Nash, M.S., W.G. Whitford, J. Van Zee, and K.M. Havstad. 2000. Ant (Hymenoptera: Formicidae) response to environmental stressors in the northern Chihuahuan Desert. Environmental Entomology 29:200–206.

Nash III, T.H., S.L. White, and J.E. Marsh. 1977. Lichen and moss distribution and biomass in hot desert ecosystems. Bryologist 80:470–479.

Nelson, T., J.L. Holechek, R. Valdez, and M. Cardenas. 1997. Wildlife numbers on late and mid seral Chihuahuan Desert rangelands. Journal of Range Management 50:593–599.

Noy-Meir, I. 1973. Desert ecosystems: environment and producers. Annual Review of Ecology and Systematics 4:25–51.

Noy-Meir, I. 1974. Desert ecosystems: higher trophic levels. Annual Review of Ecology and Systematics 5:195–214.

Noy-Meir, I. 1993. Compensating growth of grazed plants and its relevance to the use of rangelands. Ecological Applications 3:32–34.

Oesterheld, M., O.E. Sala, and S.J. McNaughton. 1992. Effect of animal husbandry on herbivore-carry capacity at a regional scale. Nature 356:234–236.

Oftedal, O. 2002. Nutritional ecology of the desert tortoise in the Mohave and Sonoran Deserts. Pages 194–241 in T.R. Van Devender (ed.), The Sonoran Desert Tortoise: Natural History, Biology, and Conservation. The University of Arizona Press and Arizona-Sonora Desert Museum. Tucson.

Ogle, K., and J.F. Reynolds. 2004. Plant responses to precipitation in desert ecosystems: integrating functional types, pulses, thresholds, and delays. Oecologia 141:282–294.

Painter, E.L., and A.J. Belsky. 1993. Application of herbivore optimization theory to rangelands of the western United States. Ecological Applications 3:2–9.

Parker, K.C. 1993. Climatic effects on regeneration trends for two columnar cacti in the northern Sonoran Desert. Annals of the Association of American Geographers 83:452–474.

Patten, D.T. 1978. Productivity and production efficiency of an upper Sonoran Desert ephemeral community. American Journal of Botany 65:891–895.

Peek, J.W., and P.R. Krausman. 1996. Grazing and mule deer. Pages 183–192 in P.R. Krausman (ed.), Rangeland Wildlife. 1st edition. The Society for Range Management, Denver, Colorado.

Peterson, F.F. 1981. Landforms of the Basin and Range Province: Defined for Soil Survey. Technical Bulletin 28. Nevada Agricultural Experiment Station, Max C. Fleischmann College of Agriculture, University of Nevada, Reno.

Pierson, E.A., and R.M. Turner. 1998. An 85-year study of Saguaro (*Carnegiea gigantea*) demography. Ecology 79:2676–2693.

Pima County. 2001. Priority Vulnerable Species: Analysis and Review of Species Proposed for Coverage by the Multi-Species Conservation Plan. Sonoran Desert Conservation Plan. Pima County Administrator's Office, Tucson, Arizona.

Price, M.V., and J.H. Brown. 1983. Patterns of morphology and resource use in North American desert rodent communities. Great Basin Naturalist Memoirs 7:117–134.

Ragotzkie, K.E., and J.A. Bailey. 1991. Desert mule deer use of grazed and ungrazed habitats. Journal of Range Management 44:487–490.

Rebollo, S., D.G. Milchunas, I. Noy-Meir, and P.L. Chapman. 2002. The role of a spiny plant refuge in structuring grazed shortgrass steppe plant communities. Oikos 98:53–64.

Reichenbacher, F.W. 1990. Tumamoc Globeberry Studies in Arizona and Sonora, Mexico. Final report prepared for the U.S. Department of Interior, Bureau of Reclamation, Phoenix, Arizona.

Reichman, O.J., and M.V. Price. 1993. Ecological aspects of heteromyid foraging. Pages 539–574 in H.H. Genoways and J.H. Brown (eds.), Biology of the Heteromyidae. American Society Mammalogists, Special Publication No. 10. Provo, Utah.

Reynolds, H.G. 1950. Relation of Merriam kangaroo rats to range vegetation in southern Arizona. Ecology 31:456–463.

Reynolds, H.G. 1958. The ecology of the Merriam kangaroo rat (*Dipodomys merriami* Mearns) on the grazing lands of southern Arizona. Ecological Monographs 28:111–127.

Reynolds, J.F., P.R. Kemp, K. Ogle, and R.J. Fernández. 2004. Modifying the 'pulse-reserve' paradigm for deserts of North America: precipitation pulses, soil water, and plant responses. Oecologia 141:194–210.

Richard, S.M., S.J. Reynolds, J.E. Spencer, and P.A. Pearthree (compilers). 2000. Geologic Map of Arizona, Map 35. Arizona Geological Survey, Tucson.

Robinett, D. 1992. Drought and recovery in the upper Sonoran Desert. Rangelands 14:219–222.

Rogers, G.F. 1985. Mortality of burned *Cereus giganteus*. Ecology 66:630–632.

Rogers, G.F., and J. Steele. 1980. Sonoran Desert fire ecology. Pages 15–19 in M.A. Stokes and J.H. Dieterich (tech. coords.), Proceedings of the Fire History Workshop, October 20–24, 1980, Tucson, Arizona. General Technical Report RM-81. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Rogers, G.F., and M.K. Vint. 1987. Winter precipitation and fire in the Sonoran Desert. Journal of Arid Environments 13:47–52.

Romero-Schmidt, H.L., and A. Ortega-Rubio. 1999. Changes in lizard abundance on protected versus grazed desert scrub in Baja California Sur, Mexico. Brazilian Archives of Biology and Technology 42:175–180.

Rosenstock, S.S. 1996. Shrub-grassland small mammal and vegetation responses to rest from grazing. Journal of Range Management 49:199–203.

Rosentreter, R., and J. Belnap. 2001. Biological soil crusts of North America. Pages 31–50 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Roundy, B.A., and G.B. Ruyle. 1989. Effects of herbivory on twig dynamics of a Sonoran Desert shrub *Simmondsia chinensis* (Link) Schn. Journal of Applied Ecology 26:701–710.

Rutman, S. 1998. Dirt is not cheap: Livestock grazing and a legacy of accelerated soil erosion on Organ Pipe Cactus National Monument, Arizona. Pages 360–375 in Proceedings of a Symposium on Environmental, Economic, And Legal Issues Related to Rangeland Water Developments. 13–15 November 1997, Tempe, Arizona. Center for the Study of Law, Science, and Technology, Arizona State University, Tempe.

Ruyle, G.B., and D.J. Young (eds.). 1997. Arizona Range Grasses: Their Description, Forage Value, and Grazing Management. 2nd edition. Cooperative Extension, College of Agriculture, University of Arizona, Tucson.

Rychert, R., J. Skujiņš, D. Sorensen, and D. Porcella. 1978. Nitrogen fixation by lichens and free-living microorganisms in deserts. Pages 20–30 in N.E. West and J. Skujiņš (eds.), Nitrogen in Desert Ecosystems. US/IBP Synthesis Series 9. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Ryerson, D.E., and R.R. Parmenter. 2001. Vegetation change following removal of keystone herbivores from desert grasslands in New Mexico. Journal of Vegetation Science 12:167–180.

Sayre, N.F. 2001. The New Ranch Handbook: A Guide to Restoring Western Rangelands. 1st edition. Quivira Coalition, Santa Fe, New Mexico. 102 p.

Schmid, M.K., and G.F. Rogers. 1988. Trends in fire occurrence in the Arizona Upland subdivision of the Sonoran Desert, 1955 to 1983. Southwestern Naturalist 33:437–444.

Schwinning, S., and O.E. Sala. 2004. Hierarchy of responses to resource pulses in arid and semi-arid ecosystems. Oecologia 141:211–220.

Schwinning, S., O.E. Sala, M.E. Loik, and J.R. Ehleringer. 2004. Thresholds, memory, and seasonality: understanding pulse dynamics in arid/semi-arid ecosystems. Oecologia 141:191–193.

Senft, R.L. 1983. The Redistribution of Nitrogen by Cattle. Unpublished doctoral dissertation. Colorado State University, Fort Collins. xi + 151 p.

Sheley, R.L., and J.K. Petroff. 1999. Biology and Management of Noxious Rangeland Weeds. Oregon State University Press, Corvallis.

Sher, A.A., D.E. Goldberg, and A. Novoplansky. 2004. The effect of mean and variance in resource supply on survival of annuals from Mediterranean and desert environments. Oecologia 141:353–362.

Shreve, F. 1911. The influence of low temperatures on the distribution of the giant cactus. Plant World 14:136–146.

Shreve, F. 1929. Changes in desert vegetation. Ecology 10:364–373.

Shreve, F., and A.L. Hinckley. 1937. Thirty years of change in desert vegetation. Ecology 18:463–478.

Smith, G., J.L. Holechek, M. Cardenas. 1996. Wildlife numbers on excellent and good condition Chihuahuan Desert rangelands: an observation. Journal of Range Management 49:489–493.

Sredl, M.J., and L.S. Saylor. 1998. Conservation and management zones and the role of earthen cattle tanks in conserving Arizona leopard frogs on large landscapes. Pages 211–226 in Proceedings of a Symposium on Environmental, Economic, And Legal Issues Related to Rangeland Water Developments. November 13–15, 1997, Tempe, Arizona. Center for the Study of Law, Science, and Technology, Arizona State University, Tempe.

[SRM] Society for Range Management. 1974. A Glossary of Terms Used in Range Management. 2nd edition. Compiled and edited by the Range Term Glossary Committee (M.M. Kothmann, Chairman), Society for Range Management, Denver, Colorado. viii + 36 p.

[SRM] Society for Range Management. 1989. A Glossary of Terms Used in Range Management. 3rd edition. Compiled and edited by the Glossary Revision Special Committee (P.W. Jacoby, Chairman), Publications Committee, Society for Range Management, Denver, Colorado. iv + 20 p.

Stauber, E.H., R. Autenrieth, O.D. Markham, and V. Whitbeck. 1980. A seroepidemiologic survey of three pronghorn (*Antilocapra americana*) populations in southeastern Idaho, 1975–1977. Journal of Wildlife Diseases 16:109–115.

Steenbergh, W.F., and C.H. Lowe. 1969. Critical factors during the first years of life of the saguaro (*Cereus giganteus*) at Saguaro National Monument. Ecology 50:825–834.

Steenbergh, W.F. and C.H. Lowe. 1977. Ecology of the Saguaro: II. Reproduction, Germination, Establishment, and Survival of the Young Plant. National Park Service Scientific Monograph Series Number 8. U.S. Department of the Interior, National Park Service, Washington, DC.
Steenbergh, W.F. and C.H. Lowe. 1983. Ecology of the Saguaro: III. Growth and Demography. National Park Service Scientific Monograph Series Number 17. Department of the Interior, National Park Service, Washington, DC.

Stitt, E.W., D.E. Swann, C.R. Schwalbe, T.A. Edwards, R.C. Averill-Murray, and T.C. Esque. 2002. Desert tortoise ecological studies at Saguaro National Park. Pages 128-129 in W.L. Halvorson and B.S. Gebow (eds.), Meeting Resource Management Information Needs: Fourth Conference on Research and Resource Management in the Southwestern Deserts, Extended Abstracts. U.S. Geological Survey, Sonoran Desert Field Station, The University of Arizona, Tucson.

Szarek, S.R. 1979. Primary production in four North American deserts: indices of efficiency. Journal of Arid Environments 2:187–209.

Taylor, W.P., C.T. Vorhies, and P.B. Lister. 1935. The relation of jack rabbits to grazing in southern Arizona. Journal of Forestry 3:490–498.

Thurow, T.L., and C.A. Taylor, Jr. 1999. Viewpoint: the role of drought in range management. Journal of Range Management 52:413–419.

Turner, D.S., and C.S. Funicelli. 2004. Demographic changes and epidermal browning in two protected populations of saguaro cactus (*Carnegiea gigantea*). Desert Plants 20:16–23.

Turner D.S., Felger R.S., Mauz K., Funicelli C.S., Van Devender T., and Malusa J. 2001. Biological Resources of the Proposed Sonoran Desert National Monument, Arizona. Prepared for the Sonoran Desert National Park Project by the Drylands Institute, Tucson, Arizona.

Turner, R.M. 1990. Long-term vegetation change at a fully protected Sonoran Desert site. Ecology 71:464–477.

Turner, R.M., S.M. Alcorn, G. Olin, and J.A. Booth. 1966. The influence of shade, soil, and water on saguaro seedling establishment. Botanical Gazette 127:95–102.

Turner, R.M., R.H. Webb, J.E. Bowers, and J.R. Hastings. 2003. The Changing Mile Revisited: An Ecological Study of Vegetation Change with Time in the Lower Mile of an Arid and Semiarid Region. The University of Arizona Press, Tucson. xvi + 334 p.

Tyburec, J. 2000. Cactaceae (cactus family). Pages 461–472 in S.J. Phillips and P. Wentworth Comus (eds.), A Natural History of the Sonoran Desert. Arizona-Sonora Desert Museum Press, Tucson, Arizona.

[USFS] U.S. Forest Service. 1998. Biological Assessment of on-Going and Long-Term Grazing on the Coronado National Forest. Coronado National Forest Supervisor's Office, Tucson, Arizona. 428 p.

[USFWS] U.S. Fish and Wildlife Service. 1981. Final Environmental Impact Statement on the Proposal to Eliminate Cattle Grazing and Wild Burro Population on the Kofa National Wildlife Refuge. U.S. Fish and Wildlife Service, Albuquerque, New Mexico. 86 + ix p.

[USFWS] U.S. Fish and Wildlife Service. 1986. Endangered and threatened wildlife and plants; determination of *Tumamoca macdougalii* to be endangered. April 29, 1986. Federal Register 51(82):15906–15911.

[USFWS] U.S. Fish and Wildlife Service. 1993. Endangered and Threatened Wildlife and Plants; Final Rule to Delist the Plant *Tumamoca macdougalii*. June 18, 1993. Federal Register 58(116):33562–33565.

[USFWS] U.S. Fish and Wildlife Service. 1998. Final Revised Sonoran Pronghorn Recovery Plan (*Antilocapra americana sonoriensis*). U.S. Fish and Wildlife Service, Albuquerque, New Mexico. 70 p.

Van de Graaff K.M, and R.P. Balda. 1973. Importance of green vegetation for reproduction in the kangaroo rat, *Dipodomys merriami merriami*. Journal of Mammalogy 54:509-512.

Van Devender, T.R. 2000. The deep history of the Sonoran Desert. Pages 61–69 in J.J. Philips and P. Wentworth Comus (eds.), A Natural History of the Sonoran Desert. Arizona-Sonora Desert Museum. Tucson.

Van Devender, T.R., R.C. Averill-Murray, T.C. Esque, P.A. Holm, V.M. Dickinson, C.R. Schwalbe, E.B. Wirt, and S.L. Barrett. 2002. Grasses, mallows, desert vine, and more: diet of the desert tortoise in Arizona and Sonora. Pages 159–193 in T.R. Van Devender (ed.), The Sonoran Desert Tortoise: Natural History, Biology, and Conservation. The University of Arizona Press and Arizona-Sonora Desert Museum, Tucson.

Venable, D.L., and C.E. Pake. 1999. Population ecology of Sonoran Desert Plants. Pages 115–142 in R.H. Robichaux (ed.), Ecology of Sonoran Desert Plants and Plant Communities. The University of Arizona Press, Tucson.

Wallace, A., E.M. Romney, and R.B. Hunter. 1978. Nitrogen cycle in the northern Mohave Desert: implications and predictions. Pages 207–218 in N.E. West and J. Skujiņš (eds.), Nitrogen in Desert Ecosystems. US/IBP Synthesis Series 9. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Walter, H. 1971. Ecology of Tropical and Subtropical Vegetation. Oliver and Boyd, Edinburgh, United Kingdom. 539 p.

Warren, P.L., and L.S. Anderson. 1992. Ecosystem Recovery from Grazing at Organ Pipe Cactus National Monument: Plant and Rodent Community Changes between 1975–76 and 1987–88. Arizona Nature Conservancy, Tucson. 55 p.

Warren, S.D. 2001a. Biological soil crusts and hydrology in North American deserts. Pages 327–337 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Warren, S.D. 2001b. Synopsis: influence of biological soil crusts on arid land hydrology and soil stability. Pages 349–360 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Warren, S.D. and Elderidge D.J. 2001. Biological soil crusts and livestock in arid ecosystems: are they compatible? Pages 401–415 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Warren, S.D., M.B. Nevill, W.H. Blackburn, and N.E. Garza. 1986. Soil response to trampling under intensive rotation grazing. Soil Science Society of America Journal 50:1336–1341.

Waser, N.M., and M.V. Price. 1981. Effects of grazing on diversity of annual plants in the Sonoran Desert. Oecologia 50:407–411.

Watson, I.W., D.G. Burnside, and A.M. Holm. 1996. Event-driven or continuous: which is the better model for managers? Rangelands Journal 18:351–369.

Webb, W., S. Szarek, W. Lauenroth, R. Kinerson, and M. Smith. 1978. Primary productivity and water use in native forest, grassland, and desert ecosystems. Ecology 59:1239–1247.

West, N.E. 1979. Formation, distribution and function of plant litter in desert ecosystems. Pages 647–659 in I.A. Perry and D.W. Goodall (eds.), Arid Land Ecosystems: Their Structure, Functioning and Management. Volume I. Cambridge University Press, Cambridge.

West, N.E., and J.O. Klemmedson. 1978. Structural distribution of nitrogen in desert ecosystems. Pages 1–16 in N.E. West and J. Skujiņš (eds.), Nitrogen in Desert Ecosystems. US/IBP Synthesis Series 9. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

West, N.E., and J. Skujiņš. 1978. Summary, conclusions and suggestions for further research. Pages 244–253 in N.E. West and J. Skujiņš (eds.), Nitrogen in Desert Ecosystems. US/IBP Synthesis Series 9. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Westoby, M., B. Walker, and I. Noy–Meir. 1989. Opportunistic management for rangelands not at equilibrium. Journal of Range Management 42:266–274.

Whittaker, R.H., and W.A. Niering. 1975. Vegetation of the Santa Catalina Mountains, Arizona. V. Biomass, production, and diversity along the elevation gradient. Ecology 56:771–790.

Wiens, J.A. 1984. On understanding a non-equilibrium world: myth and reality in community patterns and processes. Pages 439–457 in D.R. Strong, D. Simberloff, L. Abele, and A.B. Thistle (eds.), Ecological Communities: Conceptual Issues and the Evidence. Princeton University Press, Princeton, New Jersey.

Wilson, R.C., M.G. Narog, B.M. Corcoran, and A.L. Koonce. 1996. Postfire saguaro injury in Arizona's Sonoran Desert. Pages 247–252 in L.F. DeBano (tech coord.), Effects of Fire on Madrean Province Ecosystems: A Symposium Proceedings. RM–GTR–289. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Witham, J.H. 1983. Desert Bighorn Sheep in Southwestern Arizona. Unpublished doctoral dissertation. Colorado State University, Fort Collins.

Woodward, B.D. 1983. Predator-prey interactions and breeding-pond use of temporary-pond species in a desert anuran community. Ecology 64:1549–1555.

Wright, R.L., and J.C. deVos, Jr. 1986. Final Report on Sonoran Pronghorn Status in Arizona. Arizona Game and Fish Department, Phoenix. 131 + v p.

Yoakum, J.D. 1975. Antelope and livestock on rangelands. Journal of Animal Science 40:985–992.

Yoakum, J.D., and B.W. O'Gara. 1990. Pronghorn/livestock relationships. Transactions North American Wildlife and Natural Resources Conference 55:475–487.

Yoakum, J.D., B.W. O'Gara, and V.W. Howard, Jr. 1996. Pronghorn on western rangelands. Pages 211–226 in P.R. Krausman (ed.), Rangeland and Wildlife. 1st edition. The Society for Range Management, Denver, Colorado.

APPENDIX A

SONORAN DESERT NATIONAL MONUMENT PROCLAMATION

THE WHITE HOUSE
Office of the Press Secretary
For Immediate Release, January 17, 2001
ESTABLISHMENT OF THE SONORAN DESERT NATIONAL MONUMENT
BY THE PRESIDENT OF THE UNITED STATES OF AMERICA

The Sonoran Desert National Monument is a magnificent example of untrammeled Sonoran desert landscape. The area encompasses a functioning desert ecosystem with an extraordinary array of biological, scientific, and historic resources. The most biologically diverse of the North American deserts, the monument consists of distinct mountain ranges separated by wide valleys, and includes large saguaro cactus forest communities that provide excellent habitat for a wide range of wildlife species.

The monument's biological resources include a spectacular diversity of plant and animal species. The higher peaks include unique woodland assemblages, while the lower elevation lands offer one of the most structurally complex examples of palo verde/mixed cacti association in the Sonoran Desert. The dense stands of leguminous trees and cacti are dominated by saguaros, palo-verde trees, ironwood, prickly pear, and cholla. Important natural water holes, known as tinajas, exist throughout the monument. The endangered acuna pineapple cactus is also found in the monument.

The most striking aspect of the plant communities within the monument are the abundant saguaro cactus forests. The saguaro is a signature plant of the Sonoran Desert. Individual saguaro plants are indeed magnificent, but a forest of these plants, together with the wide variety of trees, shrubs, and herbaceous plants that make up the forest community, is an impressive site to behold. The saguaro cactus forests within the monument are a national treasure, rivaling those within the Saguaro National Park.

The rich diversity, density, and distribution of plants in the Sand Tank Mountains area of the monument is especially striking and can be attributed to the management regime in place since the area was withdrawn for military purposes in 1941. In particular, while some public access to the area is allowed, no livestock grazing has occurred for nearly 50 years. To extend the extraordinary diversity and overall ecological health of the Sand Tanks Mountains area, land adjacent and with biological resources similar to the area withdrawn for military purposes should be subject to a similar management regime to the fullest extent possible.

The monument contains an abundance of packrat middens, allowing for scientific analysis of plant species and climates in past eras. Scientific analysis of the midden shows that the area received far more precipitation 20,000 years ago, and slowly became more arid. Vegetation for the area changed from juniper-oak-pinion pine woodland to the vegetation found today in the Sonoran Desert, although a few plants from the more mesic period, including the Kofa Mountain barberry, Arizona rosewood, and junipers, remain on higher elevations of north-facing slopes.

The lower elevations and flatter areas of the monument contain the creosote-bursage plant community. This plant community thrives in the open expanses between the mountain ranges, and connects the other plant communities together. Rare patches of desert grassland can also be found throughout the monument, especially in the Sand Tank Mountains area. The washes in the area support a much denser vegetation community than the surrounding desert, including mesquite, ironwood, paloverde, desert honeysuckle, chuperosa, and desert willow, as well as a variety of herbaceous plants. This vegetation offers the dense cover bird species need for successful nesting, foraging, and escape, and birds heavily use the washes during migration.

The diverse plant communities present in the monument support a wide variety of wildlife, including the endangered Sonoran pronghorn, a robust population of desert bighorn sheep, especially in the Maricopa Mountains area, and other mammalian species such as mule deer, javelina, mountain lion, gray fox, and bobcat. Bat species within the monument include the endangered lesser long-nosed bat, the California leaf-nosed bat, and the cave myotis. Over 200 species of birds are found in the monument, including 59 species known to nest in the Vekol Valley area. Numerous species of raptors and owls inhabit the monument, including the elf owl and the western screech owl. The monument also supports a diverse array of reptiles and amphibians, including the Sonoran desert tortoise and the red-backed whiptail. The Bureau of Land Management has designated approximately 25,000 acres of land in the Maricopa Mountains area as critical habitat for the desert tortoise. The Vekol Valley and Sand Tank Mountain areas contain especially diverse and robust populations of amphibians. During summer rainfall events, thousands of Sonoran green toads in the Vekol Valley can be heard moving around and calling out.

The monument also contains many significant archaeological and historic sites, including rock art sites, lithic quarries, and scattered artifacts. Vekol Wash is believed to have been an important prehistoric travel and trade corridor between the Hohokam and tribes located in what is now Mexico. Signs of large villages and permanent habitat sites occur throughout the area, and particularly along the bajadas of the Table Top Mountains. Occupants of these villages were the ancestors of today's O'odham, Quechan, Cocopah, Maricopa, and other tribes. The monument also contains a much used trail corridor 23 miles long in which are found remnants of several important historic trails, including the Juan Bautista de Anza National Historic Trail, the Mormon Battalion Trail, and the Butterfield Overland Stage Route.

Section 2 of the Act of June 8, 1906 (34 Stat. 225, 16 U.S.C. 431), authorizes the President, in his discretion, to declare by public proclamation historic landmarks, historic and prehistoric structures, and other objects of historic or scientific interest that are situated upon the lands owned or controlled by the Government of the United States to be national monuments, and to reserve as a part thereof parcels of land, the limits of which in all cases shall be confined to the smallest area compatible with the proper care and management of the objects to be protected.

WHEREAS, it appears that it would be in the public interest to reserve such lands as a national monument to be known as the Sonoran Desert National Monument.

NOW, THEREFORE, I, WILLIAM J. CLINTON, President of the United States of America, by the authority vested in me by section 2 of the Act of June 8, 1906 (34 Stat. 225, 16 U.S.C. 431), do proclaim that there are hereby set apart and reserved as the Sonoran Desert National Monument, for the purpose of protecting the objects identified above, all lands and interest in lands owned or controlled by the United States within the boundaries of the area described on the map entitled "Sonoran Desert National Monument" attached to and forming a part of this proclamation. The Federal land and interests in land reserved consist of approximately 486,149 acres, which is the smallest area compatible with the proper care and management of the objects to be protected.

For the purpose of protecting the objects identified above, all motorized and mechanized vehicle use off road will be prohibited, except for emergency or authorized administrative purposes. Nothing in this proclamation shall be deemed to enlarge or diminish the jurisdiction of the State of Arizona with respect to fish and wildlife management.

The establishment of this monument is subject to valid existing rights.

All Federal lands and interests in lands within the boundaries of this monument are hereby appropriated and withdrawn from all forms of entry, location, selection, sale, or leasing or other disposition under the public land laws, including but not limited to withdrawal from location, entry, and patent under the mining laws, and from disposition under all laws relating to mineral and geothermal leasing, other than by exchange that furthers the protective purposes of the monument. Lands and interests in lands within the monument not owned by the United States shall be reserved as a part of the monument upon acquisition of title thereto by the United States.

This proclamation does not reserve water as a matter of Federal law nor relinquish any water rights held by the Federal Government existing on this date. The Federal land management agencies shall work with appropriate State authorities to ensure that water resources needed for monument purposes are available.

The Secretary of the Interior shall manage the monument through the Bureau of Land Management, pursuant to applicable legal authorities, to implement the purposes of this proclamation. That portion identified as Area A on the map, however, shall be managed under the management arrangement established by section 3 of Public Law No. 99-606, 100 Stat. 3460-61, until November 6, 2001, at which time, pursuant to section 5(a) of Public Law No. 99-606, 100 Stat. 3462-63, the military withdrawal terminates. At that time, the Secretary of the Interior shall assume management responsibility for Area A through the Bureau of Land Management.

The Secretary of the Interior shall prepare a management plan that addresses the actions, including road closures or travel restrictions, necessary to protect the objects identified in this proclamation. Laws, regulations, and policies followed by the Bureau of Land Management in issuing and administering grazing permits or leases on all lands under its jurisdiction shall continue to apply with regard to the lands in the monument; provided, however, that grazing permits on Federal lands within the monument south of Interstate Highway 8 shall not be renewed at the end of their current term; and provided further, that grazing on Federal lands north of Interstate 8 shall be allowed to continue only to the extent that the Bureau of Land Management determines that grazing is compatible with the paramount purpose of protecting the objects identified in this proclamation.

Nothing in this proclamation shall be deemed to revoke any existing withdrawal, reservation, or appropriation; however, the national monument shall be the dominant reservation.

Nothing in this proclamation shall preclude low level overflights of military aircraft, the designation of new units of special use airspace, or the use or establishment of military flight training routes over the lands included in this proclamation.

In order to protect the public during operations at the adjacent Barry M. Goldwater Range, and to continue management practices that have resulted in an exceptionally well preserved natural resource, the current procedures for public access to the portion of the monument depicted as Area A on the attached map shall remain in full force and effect, except to the extent that the United States Air Force agrees to different procedures which the Bureau of Land Management determines are compatible with the protection of the objects identified in this proclamation.

Warning is hereby given to all unauthorized persons not to appropriate, injure, destroy, or remove any feature of this monument and not to locate or settle upon any of the lands thereof.

IN WITNESS WHEREOF, I have hereunto set my hand this seventeenth day of January, in the year of our Lord two thousand one, and of the Independence of the United States of America the two hundred and twenty-fifth.

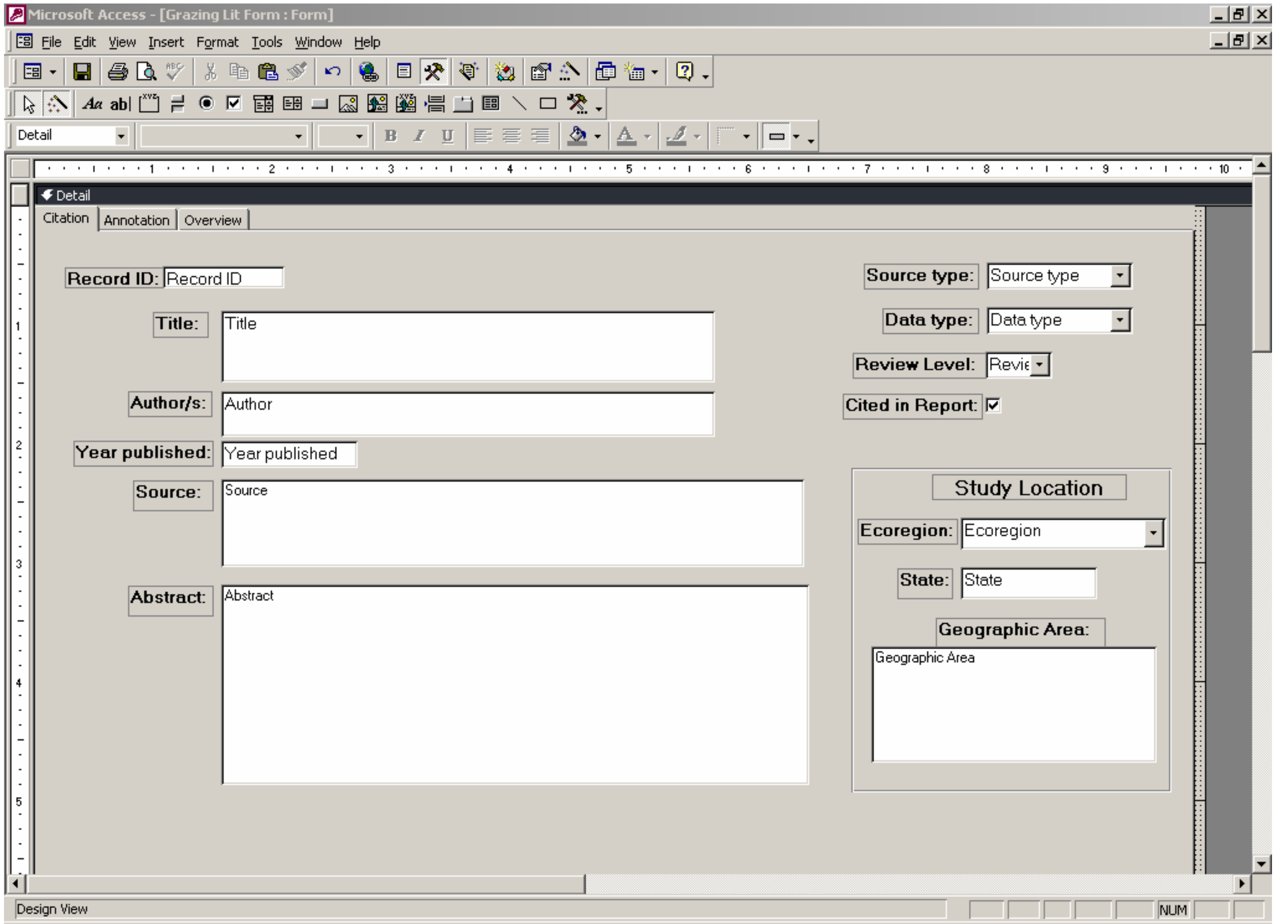
WILLIAM J. CLINTON

APPENDIX B

ACCESS DATABASE TEMPLATE

Each record (scientific paper) in the database has three “tabs” or pages, shown below: (1) citation information; (2) annotation, including a detailed account of the questions, methods, and results; and (3) a summary of the main findings and questions addressed.

PAGE 1: CITATION INFORMATION



Record ID: Record ID

Title: Title

Author/s: Author

Year published: Year published

Source: Source

Abstract: Abstract

Source type: Source type

Data type: Data type

Review Level: Revie

Cited in Report: ☑

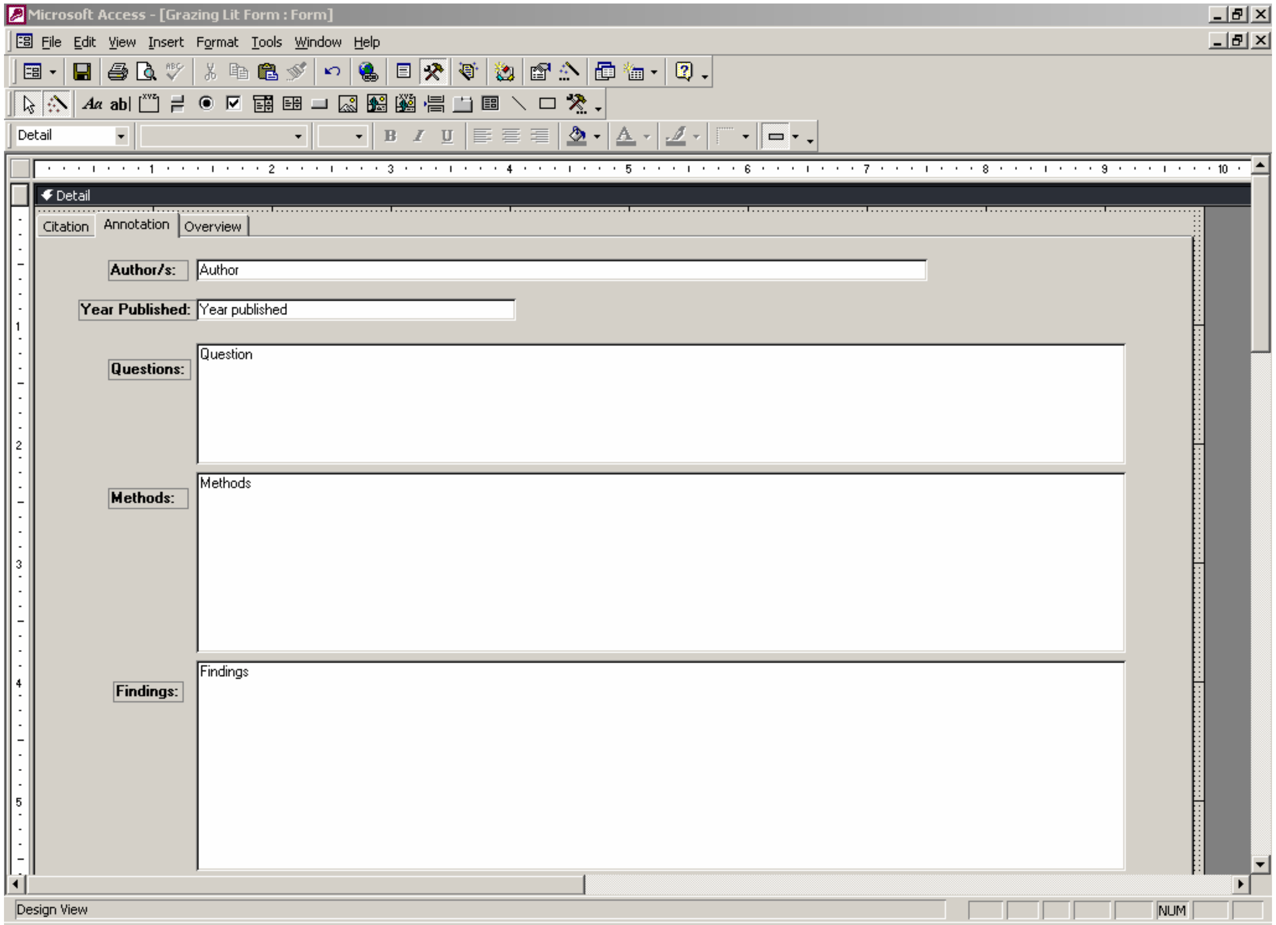
Study Location

Ecoregion: Ecoregion

State: State

Geographic Area: Geographic Area

PAGE 2: ANNOTATION



Author/s: Author

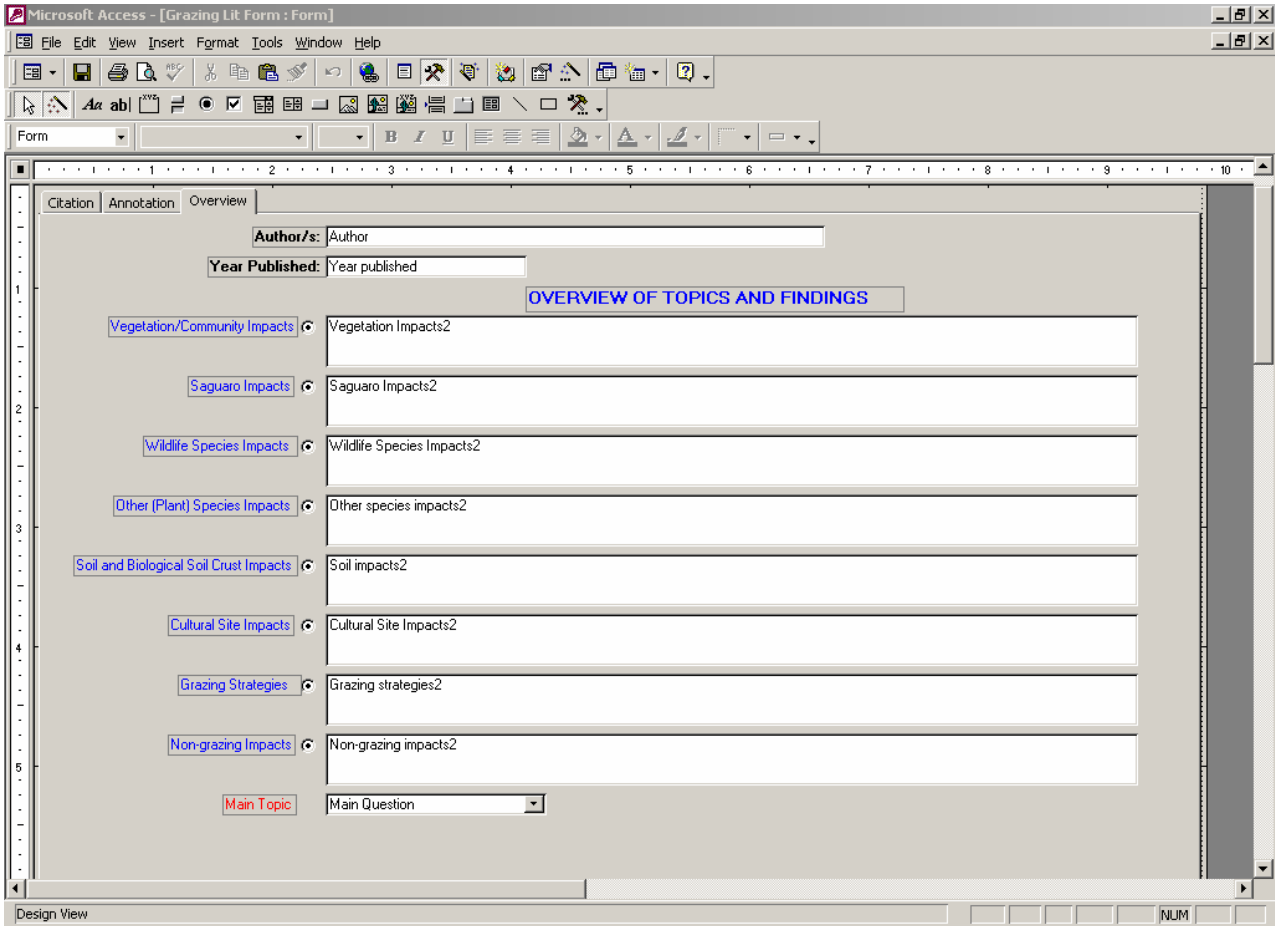
Year Published: Year published

Questions: Question

Methods: Methods

Findings: Findings

PAGE 3: OVERVIEW OF TOPICS AND FINDINGS



Author/s: Author

Year Published: Year published

OVERVIEW OF TOPICS AND FINDINGS

Vegetation/Community Impacts ● Vegetation Impacts2

Saguaro Impacts ● Saguaro Impacts2

Wildlife Species Impacts ● Wildlife Species Impacts2

Other (Plant) Species Impacts ● Other species impacts2

Soil and Biological Soil Crust Impacts ● Soil impacts2

Cultural Site Impacts ● Cultural Site Impacts2

Grazing Strategies ● Grazing strategies2

Non-grazing Impacts ● Non-grazing impacts2

Main Topic: Main Question

APPENDIX C

LITERATURE COMPILED IN DATABASE

Abou-Haidar, F. 1989. Influence of Livestock Grazing on Saguaro Seedling Establishment. Unpublished master's thesis. Arizona State University, Tempe. 50 p.

Abou-Haidar, F. 1992. Influence of livestock on saguaro seedling establishment. Pages 57–61 in C.P. Stone and E.S. Bellantoni (eds.), Proceedings of the Symposium on Research in Saguaro National Monument. 23–24 January 1991, Tucson, Arizona. National Park Service, Rincon Institute, and Southwest Parks and Monument Association, Tucson, Arizona.

Alford, E. 1993. Tonto rangelands—a journey of change. Rangelands 15:261–268.

Anderson, D.C., K.T. Harper, and R.C. Holmgren. 1982. Factors influencing development of cryptogamic soil crusts in Utah deserts. Journal of Range Management 35:180–185.

Anderson, D.C., K.T. Harper, and S.R. Rushforth. 1982. Recovery of cryptogamic soil crusts from grazing on Utah winter ranges. Journal of Range Management 35:355–359.

Anderson, D.M. 1988. Seasonal stocking of tobosa managed under continuous and rotation grazing. Journal of Range Management 41:78–83.

Anderson, H.L. 1977. Barbed wire impales another Great Horned Owl. Raptor Research 11:71–72.

Andrew, M.H. 1988. Grazing impact in relation to livestock watering points. Trends in Evolutionary Ecology 3:336–339.

Angell, D.L., and M.P. McClaran. 2001. Long-term influences of livestock management and a non-native grass on grass dynamics in the desert grassland. Journal of Arid Environments 49:507–520.

Arizona Interagency Range Committee. 1975. Interrelationships of Livestock and Wildlife on Arizona Rangelands. Report 3. Arizona Game and Fish Department, Phoenix. 27 p.

Bahre, C.J. 1991. Livestock grazing. Pages 108–123 in C.J. Bahre, A Legacy of Change. University of Arizona Press, Tucson.

Bahre, C.J., and M.L. Shelton. 1996. Rangeland destruction: cattle and drought in southeastern Arizona at the turn of the century. Journal of the Southwest 38:1–22.

Balling Jr., R.C. 1988. The climatic impact of a sonoran vegetation discontinuity. Climatic Change 13:99–109.

Balling, R.C., Jr., J.M. Klopatek, M.L. Hildebrandt, C.K. Moritz, and C.J. Watts. 1998. Impacts of land degradation on historical temperature records from the Sonoran Desert. Climatic Change 40:669–681.

Ballinger, R.E., and S.M. Jones. 1985. Ecological disturbance in a Sandhills Prairie: impact and importance to the lizard community on Arapaho Prairie in western Nebraska. Prairie Naturalist 17:91–100.

Barrett, S.L., and T.B. Johnson. 1990. Status Summary for the Desert Tortoise in the Sonoran Desert. Report to the U.S. Fish and Wildlife Service, Albuquerque, New Mexico. 115 p.

Bartolome, J.W. 1993. Application of herbivore optimization theory to rangelands of the western United States. Ecological Applications 3:27–29.

Beck, R.F., and D.A. Tober. 1985. Vegetational changes on creosotebush sites after removal of shrubs, cattle and rabbits. Bulletin of New Mexico State University Agricultural Experiment Station 717:1–22.

Bedunah, D.J. 1992. The complex ecology of weeds, grazing and wildlife. Western Wildlands Summer:6–11.

Belnap, J. 1992. Characteristics of cyanobacterial-lichen soil crusts in long-term saguaro monitoring plots. Pages 259–262 in C.P. Stone and E.S. Bellantoni (eds.), Proceedings of the Symposium on Research in Saguaro National Monument. 24–24 January 1991, Tucson, Arizona. National Park Service, Rincon Institute and Southwesst Parks and Monument Association, Tucson, Arizona.

Belnap, J. 1995. Surface disturbances: their role in accelerating desertification. Environmental Monitoring and Assessment 37:39–57.

Belnap, J. 2002. Impacts of off-road vehicles on nitrogen cycles in biological soil crusts: resistance in different U.S. deserts. Journal of Arid Environments 52:155–165.

Belnap, J., and D.J. Eldridge. 2001. Disturbance and recovery of biological soil crusts. Pages 363–383 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Belnap, J., K.T. Harper, and S.D. Warren. 1994. Surface disturbance of cryptobiotic soil crusts: nitrogenase activity, chlorophyll content, and chlorophyll degradation. Arid Soil Research and Rehabilitation 8:1–8.

Belnap, J., J.H. Kaltenecker, R. Rosentreter, J. Williams, S. Leonard, and D. Eldridge. 2001. Biological Soil Crusts: Ecology and Management. Technical Reference 1730–2. U.S. Department of the Interior, Bureau of Land Management, National Science and Technology Center, Denver, Colorado. 110 + v p.

Belsky, A.J. 1986. Does herbivory benefit plants? A review of the evidence. The American Naturalist 127:870–892.

Belsky, A.J., W.P. Carson, C.L. Jensen, and G.A. Fox. 1993. Overcompensation by plants: herbivore optimization or red herring? Evolutionary Ecology 7:109–121.

Bestelmeyer, B.T., and J.A. Wiens. 2001. Ant biodiversity in semiarid landscape mosaics: The consequences of grazing vs. natural heterogenity. Ecological Applications 11:1123–1140.

Bestelmeyer, B.T., J.E. Brown, K.M. Havstad, R. Alexander, G. Chavez, and J.E. Herrick. 2003. Development and use of state-and-transition models for rangelands. Journal of Range Management 56:114–126.

Bissonette, J.A., and M.J. Steinkamp. 1996. Bighorn sheep response to ephemeral habitat fragmentation by cattle. Great Basin Naturalist 56:319–325.

Blydenstein, J. 1966. Root systems of four desert grassland species on grazed and protected sites. Journal of Range Management 19:93–95.

Blydenstein, J., C.R. Hungerford, G.I. Day, and H.H. Humphrey. 1957. Effect of domestic livestock exclusion on vegetation in the Sonoran Desert. Ecology 38:522–526.

Bock, C.E., and B. Webb. 1975. Birds as grazing indicator species in southeastern Arizona. Journal of Wildlife Management 48:1045–1049.

Bock, C.E., J.H. Bock, W.R. Kenney, and V.M. Hawthorne. 1984. Responses of birds, rodents, and vegetation to livestock exclosure in a semidesert grassland site. Journal of Range Management 37:239–242.

Bock, C.E., H.M. Smith, and J.H. Bock. 1990. The effect of livestock grazing upon abundance of the lizard, *Sceloporus scalaris,* in southeastern Arizona. Journal of Herpetology 24:445–446.

Bostick, V. 1990. The desert tortoise in relation to cattle grazing. Rangelands 12:149–151.

Bowers, J.E. 1997. Demographic patterns of *Ferocactus cylindraceus* in relation to substrate age and grazing history. Plant Ecology 133:37–48.

Bowers, J.E., and R.M. Turner. 2002. The influence of climatic variability on local population dynamics of *Cercidium microphyllum* (foothill paloverde). Oecologia 130:105–113.

Bowers, J.E., R.H. Webb, and R.J. Rondeau. 1995. Longevity, recruitment and mortality of desert plants in Grand Canyon, Arizona, USA. Journal of Vegetation Science 6:551–564.

Brady, W.W., M.R. Stromberg, E.F. Aldon, C.D. Bonhan, and S.H. Henry. 1989. Response of a semidesert grassland to 16 years of rest from grazing. Journal of Range Management 42:284–288.

Briske, D.D. 1993. Grazing optimization: a plea for a balanced perspective. Ecological Applications 3:24–26.

Briske, D.D., and J.H. Richards. 1995. Plant responses to defoliation: A physiological, morphological and demographic evaluation. Pages 635–710 in D.J. Bedunah and R.E. Sosebee (eds.), Wildland Plants: Physiological Ecology and Developmental Morphology. Society for Range Management, Denver, Colorado.

Briske, D.D., S.D. Fuhlendorf, and F.E. Smeins. 2003. Vegetation dynamics on rangelands: a critique of the current paradigms. Journal of Applied Ecology 40:601–614.

Brooks, M.L. 1995. Benefits of protective fencing to plant and rodent communities of the western Mojave Desert, California. Environmental Management 19:65–74.

Brooks, M.L. 1999. Effects of protective fencing on birds, lizards, and black-tailed hares in the western Mojave Desert. Environmental Management 23:387–400.

Brooks, M.L., and D.A. Pyke. 2001. Invasive plants and fire in the deserts of North America. Pages 1–14 in K.E.K. Galley and T.P. Wilson (eds.), Proceedings of the Invasive Species Workshop: the Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: the First National Congress on Fire Ecology, Prevention, and Management. Miscellaneous Publication No. 11. Tall Timbers Research Station, Tallahassee, Florida.

Brooks, M.L., J.R. Matchett, and K.H. Berry. In Press. Effects of livestock watering sites on plant communities in the Mojave Desert. Journal of Arid Environments

Brotherson, J.D., S.R. Rushforth, and J.R. Johansen. 1983. Effects of long-term grazing on cryptogram crust cover in Navajo National Monument, AZ. Journal of Range Management 36:579–581.

Brown, B.J., and T.F.H. Allen. 1989. The importance of scale in evaluating herbivory impacts. Oikos 54:189–194.

Brown, D.E. 1994. Out of Africa. Wilderness Winter:24–31.

Brown, J.H., and W. McDonald. 1995. Livestock grazing and conservation on southwestern rangelands. Conservation Biology 9:1644–1647.

Brown, J.H., T.J. Valone, and C.G. Curtin. 1997. Reorganization of an arid ecosystem in response to recent climate change. Proceedings of the National Academy of Sciences if the United States of America 94:9729–9733.

Brown, J.R. 1994. State and transition models for rangelands. 2. Ecology as a basis for rangeland management: performance criteria for testing models. Tropical Grasslands 28:206–213.

Brown, R.L. 1982. Effects of livestock grazing on mearns quail in southeastern Arizona. Journal of Range Management 68:727–732.

Bryant, F.C., B.E. Dahl, R.D. Pettit, and C.M. Britton. 1989. Does short-duration grazing work in arid and semiarid regions? Journal of Soil and Water Conservation July–August:290–296.

Bryant, N.A., L.F. Johnson, A.J. Brazel, R.C. Balling, and C.F. Hutchingson. 1990. Measuring the effect of overgrazing in the Sonoran Desert. Climatic Change 17:243–264.

Burgess, T.L., J.E. Bowers, and R.M. Turner. 1991. Exotic plants at the Desert Laboratory, Tucson, Arizona. Madrońo 38:96–114.

Busack, S.D., and R.B. Bury. 1974. Some effects of off-road vehicles and sheep grazing on lizard populations in the Mojave Desert. Biological Conservation 6:179–183.

Caldwell, M.M. 1984. Plant requirements for prudent grazing. Pages 117–152 in Developing Strategies for Rangeland Management: A Report Prepared by the Committee on Developing Strategies for Rangeland Management. National Research Council/National Academy of Sciences. Westview Press, Boulder, Colorado.

Campbell, R.S. 1931. Plant succession and grazing capacity on clay soils in southern New Mexico. Journal of Agricultural Research 43:1027–1051.

Canfield, R.H. 1948. Perennial grass composition as an indicator of condition of southwestern mixed grass ranges. Ecology 29:190–204.

Canfield, R.H. 1957. Reproduction and life span of some perennial grasses of southern Arizona. Journal of Range Management 10:199–203.

Caraher, D.L. 1970. Effects of Longtime Livestock Exclusion Versus Grazing on the Desert Grassland of Arizona. Unpublished master's thesis. University of Arizona, Tucson. 45 p.

Carrier, W.D., and B. Czech. 1996. Threatened and endangered wildlife and livestock interactions. Pages 39–47 in P.R. Krausman (ed.), Rangeland Wildlife. 1st edition. The Society for Range Management, Denver, Colorado.

Chase, J.M., M.A. Leibold, A.L. Downing, and J.B. Shurin. 2000. The effects of productivity, herbivory, and plant species turnover in grassland food webs. Ecology 81:2485–2497.

Chew, R.M. 1982. Changes in herbaceous and suffrutescent perennials in grazed and ungrazed desertified grassland in southeastern Arizona, 1958–1978. American Midland Naturalist 108:159–169.

Clary, W.P., and D.M. Beale. 1983. Pronghorn reactions to winter sheep grazing, plant communities, and topography in the Great Basin. Journal of Range Management 36:749–752.

Craig, T.H., and L.R. Powers. 1976. Raptor mortality due to drowning in a livestock watering tank. Condor 78:412.

Curtin, C.G., and J.H. Brown. 2001. Climate and herbivory in structuring the vegetation of the Malpai Borderlands. Pages 84–94 in Vegetation and Flora of La Frontera: Vegetation Change Along the United States-Mexico Boundary. University of New Mexico Press, Albuquerque.

Curtin, C.G., N.F. Sayre, and B.D. Land. 2002. Transformations of the Chihuahuan borderlands: grazing, fragmentation, and biodiversity conservation in desert grasslands. Environmental Science and Policy 5:55–68.

Dodd, N.L., and W.W. Brady. 1986. Cattle grazing influences on vegetation of a sympatric desert bighorn range in Arizona. Desert Bighorn Council Transactions 30:8–13.

Durfee, J.A. 1988. Response of Mohave Desert Communities to Release From Grazing Pressure. Unpublished master's thesis. Brigham Young University, Provo, Utah. 28 p.

Dyer, M.I., C.L. Turner, and T.R. Seastedt. 1993. Herbivory and its consequences. Ecological Applications 3:10–16.

Dyksterhuis, E.J. 1949. Condition and management of range land based on quantitative ecology. Journal of Range Management 2:104–115.

Ellis, J.E., and D.M. Swift. 1988. Stability of African pastoral ecosystems: alternate paradigms and implications for development. Journal of Range Management 41:450–459.

Ellison, L. 1960. Influence of grazing on plant succession of rangelands. The Botanical Review 26:1–77.

Epps, C.W., D.R. McCullough, J.D. Wehausen, V.C. Bleich, and J.L. Riechel. 2004. Effects of climate change on population persistence of desert-dwelling mountain sheep in California. Conservation Biology 18:102–113.

Evans, R.D., and J.R. Johansen. 1999. Microbiotic crusts and ecosystem processes. Critical Reviews in Plant Sciences 18:183–225.

Fagerstone, K.A., and C.A. Ramey. 1996. Rodents and lagomorphs. Pages 83–132 in P.R. Krausman (ed.), Rangeland Wildlife. 1st edition. The Society for Range Management, Denver, Colorado.

Fernandez–Gimenez, M.E., and B. Allen–Diaz. 1999. Testing a non-equilibrium model of rangeland variation dynamics in Mongolia. Journal of Applied Ecology 36:871–885.

Fitzner, R.E. 1975. Owl mortality on fences and utility lines. Raptor Research 9:55–57.

Fleischner, T.L. 1994. Ecological costs of livestock grazing in western North America. Conservation Biology 8:629–644.

Flesh, A.D. 2003. Distribution, Abundance and Habitat of Cactus Ferruginous Pygmy-Owls in Sonora, Mexico. Unpublished master's thesis. University of Arizona, Tucson. 160 p.

Friedel, M.H. 1991. Range condition assessment and the concept of thresholds: a viewpoint. Journal of Range Management 44:422–426.

Fuhlendorf, S.D., and D.M. Engle. 2001. Restoring heterogeneity on rangelands: ecosystem management based on evolutionary grazing patterns. BioScience 51:625–632.

Fuhlendorf, S.D., and F.E. Smeins. 1998. The influence of soil depth on plant species response to grazing within a semi-arid savanna. Plant Ecology 138:89–96.

Fuhlendorf, S.D., and F.E. Smeins. 1999. Scaling effects of grazing in a semi-arid grassland. Journal of Vegetation Science 10:731–738.

Fuhlendorf, S.D., D.D. Briske, and F.E. Smeins. 2001. Herbaceous vegetation change in variable rangeland environments: the relative contribution of grazing and climatic variability. Applied Vegetation Science 4:177–188.

Galt, D., G. Mendez, J. Holechek, and J. Joseph. 1999. Heavy winter grazing reduces forage production: an observation. Rangelands 21:18–21.

Galt, D., F. Molinar, J. Navarro, J. Joseph, and J. Holechek. 2000. Grazing capacity and stocking rate. Rangelands 22:7–11.

Gardner, J.L. 1950. Effects of thirty years of protection from grazing in desert grassland. Ecology 31:44–50.

Gardner, J.L. 1951. Vegetation of the creosotebush area of the Rio Grande Valley in New Mexico. Ecological Monographs 21:379–403.

Gelbard, J.L., and S. Harrison. 2003. Roadless habitats as refuges for native grasslands: interactions with soil, aspect, and grazing. Ecological Applications 13:404–415.

Germano, D.J., and C.R. Hungerford. 1981. Reptile population changes with manipulation of Sonoran Desert scrub. Great Basin Naturalist 41:129–138.

Germano, D.J., R. Hungerford, and S.C. Martin. 1983. Responses of selected wildlife species to the removal of mesquite from desert grassland. Journal of Range Management 36:309–311.

Gibbens, R.P., J.M. Tromble, J.T. Hennessy, and M. Cardenas. 1983. Soil movement in mesquite dunelands and former grasslands of southern New Mexico from 1933 to 1980. Journal of Range Management 36:145–148.

Goldberg, D.E., and R.M. Turner. 1986. Vegetation change and plant demography in permanent plots in the Sonoran Desert. Ecology 67:695–712.

Grant, W.E., E.C. Birney, N.R. French, and D.M. Swift. 1982. Structure and productivity of grassland small mammal communities related to grazing-induced changes in vegetative cover. Journal of Mammalogy 63:248–260.

Griffiths, P.G., R.H. Webb, N. Lancaster, C.A. Kaehler, and S.C. Lundstrom. 2002. Long-Term Sand Supply to Coachella Valley Fringe-Toed Lizard Habitat in the Northern Coachella Valley, California. Water–Resources Investigations Report 02–4013. U.S. Department of the Interior, U.S. Geological Survey, Tucson, Arizona. 49 p.

Grover, M.C., and L.A. DeFalco. 1995. Desert Tortoise (*Gopherus Agassizii*): Status-of-Knowledge Outline With References. INT–GTR–316. U.S. Department of the Agriculture, Forest Service, Ogden, Utah. 134 p.

Hanley, T.A., and W.W. Brady. 1977. Feral burro impact on a Sonoran Desert range. Ecology 30:374–377.

Hayes Jr., J.U. 2004. Perennial Grass Abundance and Livestock Management in the Arid Rangelands of the Sif-Oidak-Oidak District, Tohono O'Odham Nation. Unpublished master's thesis. University of Arizona, Tucson. 165 p.

Helbsing, T., and N. Fisher. 1992. Demographic patterns of saguaro and fish-hook barrel cactus populations in the cactus forest of Saguaro National Monument. Pages 13–22 in C.P. Stone and E.S. Bellantoni (eds.), Proceedings of the Symposium on Research in Saguaro National Monument. 23–24 January 1991, Tucson, Arizona. National Park Service, Rincon Institute and Southwewst Parks and Monument Association, Tucson, Arizona.

Herbel, C.H., and R.P. Gibbern. 1996. Post-Drought Vegetation Dynamics on Arid Rangelands of Southern New Mexico. Agricultural Experimental Station Bulletin 776. New Mexico State University, College of Agricultre and Home Economics, Las Cruces. 102 + ii p.

Heske, E.J., and M. Campbell. 1991. Effects of an 11-year livestock exclosure on rodent and ant numbers in the Chihuahuan Desert, southeastern Arizona. Southwestern Naturalist 36:89–93.

Hobbs, R.J. 1989. The nature and effects of disturbance relative to invasions. Pages 389–405 in J.A. Drake, Biological Invasions: A Global Perspective. John Wiley & Sons Ltd, New York.

Holechek, J.L. 1983. Considerations concerning grazing systems. Rangelands 5:208–211.

Holechek, J.L., and C.H. Herbel. 1982. Seasonal suitability grazing in the western United States. Rangelands 4:252–255.

Holechek, J.L., T.T. Baker, and J.C. Boren. 2004. Impacts of Controlled Grazing Versus Grazing Exclusion on Rangeland Ecosystems: What We Have Learned. Range Improvement Task Force Report 57. New Mexico State University, Las Cruces. 42 p.

Holechek, J.L., H. Gomes, F. Molinar, D. Galt, and R. Valdex. 2000. Short-duration grazing: the facts in 1999. Rangelands 22:18–22.

Holechek, J.L., R.D. Pieper, and C.H. Herbel. 2004. Range Management: Principles and Practices. 5th edition. Pearson Prentice Hall, New Jersey. 607 p.

Holechek, J.L., R. Valdez, S.D. Schemnitz, R.D. Pieper, and C.A. Davis. 1982. Manipulation of grazing to improve or maintain wildlife habitat. Wildlife Society Bulletin 10:204–210.

Hovorka, M.D. 1996. The Impacts of Livestock Grazing on Sonoran Desertscrub Vegetation, Insect and Insectivorous Bat Communities. Unpublished master's thesis. York University, Toronto, Ontario. 84 p.

Howery, L. 1999. Rangeland Management Before, During, and After Drought. Arizona Cooperative Extension Bulletin AZ1136. University of Arizona, Tucson.

Howery, L.D., J.E. Sprinkle, and J.E. Bowns. 2000. A Summary of Livestock Grazing Systems Used on Rangelands in the Western United States and Canada. Arizona Cooperative Extension Bulletin AZ1184. University of Arizona, Tucson.

Howland, J.M., and J.C. Rorabaugh. 2002. Conservation and protection of the desert tortoise in Arizona. Pages 334–354 in T.R. Van Devender (ed.), The Sonoran Desert Tortoise: Natural History, Biology, and Conservation. The University of Arizona Press and Arizona-Sonora Desert Museum. Tucson.

Hughes, L.E. 1982. A grazing system in the Mohave Desert. Rangelands 4:256–257.

Hunter, J.E. 1991. Grazing and pocket gopher abundance in a California annual grassland. The Southwestern Naturalist 36:117–118.

Iglesias, R.M.R., and M.M. Kothman. 1997. Structure and causes of vegetation change in state and transition model applications. Journal of Range Management 50:399–408.

Illius, A.W., and T.G. O'Connor. 1999. On the relevance on nonequilibrium concepts to arid and semiarid grazing systems. Ecological Applications 9:788–813.

Illius, A.W., and T.G. O'Connor. 2000. Resource heterogenity and ungulate population dynamics. Oikos 89:283–294.

Iverson, R.M., B.S. Hinckley, R.H. Webb, and B. Hallet. 1981. Physical effects of vehicular disturbances on arid landscapes. Science 212:915–917.

Johansen, J.R. 1986. Importance of cryptogamic soil crusts to arid rangelands: implications for short duration grazing. Pages 127–136 in Proceedings of the Pacific Northwest Range Management Shortcourse. 21–23 January 1986, Kennewick, Washington. Cooperative Extension, Washington State University, Pullman.

Johansen, J.R., and L.L. St. Clair. 1986. Cryptogamic soil crusts: recovery from grazing near Camp Floyd State Park, Utah. Great Basin Naturalist 46:632–640.

Jones, A. 2000. Effects of cattle grazing on North American arid ecosystems: a quantitative review. Western North American Naturalist 60:155–164.

Jones, A. 2001. Review and Analysis of Cattle Grazing Effects in the Arid West, With Implications for BLM Grazing Management in Southern Utah. The Wild Utah Project, Utah.

Jones, A., and W.S. Longland. 1999. Effects of cattle grazing on Salt Desert rodent communities. The American Midland Naturalist 141:1–11.

Jones, K.B. 1981. Effects of grazing on lizard abundance and diversity in western Arizona. Southwestern Naturalist 26:107–115.

Jones, Z.F., C.E. Bock, and J.H. Bock. 2003. Rodent communities in a grazed and ungrazed Arizona grassland, and a model of habitat relationships among rodents in southwestern grass/shrublands. American Midland Naturalist 149:384–394.

Kade, A., and S.D. Warren. 2002. Soil and plant recovery after historic military disturbance in the Sonoran Desert, USA. Arid Land Research and Management 16:231–243.

Kelt, D.A., and T.J. Valone. 1995. Effects of grazing on the abundance and diversity of annual plants in Chihuahuan desert scrub habitat. Oecologia 103:191–195.

Kie, J.G., C.J. Evans, E.R. Loft, and J.W. Menke. 1991. Foraging behavior by mule deer: the influence of cattle grazing. Journal of Wildlife Management 55:665–674.

Kleiner, E.F., and K.T. Harper. 1977. Soil properties in relation to cryptogamic groundcover in Canyonlands National Park. Journal of Range Management 30:202–205.

Klipple, G.E., and R.E. Bement. 1961. Light grazing—is it economically feasible as a range-improvement practice. Journal of Range Management 14:57–62.

Knight, R.L., J. Skriletz, and D.C. Ryan. 1980. Four additional cases of bird mortality on barbed-wire fences. Western Birds 11:202.

Kochert, M., B.A. Millsap, and K. Steenhof. 198. Effects of livestock grazing on raptors with emphasis on the southwestern U.S. Pages 325–334 in Glinski R.L., B.G. Pendleton, Moss. M.B., M.N. LeFranc, B.A. Millsap Jr., and S.W. Hoffman (eds.), Proceedings of the Southwest Raptor Management Symposium and Workshop. 21–24 May 1986, Tucson, Arizona. National Wildlife Federation, Washington, D.C.

Krausmann, P.R. 2000. An introduction to the restoration of Bighorn Sheep. Restoration Ecology 8:3–5.

Krausman, P.R., B.D. Jansen, J.R. Heffelfinger, C.R. Anderson, J.C. DeVos Jr., and T.D. Noon. In Press. Desert bighorn sheep, disease, and urbanization. In Proceedings of the Sixth International Game Ranching Symposium. In Press, Paris, France.

Krausman, P.R., R. Valdez, and J.A. Bissonette. 1996. Bighorn sheep and livestock. Pages 237–243 in P.R. Krausman (ed.), Rangeland Wildlife. 1st edition. The Society for Range Management, Denver, Colorado.

Lacey, J.R. 1987. The influence of livestock grazing on weed establishment and spread. Pages 131–145 in Proceedings of the Montana Academy of Science: Weed Symposium. 1987,

Laycock, W.A. 1991. Stable state and thresholds of range condition on North American rangelands: a viewpoint. Journal of Range Management 44:427–433.

Loft, E.R., J.W. Menke, and J.G. Kie. 1991. Habitat shifts by mule deer: the influence of cattle grazing. Journal of Wildlife Management 55:16–26.

Longhurst, W.M., R.E. Hafenfeld, and G.E. Connoly. 1981. Deer-livestock interrelationships in the western states. Pages 409–420 in Proceedings of the Wildlife - Livestock Relationships Symposium. 20–22 April 1981, Coeur d'Alene, Idaho. University of Idaho, Moscow.

Lusby, G.C. 1970. Hydrological and biotic effects of grazing vs. non-grazing near Grand Junction, Colorado. Journal of Range Management 23:256–260.

Mack, R.N. 1981. Invasion of *Bromus tectorum* L. into western North America: an ecological chronicle. Agro-Ecosystems 7:145–165.

Mack, R.N., and J.N. Thompson. 1982. Evolution in steppe with few large, hooved mammals. The American Naturalist 119:757–773.

MacPhee, D.T. 1991. Prescribed burning and managed grazing restore tobosa grassland, antelope populations. Restoration and Management Notes 9:35–36.

Marble, J.R., and K.T. Harper. 1989. Effect of timing of grazing on soil-surface cryptogamic communities in a Great Basin low-shrub desert: a preliminary report. Great Basin Naturalist 49:105–107.

Martin, S.C. 1973. Responses of semidesert grasses to seasonal rest. Journal of Range Management 26:165–170.

Martin, S.C., and K.E. Severson. 1988. Vegetation response to the Santa Rita grazing system. Journal of Range Management 41:291–295.

Martin, S.C., and R.M. Turner. 1977. Vegetation change in the Sonoran Desert region, Arizona and Sonora. Journal of the Arizona Academy of Science 12:59–69.

Martin, S.C., and D.E. Ward. 1976. Perennial grasses respond inconsistently to alternate year seasonal rest. Journal of Range Management 29:346.

McAuliffe, J.R. 1998. Rangeland water developments: conservation solution or illusion? Pages 360–375 in Proceedings of the Environmental, Economic And Legal Issues Related To Rangeland Water Developments. 13–15 November 1997, Tempe, Arizona. Center for the Study of Law, Science, and Technology, Arizona State University, Tempe.

McIlvanie, S.K. 1942. Grass seedling establishment, and productivity - overgrazed vs. protected range soils. Ecology 23:228–231.

McNaughton, S.J. 1983. Compensatory plant growth as a response to herbivory. Oikos 40:329–336.

McNaughton, S.J. 1986. On plants and herbivores. The American Naturalist 128:765–770.

McNaughton, S.J. 1993. Grasses and grazers, science and management. Ecological Applications 3:17–20.

McNay, M.E., and B.W. O'Gara. 1982. Catte-pronghorn interactions during the fawning season in northwestern Nevada. Pages 593–606 in Proceedings of the Wildlife-Livestock Relationships Symposium. 20–22 April 1981, Coeur d’Alene, Idaho. Forest, Wildlife, and Range Experiment Station, University of Idaho, Moscow.

Memmott, K.L., V.J. Anderson, and S.B. Monsen. 1998. Seasonal grazing impact on cryptogamic crusts in a cold desert ecosystem. Journal of Range Management 51:547–550.

Milchunas, D.G. In Press. Responses of Plant Communities to Grazing in the Southwestern United States. General Technical Report. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Milchunas, D.G., and W.K. Lauenroth. 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. Ecological Monographs 63:327–366.

Milchunas, D.G., and I. Noy–Meir. 2002. Grazing refuges, external avoidance of herbivory and plant density. Oikos 99:113–130.

Milchunas, D.G., O.E. Sala, and W.K. Lauenroth. 1988. A generalized model of the effects of grazing by large herbivores on grassland community structure. American Naturalist 132:87–106.

Monson, G., and L. Sumner. 1990. The Desert Bighorn. 4th edition. The University of Arizona Press, Tucson. 370 p.

Murray, A.V. 1959. An Analysis of Changes in Sonoran Desert Vegetation for the Years 1928-1957. Unpublished master's thesis. University of Arizona, Tucson. 146 p.

Nash, M.S., D.F. Bradford, S.E. Franson, A.C. Neale, W.G. Whitford, and D.T. Heggem. 2004. Livestock grazing effects on ant communities in the eastern Mojave Desert, USA. Ecological Indicators 4:199–213.

Nash, M.S., W.G. Whitford, D.F. Bradford, S.E. Franson, A.C. Neale, and D.T. Heggem. 2001. Ant communities and livestock grazing in the Great Basin, USA. Journal of Arid Environments 49:695–710.

Nash, M.S., W.G. Whitford, A.G. de Soyze, J.W. Ven Zee, and K.M. Havstad. 1999. Livestock activity and Chihuahuan Desert annual-plant communities: boundary analysis of disturbance gradients. Ecological Applications 9:814–823.

Nash, M.S., W.G. Whitford, J. Van Zee, and K.M. Havstad. 2000. Ant (Hymenoptera: Formicidae) response to environmental stressors in the northern Chihuahuan Desert. Environmental Entomology 29:200–206.

Nash III, T.H., S.L. White, and J.E. Marsh. 1977. Lichen and moss distribution and biomass in hot desert ecosystems. Bryologist 80:470–479.

Navarro, J.M., D. Galt, J. Holechek, J. McCormick, and F. Molinar. 2002. Long-term impacts of livestock grazing on Chihuahuan Desert rangelands. Journal of Range Management 55:400–405.

Nelson, T., J.L. Holechek, R. Valdez, and M. Cardenas. 1997. Wildlife numbers on late and mid seral Chihuahuan Desert rangelands. Journal of Range Management 50:493–499.

Neuenschwander, L.F., S.H. Sharrow, and H.A. Wright. 1975. Review of tobosa grass (*Hilaria mutica*). The Southwestern Naturalist 20:255–263.

Niering, W.A., and C.H. Lowe. 1984. Vegetation of the Santa Catalina Mountains: community types and dynamics. Vegetatio 58:3–28.

Niering, W.A., R.H. Whittaker, and C.H. Lowe. 1963. The saguaro: a population in relation to environment. Science 142:15–23.

Noy-Meir, I. 1993. Compensating growth of grazed plants and its relevance to the use of rangelands. Ecological Applications 3:32–34.

Oesterheld, M., O.E. Sala, and S.J. McNaughton. 1992. Effect of animal husbandry on herbivore-carrying capacity at a regional scale. Nature 356:234–236.

Oftedal, O. 2002. Nutritional ecology of the desert tortoise in the Mohave and Sonoran Deserts. Pages 194–241 in T.R. Van Devender (ed.), The Sonoran Desert Tortoise: Natural History, Biology, and Conservation. The University of Arizona Press and Arizona-Sonora Desert Museum. Tucson.

Oldemeyer, J.K., and L.R. Allen–Johnson. 1988. Cattle grazing and small mammals on the Sheldon National Wildlife Refuge, Nevada. Pages 391–398 in Proceedings of the Management of Amphibians, Reptiles, and Small Mammals in North America. 19–21 July 1988, Flagstaff, Arizona. GTR–RM–166. U.S. Department of the Agriculture, U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Ortega, I.M., S.B.F.C. Soltero-Gardea, and D.L. Drawe. 1997. Evaluating grazing strategies for cattle: deer and cattle food partitioning. Journal of Range Management 50:622–630.

Painter, E.L., and A.J. Belsky. 1993. Application of herbivore optimization theory to rangelands of the western United States. Ecological Applications 3:2–9.

Parker, K.C. 1993. Climatic effects on regeneration trends for two columnar cacti in the northern Sonoran Desert. Annals of the Association of American Geographers 83:452–474.

Paulson Jr., H.A., and F.N. Ares. 1962. Grazing Values and Management of Black Grama and Tobosa Grasslands and Associated Shrubs Ranges of the Southwest. Technical Bulletin No. 1270. U.S. Department of Agriculture, U.S. Forest Service, Washington, D.C. 56 + v p.

Peek, J.W., and P.R. Krausman. 1996. Grazing and mule deer. Pages 183–192 in P.R. Krausman (ed.), Rangeland Wildlife. 1st edition. The Society for Range Management, Denver, Colorado.

Pieper, R.D. 1994. Ecological implications of livestock grazing. Pages 177–211 in M. Vavra, W.A. Laycock, and R.D. Pieper (eds.), Ecological Implications of Livestock Herbivory in the West. 2nd edition. Society for Range Management, Denver, Colorado.

Pieper, R.D., and R.K. Heitschmidt. 1988. Is short-duration grazing the answer? Journal of Soil and Water Conservation March–April:133–137.

Pieper, F.R., R.F. Beck, R.P. Gibbens, and G.B. Donart. 1993. Sustainable livestock grazing in New Mexico. Pages 847–854 in Proceedings of the New Mexico Conference on the Environment.

Pierson, E.A., and R.M. Turner. 1998. An 85-year study of Saguaro (*Carnegiea gigantea*) demography. Ecology 79:2676–2693.

Ragotzkie, K.E., and J.A. Bailey. 1991. Desert mule deer use of grazed and ungrazed habitats. Journal of Range Management 44:487–490.

Ralphs, M.H., M.M. Kothmann, and C.A. Taylor. 1990. Vegetation response to increased stocking rates in short-duration grazing. Journal of Range Management 43:104–108.

Rambo, J.L., and S.H. Faeth. 1999. Effect of vertebrate grazing on plant and insect community structure. Conservation Biology 13:1047–1054.

Rebello, S., D.G. Milchunas, I. Noy–Meir, and P.L. Chapman. 2002. The role of a spiny plant refuge in structuring grazed shortgrass steppe plant communities. Oikos 98:53–64.

Reynolds, H.G. 1950. Relation of Merriam kangaroo rats to range vegetation in southern Arizona. Ecology 31:456–463.

Reynolds, H.G. 1958. The ecology of the Merriam kangaroo rat (*Dipodomys merriami* Mearns) on the grazing lands of southern Arizona. Ecological Monographs 28:111–127.

Robinett, D. 1992. Drought and recovery in the upper Sonoran Desert. Rangelands 14:219–222.

Romera-Schmidt, H.L., and A. Ortega-Rubio. 1999. Changes in lizard abundance on protected versus grazed desert scrub in Baja California Sur, Mexico. Brazilian Archives of Biology and Technology 42:175–180.

Rosenstock, S.S. 1996. Shrub-grassland small mammal and vegetation responses to rest from grazing. Journal of Range Management 49:199–203.

Roundy, B.A., and G.L. Jordan. 1988. Vegetation changes in relation to livestock exclusion and root plowing in southeastern Arizona USA. Southwestern-Naturalist. 33:425–436.

Roundy, B.A., and G.B. Ruyle. 1989. Effects of herbivory on twig dynamics of a Sonoran Desert shrub *Simmondsia chinensis* (Link) Schn. Journal of Applied Ecology 26:701–710.

Roundy, B.A., G.B. Ruyle, and J. Ard. 1989. Estimating production and utilization of jojoba. Journal of Range Management 42:75–78.

Rutman, S. 1998. Dirt is not cheap: Livestock grazing and a legacy of accelerated soil erosion on Organ Pipe Cactus National Monument, Arizona. Pages 360–375 in Proceedings of the Environmental, Economic And Legal Issues Related To Rangeland Water Developments. 13–15 November 1997, Tempe, Arizona. Center for the Study of Law, Science, and Technology, Arizona State University, Tempe.

Ryerson, D.E., and R.R. Parmenter. 2001. Vegetation change following removal of keystone herbivores from desert grasslands in New Mexico. Journal of Vegetation Science 12:167–180.

Salihi, D.O., and B.E. Norton. 1987. Survival of perennial grass seedlings under intensive grazing in semi-arid rangelands. Journal of Applied Ecology 24:145–151.

Sanchez, F.C. 1993. Influences of Range Condition, Cattle, and Watering Hole Distribution on a Pronghorn Population in Southcentral New Mexico. Unpublished doctoral dissertation. New Mexico State University, Las Cruces. 130 + xvii p.

Sayre, N.F. 2001. The New Ranch Handbook: A Guide to Restoring Western Rangelands. 1st edition. Quivira Coalition, Santa Fe, New Mexico. 102 p.

Schmutz, E.M., and D.A. Smith. 1976. Successional classification of plants on a desert grassland site in Arizona. Journal of Range Management 29:476–479.

Senft, R.L. 1983. The Redistribution of Nitrogen by Cattle. Unpublished doctoral dissertation. Colorado State University, Fort Collins. xi + 151 p.

Senock, R.S., D.M. Anderson, L.W. Murray, and G.B. Donart. 1993. Tobosa tiller defoliation patterns under rotational and continuous stocking. Journal of Range Management 46:500–505.

Shreve, F. 1929. Changes in desert vegetation. Ecology 10:364–373.

Shreve, F., and A.L. Hinckley. 1937. Thirty years of change in desert vegetation. Ecology 18:463–478.

Smith, D.A., and E.M. Schmutz. 1975. Vegetative changes on protected versus grazed desert grassland ranges in Arizona. Journal of Range Management 28:453–458.

Sredl, M.J., and L.S. Saylor. 1998. Conservation and management zones and the role of earthen cattle tanks in conserving Arizona leopard frogs on large landscapes. Pages 211–226 in Proceedings of the Environmental, Economic And Legal Issues Related To Rangeland Water Developments. 13–15 November 1997, Tempe, Arizona. Center for the Study of Law, Science, and Technology, Arizona State University, Tempe.

Stauber, E.H., R. Autenrieth, O.D. Markham, and V. Whitbeck. 1980. A seroepidemiologic survey of three pronghorn (*Antilocapra americana*) populations in southeastern Idaho, 1975–1977. Journal of Wildlife Diseases 16:109–115.

Steiger, J.W., and R.H. Webb. 2000. Recovery of Perennial Vegetation in Military Target Sites in the Eastern Mojave Desert, Arizona. Open–File Report OF 00–355. U.S. Department of the Interior, U.S. Geological Survey, 28 p.

Taylor, W.P., C.T. Vorhies, and P.B. Lister. 1935. The relation of jack rabbits to grazing in southern Arizona. Journal of Forestry 3:490–498.

Thompson–Olais, L.A. 1998. Final Revised Sonoran Pronghorn Recovery Plan (*Antilocapra Americana Sonoriensis*). U.S. Fish and Wildlife Service, Albuquerque, New Mexico. 54 + viii p.

Thurow, T.L., and C.A. Taylor Jr. 1999. Viewpoint: the role of drought in range management. Journal of Range Management 52:413–419.

Turner, R.M. 1990. Long-term vegetation change at a fully protected Sonoran Desert site. Ecology 71:464–477.

Turner, R.M. 1992. Long-term saguaro population studies at Saguaro National Monument. Pages 3–11 in C.P. Stone and E.S. Bellantoni (eds.), Proceedings of the Symposium on Research in Saguaro National Monument. 23–24 January 1991, Tucson, Arizona. National Park Service, Rincon Institute and Southwewst Parks and Monument Association, Tucson, Arizona.

Turner, R.M., and J.E. Bowers. 1988. Long-term changes in populations of *Carnegiea gigantea*, exotic plant species and *Cercidium floridum* at the Desert Laboratory, Tumamoc Hill, Arizona. Pages 445–456 in Proceedings of the Arid Lands Today and Tomorrow. 20–25 October 1985, Tucson, Arizona. Westview Press, Boulder, Colorado.

Turner, R.M., S.M. Alcorn, G. Olin, and J.A. Booth. 1966. The influence of shade, soil, and water on Saguaro seedling establishment. Botanical Gazette 127:95–102.

Turner, R.M., R.H. Webb, J.E. Bowers, and J.R. Hastings. 2003. The Changing Mile Revisited: An Ecological Study of Vegetation Change With Time in the Lower Mile of an Arid and Semiarid Region. 1st edition. The University of Arizona Press, Tucson. xvi + 334 p.

U.S. Fish and Wildlife Service. 1981. Final Environmental Impact Statement on the Proposal to Eliminate Cattle Grazing and Wild Burro Population on the Kofa National Wildlife Refuge. U.S. Fish and Wildlife Service, Albuquerque, New Mexico. 86 + ix p.

U.S. Forest Service. 1998. Biological Assessment of on-Going and Long-Term Grazing on the Coronado National Forest. Coronado National Forest Supervisor's Office, Tucson, Arizona. 428 p.

U.S. General Accounting Office. 1991. Rangeland Management BLM's Hot Desert Grazing Program Merits Reconsideration. GAO/RECD–92–12. United States General Accounting Office, Washington, D.C. 68 p.

Valone, T.J., M. Meyer, J.H. Brown, and R.M. Chew. 2002. Timescale of perennial grass recovery in desertified arid grasslands following livestock removal. Conservation Biology 16:995–1002.

Van Devender, T.R. (ed.). 2002. The Sonoran Desert Tortoise: Natural History, Biology, and Conservation. The University of Arizona Press and Arizona-Sonora Desert Museum, Tucson. 389 p.

Walker, B.H., D. Ludwig, C.S. Holling, and R.M. Peterman. 1981. Stability of semi-arid savanna grazing systems. Journal of Ecology 69:473–498.

Wallace, L.L., and M.I. Dyer. 1996. Grazing effects on grassland ecosystems. Pages 13–19 in D. Finch (ed.), Proceedings of the Ecosystem Disturbance and Wildlife Conservation in Western Grasslands. 1996, RM–GTR–285. U.S. Department of the Agriculture, U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station,

Warren, P.L., and L.S. Anderson. 1987. Vegetation Recovery Following Livestock Removal Near Quitobaquito Springs Organ Pipe National Monument. Technical Report 20. University of Arizona, Tucson. 40 p.

Warren, P.L., and L.S. Anderson. 1992. Ecosystem Recovery from Grazing at Organ Pipe Cactus National Monument: Plant and Rodent Community Changes between 1975–76 and 1987–88. Arizona Nature Conservancy, Tucson. 55 p.

Warren, S.D., W.H. Blackburn, and C.A. Taylor Jr. 1986. Effects of season and state of rotation cycle on hydrologic condition of rangeland under intensive rotation grazing. Journal of Range Management 39:486–491.

Warren, S.D., and D.J. Elderidge. 2001. Biological soil crusts and livestock in arid ecosystems: are they compatible? Pages 401–415 in J. Belnap and O.L. Lange (eds.), Biological Soil Crusts: Structure, Function, and Management. 1st edition. Ecological Studies, Volume 150. Springer-Verlag, Berlin.

Warren, S.D., M.B. Nevill, W.H. Blackburn, and N.E. Garza. 1986. Soil response to trampling under intensive rotation grazing. Soil Science Society of America Journal 50:1336–1341.

Waser, N.M., and M.V. Price. 1981. Effects of grazing on diversity of annual plants in the Sonoran Desert. Oecologia 50:407–411.

Watson, I.W., D.G. Burnside, and A.M. Holm. 1996. Event-driven or continuous: which is the better model for managers? Rangelands Journal 18:351–369.

Webb, R.H. 1980. An Annotated Bibliography of the Effects of Livestock Grazing on Soils, Vegetation, and Wildlife. Open-file Report 78–149. U.S. Department of the Interior, Geological Survey. 21p.

Webb, R.H. 1982. Off-road motorcycle effects on a desert soil. Environmental Conservation 9:197–208.

Webb, R.H. 2002. Recovery of severely compacted soils in the Mojave Desert, California, USA. Arid Land Research and Management 16:291–305.

Webb, R.H., and E.B. Newman. 1982. Recovery of soils and vegetation in Mojave Desert ghost towns. Environmental Conservation 9:245–248.

Webb, R.H., and S.S. Stielstra. 1979. Sheep grazing effects on Mojave Desert vegetation and soils. Environmental Managment 3:519–529.

Webb, R.H., and H.G. Wilshire. 1980. Recovery of soils and vegetation in a Mojave Desert ghost town, Nevada, USA. Journal of Arid Environments 3:291–303.

Webb, R.H., and H.G. Wilshire. 1983. Environmental Effects of Off-Road Vehicles: Impacts and Management in Arid Regions. 1st edition. Springer-Verlag, New York. 534 p.

Webb, R.H., and K.A. Thomas. 2000. Recoverability of severely disturbed soils and vegetation in the Mojave Desert, California, USA. Pages 283–290 in A.S. Alsharhan, W.W. Wood, A.S. Goudie, A. Fowler, and E.M. Abdellatif (eds.), Proceedings of the Desertification in the Third Millennium. 12–15 February 2000, Dubai. Swets & Zeitlinger (Balkema) Publishers, The Netherlands.

Webb, R.H., T.C. Esque, P.A. Medica, L.A. DeFalco, and M.B. Murov. 2001. Monitoring of Ecosystem Dynamics in the Mojave Desert: The Beatley Permanent Plots. U.S. Geological Survey Fact Sheet FS-040-01. U.S. Department of the Interior, U.S. Geological Survey, Sacramento, California. 4 p.

Webb, R.H., M.B. Murov, T.C. Esque, D.E. Boyer, L.A. DeFalco, D.F. Haines, D. Oldershaw, S.J. Scoles, K.A. Thomas, J.B. Blainey, and P.A. Medica. 2003. Perennial Vegetation Data From Permanent Plots on the Nevada Test Site, Nye County, Nevada. Open-File Report 03-336. U.S. Department of the Interior, U.S. Geological Survey, Sacramento, California. 257 p.

Webb, R.H., H.C. Ragland, W.H. Godwin, and D. Jenkins. 1978. Environmental effects of soil property changes with off-road vehicle use. Environmental Managment 2:219–233.

Webb, R.H., J.W. Steiger, and E.B. Newman. 1988. The Response of Vegetation to Disturbance in Death Valley National Monument, California. U.S. Geological Survey Bulletin 1793. U.S. Department of the Interior, U.S. Geological Survey, Washington, D.C. 103 p.

Webb, R.H., J.W. Steiger, and R.M. Turner. 1987. Dynamics of Mojave Desert scrub assemblages in the Panamint Mountains, California. Ecology 68:478–490.

Webb, R.H., J.W. Steiger, and H.G. Wilshire. 1986. Recovery of compacted soils in Mojave Desert ghost towns. Soil Science Society of America Journal 50:1341–1344.

Weigel, J.R., C.M. Britton, and G.R. McPherson. 1990. Trampling effects from short-duration grazing on tobosa-grass range. Journal of Range Management 43:92–95.

West, N.E., F.D. Provenza, P.S. Johnson, and M.K. Owens. 1984. Vegetation change after 13 years of livestock grazing exclusion on sagebrush semidesert in west central Utah. Journal of Range Management 37:262–264.

Westoby, M., B. Walker, and I. Noy–Meir. 1989. Opportunistic management for rangelands not at equilibrium. Journal of Range Management 42:266–274.

Whitford, W.G., R. Repass, L.W. Parker, and N.Z. Elkins. 1982. Effects of initial litter accumulation and climate on litter disappearance in a desert ecosystem. American Midland Naturalist 108:105–110.

Whitford, W.G., J. Van Zee, M.S. Nash, W.E. Smith, and J.E. Herrick. 1999. Ants as indicators of exposure to environmental stressors in North American desert grasslands. Environmental Monitoring and Assessment 54:143–171.

Wright, H.A. 1973. Fire as a tool to manage tobosa grasslands. Pages 153–167 in Proceedings of the Tall Timbers Fire Ecology Conference. 8-9 June, Lubbock, Texas. Tall Timbers Research Station, Tallahassee, Florida.

Wright, R.L., and J.C. deVos Jr. 1986. Final Report on Sonoran Pronghorn Status in Arizona. Arizona Game and Fish Department, Phoenix, Arizona. 131 + v p.

Yoakum, J.D. 1975. Antelope and livestock on rangelands. Journal of Animal Science 40:985–992.

Yoakum, J.D., and B.W. O'Gara. 1990. Pronghorn/livestock relationships. Transactions North American Wildlife and Natural Resources Conference 55:475–487.

Yoakum, J.D., B.W. O'Gara, and V.W. Howard Jr. 1996. Pronghorn on western rangelands. Pages 211–226 in P.R. Krausman (ed.), Rangeland Wildlife. 1st edition. The Society for Range Management, Denver, Colorado.

APPENDIX D

SUMMARY OF MAIN FINDINGS IN REVIEWED LITERATURE

NOTE: THIS TABLE IS INCOMPLETE BUT IS PRESENTED AS AN EXAMPLE OF THE TYPE OF INFORMATION THAT WILL BE PROVIDED FOR ALL THE REVIEWED GRAZING LITERATURE IN THE DATABASE.

Author	**Year published**	**Ecoregion**	**Main Question**	**Summary**	**Other Question**	**Summary**	**Other Question**	**Summary**
Abou-Haidar, F.	1989	Sonoran Desert	Saguaro Impacts	The author found no significant differences in saguaro density, nurse plant density or canopy cover between adjoining grazed and ungrazed sites at Saguaro NP East. However, the age structures were divergent with significantly more young saguaro (less than 20 years old) in an area excluded from grazing for over 20 years than on the adjoining grazed area.				
Andrew, M.H.	1988	N/A	Vegetation/ Community Impacts	The relationship between an ecological variable and distance from a livestock watering point ("piosphere effect") is modeled. Ecological variables change exponentially with distance from water and level out at an asymptote after a given distance, depending on the landscape, stocking rate, and livestock behavior. Impacts are concentrated within a discrete zone, beyond which (at the asymptote portion of the curve) there is little change in a given ecological variable.				

Author	**Year published**	**Ecoregion**	**Main Question**	**Summary**	**Other Question**	**Summary**	**Other Question**	**Summary**
Barrett, S.L., and T.B. Johnson	1990	Sonoran Desert	Wildlife Species Impacts	The author's speculate that the Sonoran Desert tortoise may not be impacted by cattle grazing less than other wildlife in the Sonoran Desert based mainly on habitat factors such as distance to waters and percent slope that may segregate cattle from tortoises.				
Flesh, A.D.	2003	Sonoran Desert	Wildlife Species Impacts	The effects of grazing on the cactus ferruginous pygmy-owl are mixed depending on the present vegetation. In the short-term, livestock grazing could increase habitat suitability for pygmy-owls, however, in the long-term, it could adversely affect habitat-specific prey diversity and abundance and cacti regeneration.				
Goldberg, D.E., and R.M. Turner	1986	Sonoran Desert	Vegetation/ Community Impacts	On a site protected from grazing for 72 years, there were large fluctuations in absolute cover and density of most species with no consistent, directional change in vegetation composition. Changes in cover were largely due to climate and not grazing history. The exception to these general results was that *Janusia gracilis* and *Krameria grayi* showed continuous increases in density and cover with time since protection from grazing.				

Author	**Year published**	**Ecoregion**	**Main Question**	**Summary**	**Other Question**	**Summary**	**Other Question**	**Summary**
Hanley, T.A., and W.W. Brady	1977	Sonoran Desert	Vegetation/ Community Impacts	Feral burro grazing in secondary washes reduced total canopy cover and in particular the canopy cover of white bursage. The authors consider these washes to be the most important forage resource in the area and found that grazing impacts were the most pronounced in the secondary washes as compared to other communities.				
Hovorka, M.D.	1996	Sonoran Desert	Vegetation/ Community Impacts	Plant species richness, diversity, abundance, palatable species abundance, percentage cover and saguaro density were greater at an ungrazed site than a grazed site in the Rincon Mountains. There was no significant difference in these attributes at another site with paired grazed/ungrazed plots (in the Tucson and Silverbell Mtns).	Wildlife Species Impacts	There was no significant difference in insect order composition, insect abundance, insectivorous bat activity, or bat abundance between grazed and ungrazed sites. Insect abundance was largely dependent on local ambient conditions, independent of grazing history. Bat activity and abundance was not significantly different between grazed and ungrazed sites. Bat abundance is more likely to be dependent upon the availability of roost sites and water than insect composition or abundance.		

Author	**Year published**	**Ecoregion**	**Main Question**	**Summary**	**Other Question**	**Summary**	**Other Question**	**Summary**
Jones, K.B.	1981	Multiple (w/ SD or MD)	Wildlife Species Impacts	In vegetation communities where heavy livestock grazing affected vegetation structure (loss of perennial grasses and palatable shrubs; i.e. all vegetation communities except Sonoran Desertscrub), sites with heavy grazing had lower overall lizard abundance and species diversity. The effect of grazing intensity on particular lizard species depends on the foraging guild of the lizard. The strongest effect of grazing in all habitats, including Sonoran desertscrub, was observed for widely foraging species, such as whiptails (*Cnemidophorus* spp.), which had significantly greater relative abundance in lightly grazed or ungrazed areas in comparison to heavily grazed areas. The cause of the decrease in this lizard foraging guild in heavily grazed areas is unknown, but may be due to a reduction in their invertebrate prey or because the lack of perennial grasses makes microhabitats unsuitable.				

Author	**Year published**	**Ecoregion**	**Main Question**	**Summary**	**Other Question**	**Summary**	**Other Question**	**Summary**
Kade, A., and S.D. Warren	2002	Sonoran Desert	Soil and Biological Soil Crust Impacts	56 years after disturbance, there remain significant differences in soil attributes between disturbed and control sites. Biological soil crusts had mostly recovered at a site of vehicular traffic ("motor pool"), but were significantly reduced (84% of the control site) at a more heavily disturbed site which had been leveled ("tent camp"). All disturbed sites had significantly lower soil penetrance (greater soil compaction) than the control site. The control site had significantly higher N content than the disturbed sites; the tent city had significantly greater N content than the motorpool.	Non-grazing Impacts	The paper addressed disturbances caused by historic military training, including intense foot and vehicular traffic.	Vegetation/Community Impacts	There was significantly less vegetation cover and density in the control site and most heavily disturbed "tent city" site than at the "motor pool" site. Soil compaction at the motor pool site likely benefited shallow-rooted plant species by providing them with more moisture in upper soil layers.
Knight, R.L., J. Skriletz, and D.C. Ryan	1980	Other	Wildlife Species Impacts	Short-eared owls (*Asio flammeus*), Barn owls (*Tyto alba*), Great Blue Herons (*Ardea herodias*), and Soras (*Porzana carolina*) have been found dead and impaled by barbed wire fences. The birds all appeared to have hit the fence at high speed indicating that they either did not perceive the fence as a threat or did not see it. Barbed-wire fences present a hazard to all bird species that fly close to the ground.				

Author	**Year published**	**Ecoregion**	**Main Question**	**Summary**	**Other Question**	**Summary**	**Other Question**	**Summary**
Ragotzkie, K.E., and J.A. Bailey	1991	Apache Highlands	Wildlife Species Impacts	Desert mule deer, particularly females during the pre-monsoon drought, use ungrazed portions of their home range significantly more than expected and used grazed upland portions significantly less than expected. It is unclear if the mule deer are selecting ungrazed sites based on ecological attributes or to avoid cattle.				
Sredl, M.J., and L.S. Saylor	1998	Multiple (w/ SD or MD)	Wildlife Species Impacts	Rangeland water developments, such as stock tanks, are important habitat refugia for native frogs such as the lowland and Chiricahua leopard frogs, which require semi-permanent or permanent aquatic habitat for reproduction and juvenile development.				

Author	**Year published**	**Ecoregion**	**Main Question**	**Summary**	**Other Question**	**Summary**	**Other Question**	**Summary**
U.S. Fish and Wildlife Service	1981	Sonoran Desert	Grazing System	A no-action, elimination of grazing, and 3 grazing management alternatives were evaluated for their potential benefit to habitat, soils, and wildlife at Kofa NWR. Livestock management alternatives included: (1) a reduced stocking rate, year-round grazing; (2) seasonal grazing from Nov-April; (3) deferred-rotation grazing system. The Proposed Action was to eliminate cattle and wild burros, which will decrease competition with bighorn sheep and other species for water, food, cover and space.	Wildlife Species Impacts	Removal of cattle and burros was expected to benefit the following wildlife species: (1) bighorn sheep, with less competition to access habitat and water; (2) mule deer, which were more abundant in ungrazed sites and compete with cattle for forage, especially jojoba; (3) small mammal and predator populations; small mammals are more abundant on ungrazed plots (with some exceptions, e.g kangaroo rats); (4) birds, including the brown towhee and crissal thrasher, who are tied to jojoba and were more abundant on robust, ungrazed plants; (5) reptiles and amphibians- expected to benefit but no pattern of abundance or composition was found with grazing intensity; (6) desert tortoise- densities on the Refuge were low in areas grazed by cattle and there may be some competition for forage between the species, but more studies are needed.	Vegetation/Community Impacts	Year-round grazing by cattle and wild burros caused significantly lower species richness, cover, and abundance of plants than at ungrazed sites. At grazed sites, jojoba had significantly lower heights, volume, flowering rates, and seed production.

Author	**Year published**	**Ecoregion**	**Main Question**	**Summary**	**Other Question**	**Summary**	**Other Question**	**Summary**
Warren, P.L., and L.S. Anderson	1992	Sonoran Desert	Vegetation/ Community Impacts	Changes in vegetation cover, density, and composition after the cessation of heavy grazing depended upon the specific plant community under consideration. Local increases in cover were observed at heavily grazed sites located within a quarter to a half mile of water sources. Communities dominated by unpalatable species, such as creosotebush-bursage, showed the least change in perennial plant cover, density, and species composition; whereas those dominated by palatable species, such as saltbush, had dramatic increases in plant cover after cessation of grazing. In the saguaro-paloverde community, there was little change in total species richness but compositional shifts were observed with the addition of numerous species to the site--mostly those that are palatable to livestock--and stochastic losses of rare species.	Wildlife Species Impacts	There was an unexpected decrease in rodent abundance at a site 8-9 years after the cessation of livestock grazing. The natural cycles (in the absence of grazing) of rodent composition and abundance are poorly known at this site.		
Waser, N.M., and M.V. Price	1981	Sonoran Desert	Vegetation/ Community Impacts	Recovery from grazing appears to involve mostly an addition of rare species, and this result seems to take effect primarily immediately following the removal of cattle. The authors attribute this result to the fact that rare species remain dormant in the seed bank and may germinate after cattle removal, but they may be eliminated in areas grazed for extended periods of time (many decades).				

Author	**Year published**	**Ecoregion**	**Main Question**	**Summary**	**Other Question**	**Summary**	**Other Question**	**Summary**
Wright, R.L., and J.C. deVos Jr.	1986	Sonoran Desert	Wildlife Species Impacts	The decline of Sonoran pronghorn numbers through the 1980s was presumed to be caused by habitat degradation, which was attributed largely to livestock grazing.				

APPENDIX E

EXTERNAL REVIEWER COMMENTS AND RESOLUTION

This appendix documents external review comments to the draft report and their resolution. It is divided into four sections: (1) a brief preface that describes the format for recording and resolving comments, (2) an overview of the major conclusions from the comment resolution, (3) individual reviewer comments and their resolution, and (4) additional literature recommended by reviewers for consideration and its disposition.

E.1 PREFACE

A total of 16 external reviewers provided written comments to the draft report. The reviewers covered a broad range of experience, disciplines, and perspective regarding livestock grazing impact science and management in the desert southwest. Comments received were of three types: (1) general comments, (2) specific comments to particular sections of text, and (3) recommendations for additional literature to consider that was not addressed in the draft report. With any peer review of this breadth, differences between reviewers may arise. Our resolution of these differences did not just attempt to reach a middle ground; rather, we evaluated the comments based on their own merits and grounding in current scientific understanding and arrived at what we felt was the most defensible resolution to the concerns raised. Section E.2 of this appendix provides an overview of the major conclusions reached during resolution of the most substantive comments received.

Reviewer identify, comments, and resolution are documented in section E.3. Reviewers are listed in alphabetical order. Reviewers are identified by name, title, and professional affiliation to indicate their professional standing; however, affiliation should not be construed as indicating official organizational endorsement of an individual's comments. We approached reviewers to access their individual expertise and not to gain a particular organization's position on domestic livestock grazing-related issues. A resolution to a comment is indicated where appropriate by bold, italic text immediately following the comment. Some reviewer comments were rhetorical and didn't warrant resolution.

Often reviewers recommended additional literature to consider as part of the review or to bolster understanding of ecosystem dynamics. To save space and to increase readability of the reviewer's comments, the full citation was deleted from the comments and placed in section E.4. To distinguish references to literature we already had considered, we indicated by bold text when the full citation was placed in section E.4.

E.2 MAJOR CONCLUSIONS DRAWN FROM THE REVIEWER COMMENT RESOLUTION

The reviewer comments were instrumental in identifying weaknesses in the draft report. At times the comments indicated areas in which we needed either to: (1) improve the balance of our presentation (for example, herbivore optimization debate), (2) expand our coverage of the primary literature rather than rely on review papers (for example, ecology of biological soil crusts, especially the state-of-knowledge relative to soil crusts in the Sonoran Desert), (3) address an additional wildlife species (for example, the Sonoran pronghorn [*Antilocapra americana sonoriensis*]), or (4) cover a relevant topic that was not addressed in the draft (for example the rangeland debate involving equilibrium-non-equilibrium dynamics). The comments also encouraged us to take a fresh look at the overall pattern of the literature and what it did and did not say. In this context, the major shift from the draft to the final report is our focus on the lack of managed grazing studies for the Sonoran Desert—that is, studies that actually shed light on thresholds of grazing intensity between benign and damaging grazing intensity levels. This compelled us to also explore deeper into the grazing management strategy literature and, combined with our review of equilibrium-non-equilibrium dynamics and its implications for livestock grazing, to derive a set of conclusions relative to what are or are not appropriate approaches to domestic livestock grazing in the Sonoran Desert.

E.3 INDIVIDUAL REVIEWER COMMENTS AND RESOLUTION

E.3.1 Roy C. Averill-Murray, formerly Amphibians and Reptiles Program Manager, Arizona Game and Fish Department; now Desert Tortoise Recovery Coordinator, U.S. Fish and Wildlife Service

General Comments

I appreciate the opportunity to review the draft report, *The Impacts of Livestock Grazing in the Sonoran Desert: a Literature Review*. The report appears to be well written and very thorough. My comments primarily concern aspects of the report relevant to amphibians and reptiles. If you have any questions, please let me know.

Specific Comments

1. Page 4.1, 1st paragraph: point number 2 seems to be incomplete ("…on how on…"). ***Corrected text.***

2. Page 8.1, 3rd paragraph (also page 8.5, 1st paragraph): although not directly related to impacts of grazing on tortoises, AIDTT (2000) could be replaced with the peer-reviewed paper, Averill-Murray, R.C. (2002; **complete citation included in section E.4.1**). I can provide a reprint of this paper, if desired. ***Added the citation, rather than used it to replace AIDTT (2000), in two of the three instances AIDTT (2000) was cited. The recommended new citation only partially addressed the information described in the text.***

3. Page 8.2, next to last line: Although is mis-spelled. ***Corrected spelling.***

4. Page 8.3, 3rd paragraph, Nash and others (2000) discussion: based on the previous discussion of "bottom-up food webs," horned lizards (*Phrynosoma* spp.) could potentially be affected detrimentally if harvester ants are negatively affected by grazing. Todd Esque, USGS/University of Nevada at Reno, has also conducted experimental research on fire/grazing/ants/small mammals in the Mojave Desert on the Arizona Strip. He recently finished his PhD dissertation on the subject and might be worth contacting for additional information. ***Contacted Dr. Esque. He indicated his doctoral research did not focus on interactions with grazing.***

5. Section 8.2.2: Felger and others (1997) should be cited as Felger and others (2001). ***Agree Felger and others (1997) was an incorrect reference; however, replaced Felger and others (2001) with Turner and others (2000) as the former is still a working draft.***

6. Section 8.2.2: general natural history information (see Stebbins 2003; **complete citation included in section E.4.1**) suggests that grazing effects on soil compaction could negatively impact the following burrowing amphibians: *Spea multiplicata* (Mexican spadefoot), *Scaphiopus couchii* (Couch's spadefoot), *Bufo alvarius* (Sonoran Desert toad), *Bufo retiformis* (Sonoran green toad), and

Pternohyla fodiens (lowland burrowing treefrog). Stebbins (2003) specifically states regarding spadefoots, "they suffer from the cratering effects of cattle hoofs that isolate water pockets where tadpoles may become trapped as the pool shrinks." However, I am unaware of any specific research investigating such effects. ***Because the Stebbins' (2003) comment is anecdotal and does not quantify an impact, we did not incorporate the information from this reference.***

7. Section 8.2.3: general natural history information (see Stebbins 2003) suggests that grazing effects on soil compaction could negatively impact the following burrowing snakes: *Chionactis occipitalis* (western shovel-nosed snake) and *Chilomeniscus variegatus* (variable sandsnake). However, I am unaware of any specific research investigating such effects. ***Because the Stebbins' (2003) does not deal directly with impacts from grazing, we did not incorporate the information from this reference.***

8. Section 8.2.3, desert tortoise: Averill-Murray and Averill-Murray (2002; **complete citation included in section E.4.1**) document greater occurrence (while still low) of desert tortoises in inter-mountain valleys than previously thought to occur. Therefore, there is slightly more overlap between livestock and desert tortoises outside of bajadas and xeroriparian areas. That said, AIDTT (2000 [and Barrett and Johnson 1990, cited therein; **complete citation included in section E.4.1**]) indicate that grazing impacts are thought to be relatively minimal to Sonoran desert tortoises, but quantitative studies have not been conducted. I can provide a copy of Averill-Murray and Averill-Murray (2002), if desired. ***Revised the first paragraph of the desert tortoise section to address the first part of this comment. Added a new summary paragraph at the end of the section to address the second part of the comment.***

9. Page 8.5, 1st paragraph: hatchling survival and juvenile recruitment rates are *presumed to be* low for Sonoran desert tortoises. Hatchlings emerge in the *fall or* spring, when water and forage are more likely to be available. ***Revised text to address both comments. Added information from Averill-Murray (2002) to provide context relative to the first comment.***

10. Page 8.5, 2nd paragraph: the risk of livestock trampling tortoises, while real, must be relatively low. Also, indirect impacts of livestock grazing to the desert tortoise would primarily be due to *potential* competition for forage. Actual competition has yet to be demonstrated (or investigated). ***Added "potential" to text. Addressed the overall sense of the comment in a new summary paragraph at the end of the desert tortoise section.***

11. Page 8.5, 3rd paragraph: filaree is actually not of inferior nutritional quality to native plants. ***Agreed. Created a separate paragraph to address the issue of non-native plants in the diets of desert tortoise.***

12. Page 8.6, 2nd paragraph: "depend" should read "depends." See also comment regarding horned lizards and harvester ants, above. ***Corrected typo. See response to Comment No. 4.***

13. Section 8.3: the first conclusion is well written. The second conclusion may be overstated with regard to the "overall negative impact on wildlife" of livestock water developments. To the extent that natural aquatic habitats are increasingly impacted or lost, livestock water developments may be the last strongholds for some species of amphibians, especially some of Arizona's less common anurans that occur in the Vekol Valley. ***Revised second conclusion to reflect that impacts of water developments may not always be negative and often maybe localized.***

E.3.2 Dr. Jayne Belnap, Research Ecologist and Station Leader, U.S. Geological Survey, Biological Resources Discipline, Southwest Biological Science Center, Canyonlands Research Station

General Comments

Thank you for the opportunity to review the report you compiled on the effects of grazing in the Sonoran Desert. I skimmed the entire report, which on the surface looked robust, well documented, and sound. In contrast to reading the entire report quickly, I read the sections on biological crusts thoroughly. I was very impressed by the grasp of this complicated subject by the authors. The conclusions reached in this report are correct as far as we understand these communities: we know they are tremendously important for soil stability in all desert ecosystems, including the Sonoran desert. They are also very important for nutrient relations in the Sonoran desert. Their effect on local hydrology is less well understood, and this document captures that uncertainty.

In conclusion, I fully support the recommendations made in this report in terms of the biological soil crusts. ***Although no response is needed to the reviewer's comments, we note that the topic of biological soil crusts generated some disagreement between reviewers and resulted in substantive revisions to the chapter. See responses to other reviewer comments received on this topic.***

E.3.3 Dr. Brandon Bestelmeyer, Research Scientist, USDA-ARS Jornada Experimental Range

General Comments

To summarize here before some specific comments below, let me say that you have done an excellent job in summarizing a diverse literature. The read was enjoyable, and I found little to argue with in the general recommendations. Despite the limited information available about the Sonoran region, I also feel that there is an unfulfilled opportunity to focus the discussion on specific parts of the landscape and organize it so that the reader understands the dominant processes and possible futures where he or she stands within parts of the Sonoran Desert or SDNM. Among the most difficult and neglected ecological questions of our time is how to use regional information to contribute to local understanding. One challenge, as is clear in your report, is to sift through the facts and interpretations derived from other locations and make decisions about which facts are likely to have relevance at your location, through the filter of local knowledge about ecology, history, and soils/climate (and a reasonable level of skepticism). There is also the decision of what attributes and scales define your 'location' (i.e., the Sonoran Desert, or a Typic Torripsamment within the 8-10" ppt zone). Such an approach would serve to focus the discussion and recommendations. ***The reviewer's comments describe some of the general challenges we faced in conducting our review of the literature. We did attempt to limit our analysis of the impact literature and ecosystem dynamics to a portion of the "landscape," namely the non-aquatic/non-riparian (permanent or intermittent flow), three to 12 inch precipitation zones of the Sonoran Desert, which generally corresponds to plant communities characteristic of the Lower Colorado River Valley and Arizona Upland subdivisions as mapped by Brown and Lowe (1980). Our use of the literature from outside the Sonoran Desert generally focused on literature that either addressed a geographic locale with similar physical conditions or on species that occurred within the Sonoran Desert. When addressing broadly applicable ecological hypotheses, we sometimes considered a broader geographic extent for relevant literature. In general, we applied the types of filters recommended by the reviewer. Within our chosen analysis landscape, we tried to identify when information was more narrowly applicable, as appropriate, or conversely when the literature failed to consider impacts at a finer level of resolution that would be relevant to land managers: for example, impacts to xeroriparian habitats. One critical decision we made was to exclude studies from semidesert grassland areas of Arizona and***

New Mexico as having general applicability to livestock grazing impacts and management strategies within the Sonoran Desert (though we recognize some individual forage plant species may be shared).

Specific Comments

1. Page 3.4. What is a "large patch community"? PLMU is better described as a rhizomatous grass than a bunchgrass. ***Added a definition footnote for matrix, large patch, and small patch communities. Ruyle and Young (1997) identify Pleuraphis mutica as a bunchgrass; however, since identifying the grass in this manner is not critical in this part of the report we simply dropped the adjective.***

2. Page 3.6. It would be useful to classify landforms according to Peterson 1981 **(complete citation provided in section E.4.3)** here, "flats" is not very useful. ***Incorporated Peterson's (1981) terminology where appropriate.***

3. Page 3.9. Andrew Comrie and students have produced regional maps of multivariate ppt patterns based on many aspects of rainfall timing and amount. I wonder if they capture aspects of the physical environment that are relevant to plants. Also, can you make statements about the points in the mean of ppt beyond which increases in CV become significant for management? **(Complete citations of applicable references provided in section E.4.3.)** ***We incorporated the Comrie and Glenn (1998) citation, but did so in section 4.1.2 rather than in Chapter 3. We're not prepared to make a definitive statement regarding an appropriate threshold for when a mean precipitation and associated CV becomes significant for management. The best we can do is to say that it likely is important across the entirety of the Sonoran Desert.***

4. Page 4.9. What is clear is that 'overcompensation' is not general. ***Agree. This section was revised to provide a balance to the issue and put it in perspective to what it means for management.***

5. Page 4.11. Some of the clearest evidence of grazing effects occurs when plant communities are constrained in their responses to pulses of ppt in grazed but not in ungrazed settings in the same soil/climate zones (i.e., that climate is primary driver is clear in desert systems, but this does not negate the importance of grazing as some have argued). ***We agree. These types of studies, involving exclosures no doubt, would be beneficial to have.***

6. Page 4.11. Re: Turner's study on LATR, what happened outside the Tumamoc plots over the same period, did LATR persist? If there are no other data, then these are very weak speculations not worth discussing. ***By 1980 the Desert Laboratory grounds, which include Tumamoc Hill and the level to gently rolling plain to the west (880 acres [352 ha]), were almost surrounded by suburban developments. We added caveats relative to Turner and other's (1993) matched photo study to put their findings in the appropriate context. Matched photo studies certainly have their limitations, but that doesn't mean they should be ignored.***

7. Page 4.11. What are the soils/climate zone of Tumamoc Hill? Statements must be limited to (at least) to particular soil and climate zones, in addition to species. ***We added information from Goldberg and Turner (1986) to provide general characteristics of the site.***

8. Page 4.14. Last sentence unclear--sparse but abundant? ***We clarified the meaning of the sentence.***

9. Page 4.15. The Bower's and Turner speculation seems weakly supported. Is the pattern replicated? I am beginning to detect a mix of relatively firm (e.g., McAuliffe) and poorly supported evidence in this section. I would prefer to have seen a series of assertions about grazing and other management impacts derived from the regional literature (e.g., temporary reductions in perennial grass cover, long-

term reductions, etc.) and an evaluation of evidence and local patterns for each assertion in different parts of the Sonoran Desert and proposed solutions. As it is, the assertions and evidence for them are mixed throughout such that it is difficult to separate the strong and weak evidence for generic "grazing effects". In this way, the structure of the argument seems to emerge from an implied question such as "should we allow grazing on SDNM" vs. a question such as "what is and how can we sustain an acceptable level of ecological conditions across SDNM". I think the motivation behind the presentation of evidence needs to be explicitly laid out, lest this work be thrown in the advocacy bin (which serves a purpose, but is useless from a management perspective). My impression was that a 'yes or no' grazing policy position is not what you were going for. ***Because the Bowers and Turner (2002) speculations about the effects of grazing were included among a suite of other hypotheses regarding foothill paloverde population dynamics, we decided it was not an appropriate study to include as part of our detailed analysis. We decided to use the study instead to illustrate the additional complexity involved when biotic interactions in addition to livestock grazing are considered. Section 4.2 was reorganized to (1) expand on the general limitations of the studies reviewed and (2) to group the studies by plant functional type, xeroriparian plant communities, and piosphere studies. The latter reorganization was done in part to respond to your comment. The organization of the literature by appropriate topic is overall problematic given the general lack of studies, the few locales in which studies took place, the variation in study designs, and differences in ecological variables that each study assessed. Most importantly, few studies even touched upon quantifiable variation in grazing intensity (or other grazing management practices) as a study variable. We assessed the importance of these limitations in a revised conclusion section.***

10. Page 4.16. It is difficult to evaluate these comparisons without a documentation of soils. ***We decided that similar to the Bowers and Turner (2002) paper these speculations about livestock impacts also involved complex biotic interactions that had not been directly tested. Although the discussion was based on the matched photos of Turner and others (2003), the speculations are not contained in that reference. We decided to delete the paragraph.***

11. Page 4.17. Human activities in general may contribute to invasive spread, via ranching or recreation. Thus this is not a unique attribute of grazing, unlike the other processes discussed thus far. ***True, but livestock and livestock management practices contribute, sometimes in unique ways. The information about livestock interactions with non-native plants is now split between section 4.1.4 (which addresses fire as an ecological process) and the piosphere studies subsection of section 4.2.2.***

12. Page 4.19. The conclusions are offered as generalities, yet there is no evidence that the patterns are general, and quite a bit that they are not. ***The conclusion section was extensively revised and focuses on the specific results of the studies evaluated.***

13. Page 5.6. Did soils differ across the fence? ***The author (Abou-Haidar 1989) doesn't mention soils as part of his study area description. He simply implies that the sites are similar across the fence with the exception of his grazing treatment.***

14. Page 5.6. If trees (esp. paloverdes, Page. 4.15) increase in response to grazing, shouldn't this increase favorable establishment sites (shade) for saguaro (see Page. 5.3 paloverde ref)? The presentation of evidence suggests bias. ***See the response to Comment No. 9 above. We think the most parsimonious conclusion reached in Chapter 4 in regard to woody perennials is that once released from grazing overall plant density and cover increase and bare ground decreases. The Turner and others (1966) speculation seems to be consistent with this finding; however, we did modify the sentence as the authors' speculation was not limited to just the effects of grazing on the loss of shade-producing perennial plants.***

15. Page 7.1. There is no evidence that soil crusts are generally dominant N sources in desert grasslands of the northern Chihuahuan Desert. ***Changed the text to indicate the evidence is relatively weak for leguminous plants in hot deserts, including the Chihuahuan, to be the primary provider of fixed nitrogen, which does not automatically lead to biological soil crusts assuming that role without more empirical support.***

16. Page 7.5. There is evidence that biological crusts are most evident in degraded areas dominated by tarbush on silt loams formerly dominated by grasses. ***This observation may be in keeping with the hypothesis that biological soil crusts, especially when proceeding along a continuum of wetter ecosystems, may in some cases increase in response to disturbance (though it may be a secondary response to reduced vascular plant competition). We added text to better frame the possibilities.***

17. Page 7.6. Soil crust development, SEP and vegetation cover, and soil compaction (subsurface) are distinct issues/processes and should not be interspersed, the organization here could be improved. Further, it is not clear the conditions under which soil erosion thresholds may be important in the Sonoran Desert. It might be prudent to reorganize this section under the heading "Regulation of soil quality" or the like, and reorganize the subheadings. There needs to be a clear connection to soil types here, and this might provide a useful basis for internal organization (e.g., what regulates/diminishes soil quality on Holocene-aged coarse or fine soils vs. older soils, etc.). This gets at how land can be managed in a spatially-explicit way. ***The current subsections within the overall section on disturbance impacts (section 7.3) separate soil compaction studies (section 7.3.2) from erosion studies (7.3.5). A discussion of site erosion potential (SEP) is included in the accelerated soil erosion subsection as appropriate. We also discussed the role of soil type and age (or soil condition, wet or dry, as applicable) in influencing compaction or erosion. Specific environmental conditions and accompanying soil erosion thresholds for Sonoran Desert soils should be identified, but it is beyond the scope of this review to define explicitly what they may be for each soil type of concern and how such thresholds may relate to cover values and condition of biological soil crusts. Clearly, this needs to be done if the information is not available already to make a first attempt at identifying appropriate conditions and thresholds in a spatially explicit way, especially for the most erosion-susceptible soils. A conservative approach would remove from livestock grazing use those soils considered potentially prone to accelerated erosion.***

18. Page 7.10. The conclusion indicates that biopedturbation by lagomorphs, rodents and ants is historically an unimportant ecosystem process. If it is important, as it currently is in many warm desert soils, should biological crusts be common, and should they be dominant N providers? Also, if ungrazed areas are expected to have more rodents (Page 8.10), shouldn't this translate into more biopedturbation? This strikes me as an important inconsistency with your argument, and points out some complexities that are overlooked. Again, the conclusions are distillations of problems observed in specific places across the west that are offered as general problems for the Sonoran Desert. How is this going to support management? ***The conclusion section was extensively revised. The revised text clarifies the hypothesis related to the evolutionary relationship of surface disturbance to the occurrence of biological soil crusts. The hypothesis offered in the literature does not equate all forms of biopedturbation as equivalent (that is, biopedturbation caused by ungulates versus other faunal groups) so the argument alluded to is not necessarily inconsistent. The effect on management, if the hypothesis is accepted as at least potentially relevant to the Sonoran Desert, is a conservative, low risk approach with respect to stocking rates and other facets of grazing administration.***

19. Page 8.16. Note that kangaroo rats and kangaroo mice are different genera, are you sure of the statement in top paragraph? ***The reference should have been to kangaroo rats and not to kangaroo mice. Corrected text.***

20. Page 10.5. The scale of the operation is essential to real ecological and economic flexibility. Rotation at broader scales than is possible on most individual BLM allotments seems necessary where recovery/sustainability is desired on many desert soils. ***We agree. Rotation per se does not seem to be a feasible component of a grazing strategy within the Sonoran Desert.***

21. Page 10.8. S&T models are applicable anywhere there are changes in ecosystem properties of interest that are too complex to describe in simpler (e.g., linear) quantitative terms. It is a misconception that "threshold" processes such as a soil erosion need to be important (e,g., see models from Mediterranean annual grasslands of central California, and the complexity of rainfall x residual dry matter interactions. There are no "thresholds" of irreversibility here). ***Our revision of the discussion about state-and-transition models makes it clear that thresholds of change do not need to be involved for the model to be useful.***

22. Pages 10.8/9. I think the text (the ppt variability part) was on the right track for a model, but the Fig. 10.1 doesn't really deliver. I think you have an opportunity to vastly improve upon this model, and create several models to address specific processes on specific types of soil (even if they do not necessarily get to the resolution of ecological sites). The raw materials are summarized in the text, even though the discussions are not organized by soils and climate zones. Where are soil erosion thresholds most likely? What will the destruction of soil crusts do to nutrient balance and how will that have measurable effects on NPP or particular species of plants, and over what timeframe? The model does not do justice to your discussion, and explicit model statements might help to focus your discussion. What we have not done yet is to connect S&T conceptual models to particular grazing strategies, especially within the context of a particular site. This would be a useful thing to do for SDNM. ***We eliminated Figure 10.1 and streamlined our discussion of the Muleshoe Ecosystem example. We do not think this document is the appropriate place to attempt development of detailed state-and-transition models applicable to Sonoran Desert plant communities. We chose instead to outline in broad terms what such models should encompass. We agree it would be useful to incorporate particular grazing strategies, in general, into model development and mentioned the need to do this.***

E.3.4 Dr. Matt Brooks, Research Botanist, U.S. Geological Survey, Western Ecological Research Center, Las Vegas Field Station

General Comments

At your request I have reviewed the report titled "the impacts of livestock grazing in the Sonoran Desert: a literature review." In general, the report is well written, objective, and contains ample citations where needed. I reviewed chapters 4 and 8 most carefully for technical accuracy, since they reviewed topics I am particularly familiar with. I also reviewed in detail the recommendations presented in Chapter 11. My comments on each of these chapters are as follows:

Specific Comments

Chapter 4:

1. Section 4.1.4. The following review publications should provide additional information necessary to round out the discussion on desert fire ecology and the influence of invasive plants. I will send electronic copies of these documents to you via email.

The recommended citations, Brooks and Esque (2002) and Brooks and others (2003, 2004), are included in section E.4.3. Brooks and Pyke (2001) is included in section E.4.1. *We added discussion to the topic concerning desert fire ecology and invasive plants from Brooks and Esque (2002), Brooks and Pyke (2001), and Brooks and others (2004), but not from Brooks and others (2003).*

2. Section 4.2. In the second to the last paragraph in this section, studies comparing previously grazed with ungrazed areas are characterized as being more robust that studies reporting vegetation change over time. However, it should additionally be noted that studies comparing grazed to ungrazed areas often lack pre-grazing data or other assurances that the grazed and ungrazed areas would have been similar if not for livestock grazing. These are typically, "post-hoc" studies, with their own sets of limitations. ***We added this insight.***

3. *Chapter 8:* I found no major needs for improvement in this chapter.

Chapter 11:

4. Section 11.1. I found no major needs for improvement in this section.

5. Section 11.2. One recommendation is to set grazing rates based on current within-year conditions, rather than average among-year conditions. This may help drought-tolerators (e.g. perennial shrubs) which may be damaged by excess herbivory during dry years, but this may inadvertently hurt drought-avoiders (e.g. annual plants) that depend on massive seed production during years of high rainfall to produce sufficient seed to make it through to the next year of high rainfall. That said, I think the recommendation provided is the best one could hope for given the existing information. ***The BLM requested that we remove specific recommendations from the report. We did, however, reassess our conclusions from the perspective of our analysis of grazing management strategies as currently practiced in the western U.S. Our conclusions relative to what may be an appropriate strategy for the Sonoran Desert should account for the needs of both drought-tolerators and drought-avoiders.***

6. Another recommendation suggests that forage utilization rates be set to allow sufficient native plant production to maintain the ecological integrity of the SDNM. This is a worthy goal, but were is the data to set these rates? Information on thresholds for ecological change is needed for this management scenario to be effective. This is a major research need. ***We agree. See response to comment No. 5 above.***

7. My final comment is on the recommendation to minimize the potential for fragmenting desert bighorn sheep habitat. I may have missed it, but the literature review did not suggest that livestock grazing may fragment bighorn sheep habitat. It did suggest that livestock and bighorn sheep may compete for the same forage. Perhaps this recommendation should be rephrased to focus on minimizing competition for forage, although the question of thresholds arises again, which presents yet another need for new research. ***See response to comment No. 5 above. Fragmentation of bighorn sheep***

habitat may occur in association with fencing used to delineate livestock grazing allotments. See Chapter 8 for a discussion of this issue.

8. Section 11.3. I agree with the general research recommendations, but would add a paragraph describing the need to compare the relative effects of livestock grazing with other types of land uses (e.g. OHVs, mining, border patrol activities) on natural resources. In a management scenario of "multiple uses" this information is needed to determine which land use is most responsible for the adverse affect one wishes to prevent or mitigate (e.g. soil degradation). The first paragraph alludes to this in the recommendation to conduct multivariate study designs to tease apart grazing from other "confounding" factors (i.e. other land uses). I just think this point needs to be made more explicitly. ***Per BLM's request, we removed all explicit recommendations from the final report.***

E.4.5 Anthony Burgess, Botanist, formerly at Biosphere 2

Specific Comments

Executive Summary:

1. The executive summary is very good. The emphasis that grazing administration should account for variability instead of averages is wise and prudent. Your recommendations are very close to those promoted by Holling (1995**; complete citation provided in section E.4.3**) as "managing from ignorance": if you manage as though you never know what the outcome will be and treat every management action as an experiment, you will watch the system more closely, and this awareness will be the best management tool. Walker and Abel (2002**; complete citation provided in section E.4.1**) provide a summary of range management historical trends in the context of the adaptive cycle model. ***Per BLM's request, we removed explicit recommendations from the final report. Instead, we derived general conclusions from our review and synthesis of the literature that still may address, even if indirectly, some of your points above.***

2. Page ES.2, 2nd bullet: "Recovery should be based on the ecological integrity...." Ecological integrity is a value-laden term. If it is to be the basis for management, help the future manager by giving some measurable criteria or an operational definition, so that it is clear what you mean by ecological integrity. ***See response to comment No. 1 above. We no longer use the term "ecological integrity" in the report.***

3. Page ES.3, top: "litter conservation" might be misunderstood by a casual reader. You might say "soil surface organic litter" or "dead plant litter." ***See response to comment No. 1 above. In our discussion of litter in Chapter 4, we tried to be a bit more explicit about defining what is meant by litter.***

4. Page ES.3, 5th bullet: Have you described or referred to "landscape-level assessments" in the main text? Be sure that this term and the practices it refers to are clearly defined. ***See response to comment No. 1 above. We do touch on, however, the issue of spatial scale and its importance relative to assessments in our revised Chapter 10.***

5. Page ES.3, last sentence: You provide in that sentence an excellent rationale. Be sure it's emphasized. ***Specific recommendations regarding how BLM might use the information in the report relative to its decisions on grazing administration for the Sonoran Desert National Monument were removed from the final report.***

Chapter 1

6. Good overview.

Chapter 2

7. Straightforward and clear—very good.

Chapter 3:

8. Page 3.4: Mountain Upland "is defined by a number of species ...." please give an example or two of the diagnostic species, so we can begin to visualize the community when it's first mentioned. ***Added a couple of diagnostic species.***

9. Section 3.5: Overall you have done a thorough analysis of basic rainfall statistics, with a prudent interpretation of the implications for grazing management.

10. Figure 3.4: Does the vertical line at the top of each histogram bar show one standard deviation above and below the mean, or is it the standard error? Please explain specifically in the Figure caption. ***Added an explanatory sentence to the figure caption.***

11. Figure 3.5: Add a sentence to the caption that the dashed line shows where SDNM would fit. This makes quick scanning a lot clearer. ***Added a sentence to the figure legend that indicates what the dashed line represents and deleted similar sentences from the title to each figure portion.***

12. Page 3.13, 2nd paragraph: Change "course estimate" to "coarse estimate." ***Corrected.***

13. Figure 3.6: Could you lighten the background so the horizontal bars show better? The explanation above the graph would be easier to scan if it were part of the caption. ***We removed the gray background from Figure 3.4 and Figures 3.6 through Figures 3.13 and moved explanatory material from above the graphs to the figure legends.***

14. Page 3.22, 2nd paragraph: "The tendency that more often than not years and seasons are below average...." This is an outstanding interpretation. You have anchored powerful meaning into the analysis.

15. Section 3.5.3: In contrast to the excellent rainfall analysis, you give a very cursory analysis of freezing temperatures with no interpretation for management. Is freezing an important management consideration or not? If there is a catastrophic freeze, should there be any change in grazing practices to help the community recover? ***We added some text discussion to address this comment.***

16. Section 3.5.3: "Temperature can be a limiting factor...." Make your assertion more credible by citing evidence. Many distribution maps in Turner et al. (1995**; complete citation provided in section E.4.3**) show northern limits consistent with freeze limits, and several of their species accounts cite freeze damage observations. You cite some studies of freeze mortality in the saguaro chapter, but it would be good to put a few references in this section, too. ***We added some text discussion and appropriate citations, including Turner and others (1995) to address the comment.***

17. Section 3.5.3: The cautionary note about microhabitats is wise.

18. Section 3.5.3: What about high temperatures? Some climatic analyses indicate a warming trend. Is the trend based on warmer winter nights, or more extremely hot summer days? If high temperature extremes increase, what are the management implications? A paragraph or two about how high temperatures exacerbate drought stress and mortality could be very useful to novice managers. There have been anecdotal reports of mature saguaro damaged by record high temperature events in the vicinity of SDNM (Ray Turner pers. comm.). A note added recommending that managers watch for damage after extremely hot events could cultivate a useful awareness. ***We added a brief paragraph about high temperatures but in the context of how it may affect plant available moisture.***

19. Figure 3.14: "Average Number of Days per Month and Year...." Are the days per year to be inferred from the monthly histogram, or did I miss something in the graph? ***Clarified the figure and text that the histograms show the monthly means, though one could potentially calculate the annual mean from the data presented.***

Chapter 4:

20. Overall this is an excellent review. I offer a few suggestions below.

21. Section 4.1, 1st paragraph: This is essentially a description of the Arizona Upland phase of the Sonoran Desert. For example, columnar cacti are said to be the visually dominant canopy layer. However, large columnar cactus are very scarce in the Lower Colorado Valley subdivision, which extends westward from SDNM to San Diego Co., California. Slight changes in wording would insure that someone unfamiliar with the region gets a more accurate perspective. Emphasize that the vegetation of SDNM is not representative of most of the geographical extent of the Sonoran Desert, even as defined by TNC. The casual substitution of "Sonoran Desert" for "Arizona Upland" is somewhat confusing, and makes it appear that the authors do not really know the region well. ***Clarified the text in section 4.1 to eliminate the confusion.***

22. Section 4.1.1: "Within the Sonoran Desert ... a low ... in the Tucson Basin." For me this sentence was misleading. To be sure, the Tucson Basin has lower productivity than the wet margins of the desertscrub in the Santa Catalina Mts., but the reader should be reminded that Tucson itself is located near the wet end of the Arizona Upland, which is the wetter part of the Sonoran Desert. Productivity numbers are likely to be much lower in the Lower Colorado Valley subdivision; hence production in the drier parts or SDNM are also probably less than those you cite for Tucson. ***The section on Biomass and Productivity was extensively revised. The potentially misleading statement was corrected as part of the revision.***

23. Section 4.1.1: You may want to cite Larry Venable's studies an annual plant demography at the Tumamoc Desert Lab to emphasize the high spatial and temporal variance in the ephemeral community. ***We added citations by Halvorson and Patten (1975) and Patten (1978) that provide this inference within the context of spatial and temporal variation in winter annual productivity.***

24. Section 4.1.1: Because some acidic volcanic rocks in the SDNM area may have a very low P content, airborne P entering the ecosystem as dust deposits and raindrop nuclei may be a significant source of P for this area. ***We deleted the references to nitrogen and phosphorus cycles in this section. Nitrogen cycling is now addressed substantively in Chapter 7. Phosphorus may only be a limiting nutrient in arid regions of Australia (Hadley and Szarek 1981).***

25. Section 4.1.2: Your description of the rainfall gradient starts at the Colorado River, and ignores the increase in rainfall uphill to the desert margin east of San Diego. Change the wording to "...west to

east from the most arid part of the Sonoran Desert, the Colorado River Delta, ...” ***We revised the text to clarify where the gradient begins in the west.***

26. Section 4.1.3, 1st paragraph: I did not understand what you meant by the last sentence, “The persistence of these species....” Do you mean that these species are relicts from glacial climates, or the more recent Little Ice Age? Explain more fully so a bureaucrat could understand. ***We revised the text to clarify the intended meaning.***

27. Section 4.1.5, 3rd paragraph: I would add a qualifier that domestic livestock may exert substantially greater herbivory pressures and native herbivores because fencing and stocking rates concentrate them at number well above what would be chosen by free-roaming ungulates. ***This section has been extensively rearranged, but we did add the point above in an appropriate spot.***

28. Section 4.1.5: The summary of grazing literature seems to be very good. I detect a bias in favor of Belsky’s work over subsequent rebuttals, which is understandable. ***We agree that the discussion of Belsky’s opinion needed better balance. The relevant material was extensively revised and expanded.***

29. Section 4.1.5: The mention of the uncertain dynamics of belowground biomass is very important. You may want to add that longer-term reduction in root biomass and the correlated function of moisture uptake is likely to cause an overall decline in water use efficiency of the entire ecosystem. Although the concept of water use efficiency, defined as the amount of production realized per unit of water input, is typically associated with crop agriculture, it can also have useful applications for understanding ecosystem function. ***We added the point.***

30. Section 4.1.5: The assumption that the Sonoran Desert plant communities have no long history with large herbivores ignores Paul Martin’s work, which led to the controversy about burros in the Grand Canyon. There is good evidence that during most of their evolution, the plants of the Sonoran Desert or its precursor were available to several large herbivores, most of which became extinct about 10,000 years ago. Large cameloids and ground sloths (Anderson 1984**; complete citation provided in section E.4.3**) were definitely in the region. Furthermore, ground sloth dung showed that Sphaeralcea, Ephedra, Atriplex, and Acacia greggii were major dietary components (Phillips 1984**; complete citation provided in section E.4.3**). Thus there is good evidence that Sonoran Desert plants were exposed to more large herbivores than the current mule deer, pronghorn, jackrabbit, and javelina during most of their evolutionary history. These ungulates may have been more browsers than grazers, but I am concerned that a less-informed reader could get the false impression that larger herbivores played no role in the evolution of Sonoran Desert plants. To be sure, the plant communities present just before livestock introductions were formed in the absence of large herbivores, but this absence itself may be “unnatural.” Some mention of this body of work would add a deeper historical perspective. ***We added reference to this body of work (using a Paul Martin citation), but we disagree that the evidence indicates Sonoran Desert plants have a long evolutionary history with large herbivores.***

31. Section 4.2: The critique of methodologies in Sonoran Desert grazing studies is very well done.

32. Section 4.2.1: The concluding paragraph reviewing the concentration of ungulate impacts in xeroriparian sites is very important. One could infer that xeroriparian communities would be the best sites for monitoring livestock impacts.

33. Section 4.2.2: Ray Turner’s speculation about competition between big galleta and legume trees could be a specific corroboration of the general grass-tree dynamic models proposed by Walker et al.

(1981**; complete citation provided in section E.4.3**). This concept is briefly reviewed in Burgess (1995**; complete citation provided in section E.4.3**). ***We decided to remove this speculation as we wanted the review to focus strictly on published information, in which personal communications were used only to amplify information contained in a published work. We also were concerned that though grass-tree interactions may be well studied in savanna or grassland situations, we did not want to extrapolate these effects to a desert ecosystem in which such competitive interactions may not have been empirically studied. As a result, we did not incorporate the Walker and others (1981) citation and only incorporated the Burgess (1995) in a different context.***

34. Section 4.2.3: Sometimes "ecological function" or "ecological services" have been used to refer to attributes such as nutrient cycling, pedogenesis, etc., which you term "community function." A brief note about whether your definition of community function is essentially equivalent to these other terms would be helpful to link with a broader body of scholarship. ***We included a parenthetical definition of what we mean by community function in section 4.2.1.***

35. Section 4.2.3: The first paragraph of this section gave me the impression that studies of grazing impact on community function measures would follow. Instead, there was a review of the role of exotic invaders and the piosphere. I would include the invasion of exotic species as a section under 4.2.1. Community Composition. Most of the effects described as the piosphere phenomenon "reduced cover and density" are really changes in vegetation structure. The functional consequences are weakly inferred from structural changes. The changes in vegetation structure in the piosphere are very similar to grazing effects described for xeroriparian habitats in Section 4.2.1. I don't think the segregated Section 4.2.3 Community Function is needed. That topic is really not the focus of subsequent paragraphs in that section. ***We agree and in response to this comment and one by another reviewer we completely reorganized the structure of section 4.2.***

36. Section 4.2.3: The pervasiveness of filaree, red brome, and Mediterranean grass duplicates the history of exotic invasives on Tumamoc Hill (Burgess et al. 1991**; complete citation provided in section E.4.1**). This study also indicates that foxtail barley (Hordeum leporinum) may become invasive in wetter xeroriparian sites at SDNM. Historical links between invasive plants and livestock introduction are discussed in this paper. ***We incorporated the Burgess and others (1991) paper as part of our evaluated studies.***

37. Page 4.19, 3rd paragraph: I would change the second sentence to "Effects are particularly under shade trees, in xeroriparian sites, and near water sources." This would emphasize to a novice manager where to focus attention. ***We completely revised the Conclusions section. As a result, this sentence was deleted.***

38. Page 4.19, last paragraph: The second sentence, "recovery may occur in as few as ten years." You cited work that showed recovery in the ephemeral community within 2 years. You could add a qualifying sentence stating that recovery rates of different growth forms are inherently different: years for ephemerals, centuries for long-lived trees. ***In the revised Conclusions section, we did not discuss recovery times in any quantitative way as we didn't see the need to speculate about specific recovery times in this section.***

Chapters 5 and 6:

39. I see no serious problems. You may want to talk to Bill Peachey about his work with bat dispersal of organpipe seeds. Seems like bats may also be dispersers of saguaro seeds. ***We did not follow up on this suggestion.***

40. Grazing impacts of saguaro reproduction is excellent. Overall a very fine chapter [Chapter 5].

Chapter 7:

41. *Prosopis velutina* has been shown to have root nodules, and significantly contribute to soil N levels. References are cited in the species account in the Sonoran Desert Plants book (Turner et al. 1995**; complete citation provided in section E.4.3**). Your careful interpretations of site-specific and species-specific effects gave an excellent summary of a complex topic. ***The relevant studies cited in Turner and others (1995) that related to the issue of nodules and soil nitrogen contribution are Felker and Clark (1980. Plant and Soil 57:177–186.), Barth and Klemmedson (1982. Journal of Range Management 35:412–418), and Tiedemann and Klemmedson (1986. Soil Science Society of America Journal 50:472–475). Felker and Clark (1980) demonstrated nodule development in greenhouse studies, whereas Barth and Klemmedson (1982) and Tiedemann and Klemmedson (1986) demonstrated an apparent contribution of Prosopis velutina to soil nitrogen; however, neither of the latter two studies identified mesquites as the source of the fixed nitrogen. Moreover, Barth and Klemmedson (1982) found no field evidence of nodules and hypothesized the nitrogen source was external and the mesquite's contribution to soil nitrogen was via a root absorption-litter deposition mechanism.***

E.4.6 Russ Engel, Regional Habitat Biologist, Region IV, Arizona Game and Fish Department

General Comments

The Arizona Game and Fish Department (Department) has reviewed the above-referenced draft document and the following comments are provided for your consideration.

The Department understands that there has been a limited amount of research done on livestock grazing in the Sonoran Desert and notes that the document acknowledges this fact. The document states that results from studies conducted outside of the Sonoran Desert were used in this review. Therefore, we assume that conclusions presented in this paper were based, at least in part, on studies conducted outside of the Sonoran Desert. We believe that it would be beneficial to clarify when conclusions presented in this paper were based on studies conducted in the Sonoran Desert or when they were based on extrapolation from studies conducted elsewhere.

Resolution of General Comments

We have tried to be clear throughout the report on when conclusions were based solely on studies conducted in the Sonoran Desert versus when other sources of information were used.

Specific Comments

1. The Department notes that a paper authored by Holechek (In Press) entitled: "*Managed Grazing Versus Grazing Exclusion Impacts on Rangelands Ecosystems: What We Have Learned*" was used and cited in this review. However we note that several articles cited in Holechek's paper were not used in this review. We believe that adding information from the following papers referenced by Holechek would benefit this review.

The complete citations for the recommended articles, Paulsen and Ares (1962), Brown (1982), Shaw and Clary (1995), Herbel and Gibbens (1996), Smith and others (1996), Nelson and others (1997), Clary (1999), Bristow and Ockenfels (2000), and Navarro and others (2002), are included in section E.4.1.

The Brown (1982) and Bristow and Ockenfels (2000) papers address Mearns quail (**Cyrtonyx montezumae mearnsi*****) interactions with livestock grazing. This particular subspecies does not occur within Sonoran Desert habitats, as we have defined the geographic scope of this literature review. The Shaw and Clary (1995) and Clary (1999) papers address species associated with riparian systems. We specifically excluded from this review any literature regarding perennial or intermittent stream-associated riparian habitats in the Sonoran Desert. As a result, we did not incorporate or cite the preceding literature in the final report; however, we did include the Brown (1982) and Bristow and Ockenfels (2000) papers in the literature database for the project.***

The paper by Herbel and Gibbens (1996) addresses post-drought vegetation dynamics on Chihuahuan Desert rangelands in southern New Mexico. Navarro and others (2002) compared "rangeland ecological condition" on sites in southwestern New Mexico receiving 10.2 to 13.8 inches (26 to 35 centimeters) of annual precipitation. Paulsen and Ares (1962) assessed grazing impacts on black grama and tobosa grasslands located on the Jornada Experimental Range in New Mexico. Although each of the above studies is reportedly an example of a "managed" grazing study, they all occurred within New Mexico within plant communities containing significant amounts of perennial grasses that constituted the primary forage base. As a result, we don't view the findings as transferable to the Sonoran Desert in a meaningful way. We did not incorporate or cite the preceding literature in the final report; however, we did include the studies in the literature database for the project.

The papers by Smith and others (1996) and Nelson and others (1997) both address responses of wildlife to different intensities of livestock grazing on Chihuahuan Desert rangelands. We incorporated both studies, but only in regard to individual species for which they showed significant results.

2. The Department does not fully agree with the conclusions presented in the last paragraph on page 8.16 regarding behavioral avoidance of bighorn sheep to livestock. In your conclusion you state that "Habitat fragmentation…also is due to behavioral avoidance that bighorn show towards the presence of livestock". While bighorn may show some level of avoidance to livestock, the Department has evidence of bighorn sheep mingling with cattle and crossing valleys where cattle are grazing. For that reason, we do not fully support the above-referenced statement or the last sentence in this paragraph that states livestock grazing may serve to isolate bighorn populations. ***We incorporated the Department's findings and modified our conclusions somewhat, in both sections 8.2.5 (Bighorn Sheep) and 8.3, to reflect that the evidence for behavioral avoidance is mixed.***

E.4.7 Allison Jones, Conservation Biologist, Wild Utah Project

General Comments

Overall, this literature review gives fair and unbiased treatment to a potentially contentious issue, and is thorough and well written. The review contains little technical jargon, the organization is clear and tight, and the purpose and scope of the review is made clear in the Executive Summary and opening chapter.

Form my perspective, there is one section that I think could be improved. In chapter 4, Section 4.1.5 (Herbivory) introduces the topic of animal herbivory on plant communities. I think this opening section (p.4.6) could be strengthened, if, "right off the bat," Weinstein et al. note the most crucial piece of information that generally dictates whether communities are likely to suffer from impacts of herbivory or not: whether the system evolved under regular or continuous grazing pressure by large, hooved ungulates. Granted, the authors bring up this point 3 ½ pages later on page 4.9: "some scientists theorize that the degree to which plant communities are impacted by or tolerate grazing by large herbivores depends in part on the evolutionary history of the system with grazing." Why are the authors giving short shrift to a topic that is such a cornerstone of grazing effects, and why is the topic not introduced earlier? For example, it seems strange that in the third paragraph of page 4.8 (the jojoba example), the authors do not bring up evolutionary history of communities subject to grazing when the authors are citing the "overcompensation" theory and McNaughton's work in Africa (though again, I think the literature review would be even better served by this discussion preceding that topic, such as on the first page of section 4.1.5, as I suggest above). ***The section on herbivory and herbivore-plant community interactions has been significantly expanded and revised. The section begins with a section on the role of evolutionary history.***

There is another issue that warrants bringing up in a general sense. In this literature review, TNC has an important opportunity to make targeted recommendations to the BLM regarding livestock grazing management. Indeed, there is a whole chapter (Ch. 11) devoted to this topic at the close of the review. I believe, however, that TNC is missing the boat to some degree by not recommending that a GIS-based forage analysis and capacity model be used to reset cattle stocking rates. I am attaching to these comments a suggestion for such a model, and instructions on its use, that we here at Wild Utah Project, in collaboration with other scientists, are currently developing. An ecologically-based forage capacity model can incorporate both rangeland suitability and capability into the analysis. For example, many of the same recommendations that the authors make in section 11.2 (accounting for low productivity of the Sonoran Desert ecosystem, restricting grazing from erodible soils and decisions based on landscape-level assessments), can all be accomplished if the BLM utilizes a GIS based forage analysis of the forage typically available in a normal or drought year, and then makes allocations for factors like distance to water, susceptible soils, needs of wildlife, plant regeneration, incapable or unsuitable lands, etc.). There are many capacity models the BLM can draw from, ours is just one suggested approach. But as the BLM is in the process of redefining grazing management in the Sonoran Desert National Monument, it has the opportunity to effectively begin with a "clean slate" regarding the grazing program and grazing management. This does include the option to reset stocking rates in the allotments contained within the Monument. This can best be achieved by using an ecologically based forage/capacity analysis. This approach would be also scientifically defensible. ***Per BLM's request, we removed explicit recommendations from the final report. We appreciate you sending us your model documentation and note that it contains useful information that BLM may want to consider (though we are not at this time advocating for or against your recommended approach). We recommend that you send the documentation of your model directly to BLM for their consideration and use.***

Specific Comments

1. Section 6.1, Rare Plants…, Page 6.1. While trampling may not necessarily kill plants, it often destroys the meristem, and the plant fails to produce flowers, fruit, and seeds. ***Agree, but we didn't see where this warranted a text change.***

2. Section 7.2.2, Seedling Germination…, Page 7.4. There may be other citations (i.e. of studies done in sagebrush communities) to bolster the one by Belnap et al. when describing how intact crusts may play a role in limiting exotic invasions. For example, breaking up of physical and microbiotic soil crusts increases surface roughness, which favors cheatgrass germination (Tisdale and Hironaka 1981**; complete citation provided in section E.4.1**). And, the relationship of crust destruction and weeds is further supported by evidence that intact cryptobiotic crusts reduce or prohibit weed establishment by preventing weed seed germination (Eckert et al. 1986, Mack 1989 [should be 1981]**; complete citations for both papers provided in section E.4.1**). ***Because the preceding papers are specific to the Great Basin Desert, a cool desert, we chose not to incorporate them into our discussion of seedling germination and vascular plant growth. We do address the Mack (1981) paper in a subsequent section (section 7.3.4).***

3. Section 7.3, Page 7.4. The authors open this section with reference to the cold deserts: "primarily the Colorado Plateau region **of** the Great Basin Desert. Both Bailey, and The Nature Conservancy normally treat these ecoregions separately. ***The Conservancy follows Bailey's delineation of ecoregions, with some modifications, for the purposes of conservation planning. For this review, we simply accepted the traditional view of four North American deserts. It is beyond the scope of this review to determine whether the Colorado Plateau should be treated as a desert separate from the remainder of the Great Basin.***

4. Section 7.3.1, Biological Crust Vulnerability…, Page 7.5. The authors open this section with reference to recent literature reviews on the topic. Another review is my meta-analysis (Jones 2000) which the authors cite elsewhere in the literature review, and which included 6 separate studies in that portion of the meta-analysis, and which found significant impacts of grazing on crusts. ***We cited Jones (2000) as an additional review paper, but did not further discuss it in terms of specifics in this section.***

5. Section 7.3.2, Soil Compaction…, Page 7.7. Another potential citation here could be my meta-analysis, which investigated impacts of grazing on soil bulk density, water infiltration and erosion, with 26 studies grouped into those three categories. The meta-analysis identified the later two categories as having highly significant negative effects from grazing. ***We incorporated Jones (2000) and discussed its findings.***

6. Section 8.2.3, Desert Tortoise, Page 8.5. Towards the bottom of the page, the authors use the term "ephemeral grazing systems." It would probably be helpful to future readers of the literature review if this term were defined. ***Added a footnote that defines the term.***

7. Section 8.2.5, Rodents and Lagomorphs, Page 8.10. Another potential citation here is my meta-analysis, which re-analyzed the results of 16 studies in two categories (rodent species diversity and rodent species richness), and found in both cases that the effects of livestock grazing on rodents was significant. ***Added citation and an appropriate discussion of its findings and relevance to our review of the impacts of livestock grazing on rodent communities.***

8. Section 8.2.5, Rodents and Lagomorphs, Page 8.11. Towards the top of the page, it is noted that Jones and others (2003) observed shifts in k-rat and pocket mice dominance in the study area. It may be interesting for future readers to know what this shift in dominance entailed (i.e. was it exactly as Warren and Anderson 1992 had found: a shift from k-rat dominance to pocket mice, and did this happen after livestock removal or just a decrease in grazing? Over how long a period, etc.?). ***We deleted the phrase "Concordant with Warren and Anderson's (1992) findings," as the Jones and others (2003) findings were more complex than that phrase implied. We expanded our discussion of this paper, which may address the reviewer's subsequent questions to the extent the available data permit.***

9. Section 8.2.5, Rodents and Lagomorphs, Page 8.11. There is other literature that could be cited here, regarding the affinity of pocket mice for vegetative cover (i.e. Price and Brown 1983 and Reichman and Price 1993**; complete citations for both papers provided in section E.4.1**). ***Added a sentence that incorporated the general ecological observations of these two citations relative to kangaroo rat and pocket mice habitat affinities.***

10. Section 10.1.1, Continuous grazing, Page 10.1. In the first paragraph the authors refer to the "shortgrass prairie in the Great **Basin**." Don't the authors mean to say the Great **Plains** here? ***Yes. Corrected.***

11. Section 10.2.2, Other Considerations, Page 10.6. In the paragraph about grazing systems that might be compatible with biological crusts, the authors state towards the beginning of the paragraph, "grazing should be avoided when soils are wet." Then towards the end of the paragraph they recommend only "minimal grazing during dry seasons." While I think the take-home message is that crusts will never do well with grazing regardless of whether conditions are wet or dry, these conflicting statements in the same paragraph may confuse readers and do send something of a mixed message. ***In the revised Chapter 10 we deleted the referred to information as it didn't fit and we agree was confusing. We made a more general statement about the management considerations related to biological soil crusts elsewhere in the chapter.***

12. Section 11.2, Immediate Considerations…, Page 11.4. As I point out in my general comments above, I think its important to spell out to the BLM the importance and benefits of conducting a forage analysis and running a capacity model to ascertain potential baseline stocking rates for an area. ***See our response to your general comments above.***

E.4.8 Dr. Paul R. Krausman, Professor of Wildlife Ecology, College of Agriculture and Life Sciences, School of Natural Resources, University of Arizona

General Comments

I reviewed the document as requested, and overall it is well written with clear objectives. However, it could be reduced significantly in length and still meet the stated objectives. Because it is such a thorough review, I encourage you to revise it for publication in *The Wildlife Society Bulletin* or *Journal of Range Management* upon acceptance by the Bureau of Land Management.

Specific Comments

1. Use the metric system for measurements. In some areas, you use English and others English and metric. ***Although the use of the metric system is standard in technical writing, some of the key data sets we accessed as part of the review—for example, precipitation data—are provided in English units. As a result, we decided to use the English system as our primary system of units. In those cases in which a study reported methods or results in metric units, we included verbatim this information within parentheses.***

2. Avoid duplication in Tables and Figures. For example, all data from Table. 3.1 could easily be presented in Figure 3.3. ***We agree it is important to avoid duplicating information; however, in the specific example provided we see little duplication. For example, weather station elevation and years of operation information (Table 3.1) are not feasible to include in Figure 3.1.***

3. Reduce the discussion of weather stations. Present the most significant information and move on. Readers will not likely spend much time with this section, especially when you conclude with a statement that potentially discredits the data presented (i.e., Page 3.22 – "these stations may reflect below average, average, or above average conditions..." ***We feel the length of the discussion on precipitation patterns is warranted given the importance of precipitation's ecological role in the Sonoran Desert. The section on temperature is short and includes the mentioned caveat because microhabitat conditions can play a role at the locale scale in determining whether a catastrophic freeze could occur. This caveat does not discredit the information provided.***

4. Eliminate redundant material. For example, on page 4.1 and 4.4, the authors state "The Sonoran Desert is the warmest" desert in N. A. ***Deleted the second mention of this fact at the beginning of section 4.1.3.***

5. The methods are clear and could be duplicated by others - nice job.

6. Results (i.e., review of the literature) are balanced, and authors state what the literature states but also indicates the limitations of the studies reviewed. Each chapter has a "conclusion" section that summarizes the findings in a clear, concise manner.

7. Avoid use of web sites for factual information (e.g., NatureServe 2003). These are not peer reviewed. For example, the authors cite NatureServe (2003) for peak breeding of desert bighorn sheep. Some populations breed in 11 of 12 months, and the peak is in January (Witham 1983**; complete citation provided in section E.4.1**). The duration of the mating season in bighorn sheep is longer at lower elevations and southern latitudes and shorter at higher elevation and more northern latitudes. Desert bighorn are at lower elevations and southern latitudes and have different peaks in parturition Krausman et al. (1999**; complete citation provided in section E.4.1**). ***Deleted the NatureServe 2003 reference and revised the text to reflect information from Witham (1983) and Krausman and others (1999).***

8. The latest subspecies for desert mule deer is *Odocoileus hemionus eremicus*. ***Corrected.***

9. Other references you may find useful for the section on mule deer include Krausman et al. (1997**; complete citation provided in section E.4.1**) and Krausman et al. (1985**; complete citation provided in section E.4.1**). ***Incorporated both references and revised text to reflect the new information.***

10. Citation to replace Pitzl (2004) is Krausman et al. (2004**; complete citation provided in section E.4.1**). ***Replaced Pitzl (2004) with Krausman and others (2004) and revised the affected text accordingly.***

11. I suggest you consider the potential influence of livestock on pronghorn (especially the endangered Sonoran pronghorn [*Antilocapra americana sonoriensis*]). Fencing for livestock is not advantageous to pronghorn. ***We conducted a keyword search on Sonoran pronghorn and pronghorn in general for interactions with livestock. The literature is extremely scant in regard to Sonoran pronghorn. We reviewed seven papers that mostly addressed general pronghorn-livestock interactions.***

12. Other citations relating to wildlife and livestock in the Sonoran Desert can be found in Krausman and Morrison (2003**; complete citation provided in section E.4.1**) (e.g., Vorhies and Taylor [1933]). ***As we defined the Sonoran Desert for the purposes of this literature review, it does not include the semi-desert grasslands and other habitats characteristic of the Santa Rita Experimental Range. Despite this we do include a number of papers cited in Krausman and Morrison (2003) that address livestock interactions with specific species that also occur in the Sonoran Desert. Although we did not include the Vorhies and Taylor (1933) paper in our review, we included a subsequent paper by Taylor and others (1935; also cited by Krausman and Morrison [2003]) that addressed interactions between lagomorphs and livestock grazing.***

13. I did not review Chapter 9.

14. I agree with your conclusion in Chapter 10 that extreme caution and flexibility are needed with livestock management to insure that the integrity of the Sonoran Desert ecosystem is maintained.

However, in your extensive review, all of the arrows are pointing in the same direction: livestock and the Sonoran Desert ecosystem are not compatible. Livestock create negative influences in this desert. What are the positive aspects of livestock and how can livestock benefit the ecosystem? What economic benefits do livestock have to society in the Sonoran Desert? Do these benefits, if any, outweigh the negative influences livestock have on the desert? Clearly, there is room for studies to examine how livestock influence the Sonoran Desert. ***The preceding questions that conclude the comment are rhetorical questions posed by the reviewer and as such do not require any resolution.***

15. Some citations are not complete (e.g., Dodd and Brody [1986]). Also, do you consider web sites as literature? ***Corrected the Dodd and Brody citation. In addition, we reviewed and edited the other citations as appropriate to ensure completeness. We do not consider web sites per se as literature, but some electronic references can be accessed directly from web sites. After replacement of the NatureServe (2003) and Pitzl (2004) citations with other references, only the FWIE (1996) citations remains as a reference that was accessed off of a web site. This particular reference is a status summary for the Tumamoc globeberry and is used to identify biological characteristics of the plant.***

16. You will likely be interested in the publication by McClaran et al. (2003**; complete citation provided in section E.4.1**) and articles related to livestock and bighorn sheep in Krausman (2000**; complete citation provided in section E.4.1**). ***One or more of the articles in McClaran and others (2003), besides Krausman and Morrison (2003), address grazing and vegetation management on the Santa Rita Experimental Range south of Tucson. As the Santa Rita ecological system is primarily a semidesert grassland, we did not consider the articles cited within McClaran and others (2003) unless a reviewer made specific reference to a particular article. From Krausman (2000), we incorporated the individual overview article by Krausman in regard to its discussion of the role of disease transmission from livestock limiting the success of bighorn sheep translocation efforts.***

E.4.9 Dr. Joseph McAuliffe, Director of Research, Desert Botanical Garden

General Comments

I read the draft in its entirety and was impressed by the work you and your colleagues did on this. It presents a comprehensive look at the nature of the environment of the area as well as a well-rounded review of so many factors and potential impacts. I really can't think of anything that you left out. I urge that you find some way to have this review eventually published in the open literature. It is that important of a contribution and should not be eventually lost to the "gray literature" pile.

Specific Comments

I have only one comment regarding an improvement that could be made. Figures 3.7 and 3.11 are a poor visual presentation of the seasonal precipitation information. I suggest some other kind of presentation. ***We decided to leave the visual presentation of Figures 3.7 and 3.11 as they were (beyond eliminating the gray background), as we didn't come up with a better way to present the data.***

E.3.10 Dr. Daniel Milchunas, Research Scientist/Scholar, Forest, Range, and Watershed Stewardship Department and Natural Resource Ecology Laboratory, Colorado State University

General Comments

I believe this is an objective and thorough report on the effects of grazing in Sonoran Desert. There are a limited amount of studies in this ecosystem, but the authors have done an excellent job synthesizing and interpreting the existing literature. Below are some comments that I hope will be useful – I generally agree with the contents of this report and do not have any major criticisms to make.

Specific Comments

1. Page 2.2, Figure 2.1: It is fine to use the ecoregions map, but I would point out that the western boundary of the shortgrass steppe ecoregion extends much further west into New Mexico than the mapping of the shortgrass steppe grassland (Lauenroth, W. K. and D. G. Milchunas. 1991. **Complete citation included in section E.4.3.**). Further, the historic distribution of bison coincides more with the grassland mapping, even though the distribution of bison was not considered when mapping the shortgrass steppe (Milchunas 2004). The implication is just that the ecoregions map appears to give the impression of a long evolutionary history of grazing by native large herbivores to a much larger area of New Mexico than may be the case. ***The preceding may all be true; however, it's beyond the scope of this report to address this issue. To call attention to it would break up the flow of the report, as we are not concerned with defining the basis for the boundary of any ecoregion besides the Sonoran Desert.***

2. Page 4.9, belowground biomass: It is a good point to raise that the belowground plant response could negate any aboveground compensatory regrowth response, and citing a study of reduced root biomass with grazing in Arizona. I am not suggesting any change to text here. However, the statement that grazing "often reduces belowground biomass" may be slightly misleading. Grazing can just as well often increase belowground biomass, based on studies from around the world (Milchunas and Lauenroth 1993). Root biomass is not root production or live root biomass, and biomass responses may be due to decomposition rates after root mortality. Unfortunately, there are very few root production studies in the field with controlled grazing treatments. ***We added additional information, including findings from Milchunas and Lauenroth (1993), to indicate that grazing sometimes can lead to increased belowground biomass.***

3. Page 4.10, limitations or advantages of different types of studies: Good to include this type of discussion.

4. Page 4.11, selective grazing and preferred species responses: In the context of the southwestern US and with the examples given, the statements that palatable species increase with release from grazing and unpalatable species increase with grazing may be true. This should possibly be qualified as – in these particular communities with a short evolutionary history of grazing, palatable species .... This is because, in many communities with a long history of grazing, grazing-tolerant or grazing-avoiding palatable species can increase with grazing. Unpalatability is not the only way plants avoid grazing, and relative tolerances come in to play as well. ***We added a footnote that pointed out this possibility.***

5. End of Community Composition section: There was a good discussion of the advantages/disadvantages of controlled grazing treatment studies versus just following the single release from grazing or single imposition of grazing through time. Both types of studies were reviewed – how do they compare? ***We added a brief discussion on how these two approaches compare in a revised Conclusions section.***

6. Page 4.17-4.18, the water-site effect. Often people think the presence of exotic and native opportunistic, disturbance, 'weed' species around watering or resting areas is due to defoliation and trampling. While this is certainly part of the reason, the most important reason for the 'piosphere effect' is the high deposition of nitrogen in feces and urine (Senft 1983**; complete citation included in section E.4.1**). Low seral stage species are poor N-competitors and are therefore favored by disturbance that removes competitors or disturbance that increases N availability. Management

implications are 1) select watering areas with high C soils, 2) manage to maximize N volatilization or leaching, or 3) add carbon sources to the system to immobilize N (lignin may last longer than short effects of sugar, but is only now under study). ***We added a reference to the Senft (1983) citation.***

7. Non-native species: While I generally agree that non-native species are more likely to invade grazed areas in systems with a short evolutionary history of grazing, and that areas around watering points are susceptible everywhere, there is literature from the southwest showing that Lehmann lovegrass invasion and spread can be independent of grazing/no grazing (Angell and McClaran 2001**; complete citation included in section E.4.1**). Schmutz and Smith (1976**; complete citation included in section E.4.1**) found more Lehmann lovegrass in protected than grazed sites, while Brady and others (1989**; complete citation included in section E.4.1**) found the opposite. These are grassland sites, but suggest that this particular exotic species may not respond as implied. ***Although we acknowledge this possibility exists for Lehmann lovegrass and perhaps other non-native plants as well, we do not see where making this point necessarily fits into our current organization of the discussion of the topic. In the case of Lehmann lovegrass its ability to invade may be more related to its moisture requirements and reactions to fire as compared with native species rather than its interaction with livestock grazing. We did not incorporate the suggested citations. The information about livestock interactions with non-native plants is now split between section 4.1.4 (which addresses fire as an ecological process) and the piosphere studies subsection of section 4.2.2.***

8. Page 4.18 bottom: The citation for the implications of a lack of a long evolutionary history of grazing for introduced livestock effects on plant communities may want to also include Milchunas et al.1988 in addition to the 2004 reference, since the 2004 one is just a USFS GTR grey literature report. “General Technical Report” (in press) may want to be added to the literature cited section, since it will be published and not just a file report. ***The treatment of the role of evolutionary history has been expanded as part of a subsection under section 4.1.5, in which the Milchunas and others’ (1988) paper has been incorporated. In the Conclusions section we refer to the role of evolutionary history but do not include citations.***

9. After ends of plant community composition and plant community function sections: You did a great job earlier on your precipitation/climate section. It may be appropriate to make some statements about how grazing and changing climate may influence plant community dynamics and function. A shift towards greater winter precipitation can increase deep rooted shrubs and annuals that can rapidly utilize winter-stored moisture and then go dormant. In some situations, grazing may accentuate these types of climatically driven changes. The distribution of the seasonal precipitation that you very well described in the climate section has potentially important interactions with grazing responses. There are some interesting insights into these issues in papers like: Brown and others (1997), Curtin and Brown (2001), Curtin and others (1999, 2002), and Neilson (1986). **Complete citations for all papers are provided in section E.4.3.** ***Although all of the preceding suggested papers are of interest, we decided not to incorporate most of them into this review. We think it is important for this literature review to maintain a focus on the patterns and inherent variability associated with the current Sonoran Desert climatic regime and how that may influence plant community-livestock interactions rather than speculate on what may happen under a climate change scenario. We note that the suggested suite of papers addressed climatic patterns and plant community dynamics in ecosystems that occur to the east of the Sonoran Desert in which grass-shrub dynamics and fire have a prominent role. Such interactions are not likely to dominate plant community dynamics in the Sonoran Desert, except under limited circumstances such as in tobosa grasslands that depend on accumulations of runoff water. We did incorporate the Neilson (1986) paper into section 4.1.2, in which we discuss precipitation variability, as another example of the consequences of natural variability in precipitation patterns. We used examples to illustrate that if one of the effects of climate change in the Sonoran Desert is to change the present patterns of precipitation variability,***

then shifts in such patterns, even when total annual precipitation remained the same, could result in significant changes in the vegetation.

10. Wayne Polley has hypothesized and Rick Gill has shown that increased atmospheric CO_2 may also be a factor in irreversible vegetation change, and these types of issues could be another limitation to studies of only one treatment through time (Gill and others 2002, Polley and others 2002). **Complete citations for both papers are provided in section E.4.3.** ***Similar to our concern expressed in response to the preceding comment, we decided not to incorporate the suggested papers. Although the Polley and others' (2002) paper was itself of interest, it again addressed grassland ecosystems. We recognize that the general phenomenon of CO_2 enrichment also may play a significant role in influencing long-term trends in vegetation, but would prefer to have had Sonoran Desert-specific studies to make these points.***

11. Chapter 6: Data on the effects of grazing on rare plants is commonly not available. The report does a good job of assessing potential impacts due to distribution accessability to grazers. I would add only a brief comment. The following is from Rebollo (2002**; complete citation included in section E.4.1**):

    > McAuliffe (1984**; complete citation included in section E.4.1**) found refuge effects of the tree-like cactus *Opuntia fulgida* on species of small barrel-cacti (*Mammillaria microcarpa* and *Echinocerus englemannii*) in the Sonoran Desert, and suggested a direct refuge effect from small mammalian herbivores. In the shortgrass steppe, cattle do not graze barrel cacti and the refuge effect may be due to reduced trampling. *Opuntia* [*polyacantha* in the shortgrass steppe case] is conspicuous and has much longer and more rigid thorns than those of barrel-cacti.

    Two points emerge. Small barrel cacti are susceptible to cattle trampling, even though larger cacti are avoided and can serve as biotic refuges. On the other hand, small mammals do utilize barrel cacti in both the Sonoran desert and the shortgrass steppe, and small mammals generally decrease with livestock grazing. In this case, there is a potential for small mammal utilization to increase when cattle are removed. My observations in shortgrass steppe indicate that barrel cacti are utilized only when high numbers of small mammals go into a winter of particularly poor food availability. The tops are cut off, and the insides scooped out. Many of the cacti re-sprout from the base, and can be distinguished by their having many small barrels, rather than the usual one large barrel. ***We added discussion relative to the refuge effect, which included the recommended citations.***

12. Page 10.1, continuous grazing: The shortgrass prairie (more recently referred to as shortgrass steppe) is in the Great Plains not the Great Basin - this is probably a typing error. I don't think that I would say that continuous grazing "has seen most success in shortgrass prairie". I would say that shortgrass steppe is among the most tolerant ecosystems in the world to grazing, and therefore continuous grazing has relatively less effect here. However, even in shortgrass steppe deferring grazing to late spring to favor cool-season species is generally more successful than continuous grazing. There are many other examples where continuous would not be preferred. ***We changed the sense of our discussion to indicate that ecosystems such as the shortgrass prairie "have been cited as tolerant of continuous grazing," while also referring to abiotic and biotic attributes that characterize "tolerant" ecosystems.***

13. Good review of the various grazing systems. I would only add that short duration grazing has no logical basis in arid or semiarid regions simply because plant growth rate is slower than the rotation rate. The only place that I know of where short duration grazing has a non-negative impact is in highly productive, improved, non-native agronomic pastures in the mid-west and northeast, i.e., dairy

pastures. Fuhlendorf and Engle (2001**; complete citation included in section E.4.1**) do a good job of describing how short duration grazing does just the opposite of what proponents say it does when it comes to landscape heterogeneity. ***We added the comment about plant growth rates more often than not being slower than the rotation rate. We did not cite Fuhlendorf and Engle (2001). We decided not to discuss the landscape heterogeneity aspects of the issue.***

14. In many Mediterranean systems with large proportions of annual species, such as in Spain and Israel, the seasonal timing of grazing is much more critical than in perennial systems, because plants need to set seed. While we may not know what would work best in this particular desert, the general concept that timing will be important is noteworthy. ***We think timing will be an important aspect of grazing management in the Sonoran Desert with respect to how BLM may choose to manage ephemeral allotments.***

15. Good discussion on the rest of the grazing systems text. I would add only that it can be difficult to be flexible fast enough when going into drought. It takes time to decide that in fact you are entering a drought, and then time to de-stock. One means to build in a temporal safety buffer, if you have the luxury to do so, is to have emergency-use areas that are not being grazed, that animals can be moved to for short periods of light grazing while decisions and then de-stocking actions are taking place. ***We added a discussion about drought, the importance of the period in which drought is beginning to occur or is projected to occur (drought onset), and the impediments to the ability to rapidly destock.***

16. The origin of the state and transition concept should be cited: Westoby and others (1989**; complete citation included in section E.4.3**). ***We cited Westoby and others (1989) at the originators of the state-and-transition model concept.***

17. I agree with statements in section 11.2. I would possibly stress more that, if grazing is allowed in this system that does not have a long evolutionary history of grazing by large generalist herbivores, a plan to react rapidly to removal of animals during the onset of drought be given as much or more emphasis as the recovery after drought. ***We have now included throughout appropriate sections of the document the concept of three periods of drought—onset, during, and exiting—and the fact that they each deserve due consideration in the formulation of appropriate grazing management strategies in the Sonoran Desert.***

E.4.11 Dr. Phil R. Ogden, Professor and Range Extension Specialist (Retired), College of Agriculture and Life Sciences, School of Natural Resources, University of Arizona

Specific Comments

1. The purpose, scope, and approach for this report are well documented in chapters 1 and 2. The data displayed in table 2.5 show that livestock grazing impact research within the Sonoran Desert is limited. Only 25 publications, of the 100 reviewed, were found and reviewed for results of empirical research within the Sonoran Desert. This is a small amount of data to represent an area as variable over space and time as the Sonoran Desert. ***We agree. Although the numbers in the final report have changed somewhat, the number of studies addressing grazing impacts and management strategies in the Sonoran Desert is still disappointedly low.***

2. A general description, physiography, geology, soils, natural communities and variable and limited precipitation for the Sonoran Desert National Monument (SDMN) are well presented in chapter 3, and the "objects of interest" identified in the Proclamation establishing the SDMN, and BLM's obligation regarding continued grazing on SDMN also are accurately summarized in this chapter. The Proclamation provides that grazing shall be allowed to continue north of Interstate 8 only if BLM

determines that grazing is compatible with the objects for which the SDMN was established. This current literature review, apparently, is a document to provide BLM with data to determine if livestock grazing is compatible with the purposes for which the monument was established. ***In part. The report's findings and conclusions are meant to be broadly applicable to the Arizona Upland and Lower Colorado River Valley subdivisions of the Sonoran Desert.***

3. Chapter 4 provides reviews of observations and discussions of ecological processes, vegetation dynamics, and impacts of livestock grazing on Sonoran Desert Plant Communities. On page 4.10 of this chapter, the authors list some general limitations to the literature regarding effects of grazing on plant communities. They recognize that results of studies which report vegetation changes over time on a single site after livestock grazing impacts have been removed are confounded with climatic and other possible factors. They describe studies on adjacent sites such as ungrazed compared to a grazed treatment over time as studies that are more robust.

4. There also are other limitations generally associated with livestock impact studies and reviews. Livestock grazing intensity for some references are reported in this current review, but the vast majority of the reviews of livestock impact references in chapters 4 through 9 are simply referred to as livestock impact with no reference to season, duration, frequency or intensity of the impact. Also most of the discussion contains no information on ecological site characteristics where the impact was studied. Thus, the reviewed information is general and caution should be used to extrapolate results to specific ecological sites or grazing treatments. ***We incorporated these other types of limitations into our discussion.***

5. The review of saguaro recruitment and survival in chapter 5 generally is an objective review, until the final paragraph of the summary on page 5.8. The discussion in the body of the chapter does not appear to support the statement "The case of Saguaro National Park East is unique in the literature in that historic livestock grazing is strongly implicated as the primary factor responsible for a severe and long-term decline in saguaro recruitment, independent of climate." ***We deleted the last paragraph of the Conclusions section and revised the remainder to better reflect the literature review. The changes are more a matter of proper emphasis.***

6. The review of biological crusts in sections 7.2 and 7.3 of chapter 7 is very subjective. With a minimal amount of specific data and many references to statements from review documents, the case is made that "Sonoran Desert soils derive the majority of their nitrogen from biological crusts, suggesting that the biota of this region (and other arid lands west of the Rocky Mountains) evolved with low levels of soil surface disturbances (USDI 2001, Warren and Eldridge 2001)." A major research effort would be needed to document this statement for the Sonoran Desert. I do not see any such research referenced in this chapter. ***The entire chapter has been extensively revised to rely more on specific empirical studies rather than just review articles. The conclusion section, from which the reviewer's quote was taken, better reflects the state of knowledge about biological soil crusts in the Sonoran Desert and clarifies and more narrowly focuses what was meant by the above quote and its relevance.***

7. In contrast to the review in chapter 7, the review in chapter 8 is relatively objective, but is not free of unsubstantiated statements that become fact from restatements in literature reviews. An example is the statement in paragraph 3 of page 8.5 that lists a number of non-native plants, including filaree and Russian thistle, that show up in desert tortoise diets. The suggestion is made that these species may be inferior to native species in nutritional quality. This suggestion is not true. Both filaree and Russian thistle, for instance, are documented as being high in nutrition, especially protein. ***The information on non-native plants in the diet of desert tortoises was extensively revised and made its own paragraph in response to this comment and the comments of another reviewer on the subject.***

As the specific comment about nutritional value of certain non-native plants was the only example provided of supposed "unsubstantiated statements," we made no other changes in response to this comment.

8. My main question with chapter 10 is concerning the use of grazing alternatives from the Kofa National Wildlife Refuge to evaluate Sonoran Desert grazing strategies. Are we to assume that the authors of this EIS were able to locate primary scientific data on grazing strategies on which to base their grazing alternative decisions? ***In this section we were evaluating the available literature that attempted to assess grazing management strategies as applied in the Sonoran Desert. We evaluated the Kofa NWR EIS and also added a review of Hayes (2004) as frankly these were the only two documents that specifically evaluated grazing management approaches for the Sonoran Desert. This is a reflection of the paucity of such studies. The authors of the EIS apparently did not have access to data on grazing studies specific to the Sonoran Desert, because as best we can tell none exist.***

9. My comments above concerning the review of literature regarding soil crusts in the Sonoran Desert applies also to the discussion in paragraph 2 on page 10.6. In my opinion, the jury is still out on the importance of biological crusts in the Sonoran Desert. ***We deleted the information referred to as it was out of place and somewhat confusing. Our revised Chapter 7 makes the case for considering the importance of biological soil crusts in the Sonoran Desert.***

10. The first paragraph of chapter 11, General Conclusions and Recommendations, includes a sentence. "Still, the available literature suggests that livestock grazing has discernible impacts on Sonoran Desert ecosystems." This is no surprise. Is any use of this ecosystem without discernable impacts? ***The general conclusions have been revised somewhat but still capture the above point. The difficulty is in teasing out the various influences of climatic events, historic grazing, and present grazing. The point here is that despite the other factors involved, present grazing is still having an impact.***

11. I am not sure what is being suggested with the discussion in paragraph 3 on page 11.3 regarding the statement that multiple sources of anthropogenic disturbance may act synergistically. Does this imply that livestock impacts be reduced to accommodate recreation, wildcat dumping and other anthropogenic activities? ***For the Sonoran Desert National Monument this was the implication to the extent BLM was managing for other land uses besides grazing; however, per BLM's request we have removed all explicit recommendations from the final report.***

12. I agree, in general, with most of the immediate considerations shown in bold print in section 11.2 which are suggested to be incorporated into grazing administration decisions for grazing on the SDNM. The suggested consideration ("Decisions should be conservative with respect to maintaining the integrity of biological crusts at least until better quantitative measures are available to assess crust status under different grazing intensities.") should not be a consideration. ***Per BLM's request we have removed all explicit recommendations from the final report; however, as we discuss in Chapter 7, we disagree that biological soil crusts are not an important consideration when devising appropriate grazing management strategies for the Sonoran Desert.***

13. Grazing will need to be conservative and flexible to deal with drought and meet the livestock management objectives for the SDMN. What conservative and flexible grazing means for each grazing allotment, however, can not be determined from a literature review or general administration decisions. This current literature review and considerations identify the kind of livestock impacts and decisions that may be considered, but the variability and nature of the observations and the discussions in the report must be interpreted with caution for site specific application. ***As we***

concluded in Chapter 10, grazing impacts and grazing management strategies must consider multiple spatial (and temporal) scales.

14. Allotment history and current inventory data and analyses are needed to determine if impacts by current or adjusted livestock management for each allotment are below resource thresholds that significantly affect compatibility of livestock with objects specified in the Proclamation. At least part of the SDMN has been grazed by livestock for over a hundred years, and the area still retains objects and characteristics described in the Proclamation as "...a magnificent example of untrammeled Sonoran desert landscape." Livestock grazing is not a new use. Experience and past use should help identify general thresholds below which livestock impacts for an allotment are expected to be compatible with the objects identified in the Proclamation. ***Experience and past use may help to some extent; however, we suggest that much more is involved here, as little guidance can be presently gleaned from the literature on how to set appropriate stocking rates for the Sonoran Desert. Our analysis of the literature on Sonoran Desert ecosystem dynamics also indicates that numerous ecological factors that characterize the Sonoran Desert have been under-appreciated in how they may affect implementing an appropriate grazing management strategy and setting appropriate stocking rates for the Sonoran Desert.***

15. The research recommendations listed in Chapter 11 are a wish list. The Bureau of Land Management is not a research organization. Their main obligation should be to monitor the results of their decisions. ***Per BLM's request we have removed all explicit recommendations from the final report.***

E.3.12 Daniel Robinett, Rangeland Management Specialist, Natural Resources Conservation Service

General Comments

In all the draft report is well written and thorough. Thanks for your consideration.

Specific Comments

1. On page 3.3 under the discussion of NRCS ecological site classes found on the SDNM you describe them as being in a 2 – 10 inch precipitation zone (pz.) across the monument. They are in fact in a 7 – 10 inch pz. for all but the highest elevations of the monument. This zone is described by NRCS as the Middle Sonoran Desert subdivision (MLRA 40–2). The highest elevations include the tops of Table Mountain and the higher elevations of the Sand Tanks and Saucedas. This zone is recognized by NRCS as the Upper Sonoran Desert subdivision and has a 10 – 13 inch pz. ***We checked the MLRA subdivision maps. In reality a good portion of the SDNM is located in the 2 to 7 inch pz (Lower Sonoran Desert). We modified the text to separate the pz information from the ecological site class information in which the soils are described. We provided an overview of the precipitation zones included on the SDNM to lead off the description of ecological site classes.***

2. In a discussion of regional precipitation patterns, beginning on page 3.9, there is no attempt to define drought. It has been reported from various arid regions around the world that drought occurs when precipitation is less than 70% of the average annual precipitation. In my experience this is a very good figure and usually corresponds well with significant negative impacts on native plant communities. In my opinion some characterization of drought would be useful to the BLM managers of this area**. Mr. Robinett subsequently recommended three potential references to check for drought definitions: Cooke and Reeves (1976), SRM (1989), and** Holechek and others (2004). **Complete citations for the first two citations are provided in section E.4.3. We previously cited**

the Holechek reference. ***These citations, as well as others, were incorporated into a new section on drought; however, we included this information as a subsection to section 4.1.2.***

3. On page 4.7 there is some discussion of the lack of information about range livestock diets in the Sonoran Desert. The BLM (Lower Gila Resource Area) collected quite a bit of information during the late 70s and early 80s. The diet analysis was done by the UA using micro histological analysis of fecal materials. In particular they collected both plant phenology data and livestock diet data from the "Pipeline" allotment between Wickenburg and Wickieup. This ranch had a small cow herd in a three pasture rest – rotation grazing scheme that was resulting in range forage plant recovery and significant improvement in ecological conditions. The rangeland was in the Upper Sonoran Desert subdivision. Although this data was never published it should be available through BLM. ***We added cattle diet information from allotments located on the Sonoran Desert National Monument (SDNM) based on data provided by Byron Lambeth of the Bureau of Land Management (BLM). We mentioned the above allotments to BLM, but the monument allotement information is what BLM located and provided. Because this document will support BLM's decision-making process for the SDNM, monument-specific allotment data are likely the most relevant.***

E.3.13 Dr. Susan Rutman, Botanist, Organ Pipe Cactus National Monument, National Park Service

General Comments

Please accept my comments on the Livestock Grazing Literature Review. I'm sorry I wasn't able to give enough time for a thorough review, because the document is a remarkable effort. It is beautifully written.

I don't entirely agree with your exclusion of studies that occurred outside the Sonoran Desert. I recommend broadening the scope. Many studies from outside the Sonoran Desert could provide support for ecologically sound management practices or could illuminate plant responses to livestock grazing. For example, the ecology of C3 annuals in the Mohave Desert or C4 annuals from the Chihuahuan Desert could illustrate the ecology of these species in the Sonoran Desert. The book Sonoran Desert Plants: An Ecological Atlas (Turner and others 1995**; complete citation provided in section E.4.3**) includes range maps and data that provide a wealth of information regarding the ecological tolerances of species that are dominant in the Sonoran Desert and that extend beyond its boundaries. Studies conducted by researchers at the Jornada Long-Term Ecological Research station, for example, provide overarching conclusions about livestock grazing effects and the desertification cycle. This review could also consider how drainages are affected by impoundments. ***We did not entirely exclude studies from outside the Sonoran Desert, but we did apply a conservative filter to make sure the studies would have relevance.***

Most everyone would agree that overstocking or inappropriate management is damaging. The question that should be raised and answered in the conclusion for each chapter and final recommendations is this: Does *any* amount of livestock grazing affect natural and cultural resources? Is there some amount of livestock grazing that is not damaging? Is the BLM's existing methodology for determining stocking levels, utilization, etc sufficient to protect the SDNM from damage? If not, why not and what would improve the situation? ***Based on the available literature your questions cannot be answered with any certainty. We concluded that the lack of relevant studies is a major shortcoming to developing and implementing appropriate grazing management strategies in the Sonoran Desert. It is beyond the scope of this report to evaluate BLM's existing methodologies for determining stocking rates and monitoring performance beyond what is reported in the literature.***

The review focuses on the peer-reviewed and published literature. Although these are important sources of information, two other groups of information sources have more influence on grazing in the Sonoran

Desert: 1) BLM policies and procedures, and 2) local experts, including practicing range conservationists, ranchers and academic professionals (e.g. range scientists, hydrologists, ecologists). TNC's review could highlight areas where BLM practices could result in damage to natural and cultural resources as well as the practices that are well conceived. TNC could verify or question anecdotal information shared by local experts. ***The scope of this report is a literature review. We were not requested to evaluate BLM's policies and procedures. We did canvass local experts for their insights on particular issues, but in general these insights were used to support or refute points made in the literature.***

Thanks for giving me the opportunity to comment on this review. Again, I apologize for giving it less attention than it deserves. I appreciate BLM's task and also appreciate some of the difficult management decisions that will bring the SDNM into the coming century.

Specific Comments

1. Section 3.5.2: Two important climatic patterns should be addressed in this section: decadal shifts in precipitation and the increasing trend in daytime and nighttime temperatures due to global climate change. Both of these regional climate patterns are well documented in the published literature and have direct implications for livestock grazing permits. Grazing permits, which span a ten-year time period, are often adjusted based on information gathered in one decadal cycle but the permit extends into a drier or wetter decadal cycle. Ecological damage is more likely when the stocking rate is based on plant production during a wet cycle but the stocking rate is inappropriate for a dry cycle. Even though the timing of shifts from one cycle to another can not be precisely predicted, the event is predictable. A mechanism for rapidly accommodating decadal shifts in grazing permits should be examined. ***We address the global climate change portion of the comment in our response to Comment No. 2 below. The decadal shifts in precipitation are of more immediate relevance, especially if the current drought trend continues and deepens. We agree that stocking rates based on wet conditions are inappropriate for dry conditions, but the situation is even more complicated than that. In section 4.1.2 (rather than 3.5.2, which simply presents precipitation data to illustrate the general patterns), we have added discussion about precipitation variability, existence of decadal precipitation patterns, and drought and their implications for grazing management strategies.***

2. The increasing trend in temperature will have long-term but uncertain effects on plant species and communities and plant productivity. Among other significant changes, freeze frequencies have declined, growing seasons and photosynthetic periods will lengthen for some species but shorten for others, and evapotranspiration rates will change. All of these changes will affect plant production. Extreme flexibility and seasonal monitoring will be needed to avoid ecological damage due to livestock grazing. ***Although global climate change may be a reality, we are not aware that expected regional trends for the Southwest have been identified with much certainty. Specific citations would have helped here, but may be moot. We have emphasized throughout this document the variability, as well as the extremes, of the Sonoran Desert's present climate. If flexible grazing strategies can be developed that respond appropriately to this variability, they also should be robust with respect to trends that are occurring over much longer time scales.***

3. Section 3.5.3: Below-freezing temperatures certainly do occur in southwestern Arizona. On Organ Pipe Cactus National Monument, freezing temperatures are more likely to occur in lowlands where cold air settles. One of the coldest spots in ORPI is the low-elevation Growler Valley on the west side. Freezing temperatures very likely occurred routinely within the SDNM, but the frequency of freezes has probably declined since warming began in the 1980s. The review should predict the possible outcome of decreasing freeze frequencies on plant populations and communities. ***We agree that freezing temperatures do occur in southwestern Arizona and have corrected this section***

accordingly. We further discuss the phenomenon of catastrophic freeze in section 4.1.3; however, we don't think speculating on the possible outcomes of potential changes in freezing temperature patterns is relevant to the purposes of this document.

4. Section 4.1: Note that Dr. Steven McLaughlin (1989 [should be 1986]**; complete citation provided in section E.4.3**) examined the origins of the floristic provinces of the southwest. ***We incorporated relevant information from this citation.***

5. Migration of plant and animal species is an important ecological process that management practices should accommodate. Plant assemblages are never static; those of the Sonoran Desert are a fairly recent phenomena and are continuing to change. Some Sonoran Desert species have been in the area less than 2,000 years. Species will be better able to adapt, adjust or migrate to ecological change if healthy plant populations are maintained throughout the breadth of the species' ecological range. ***We agree.***

6. Section 4.1.2: The statement that annual production is less predictable in winter than in summer is unsupported and is contradicted elsewhere in the review. If you assume that a greater species richness is an indicator of a more predictable resource, then it is clear that winter season moisture is more predictable than the summer. The number of winter annual species is far greater than the number of summer annuals. A likely explanation is that the greater evapotranspiration rates in the summer create fast wetting-drying cycles and generate a higher risk for annual plants. ***Actually the situation is more complicated, though some authors (for example, Turner and others 2003) have indeed suggested that summer rainfall is more predictable (which leads to the speculation that summer productivity is more predictable). In reality, which production is more predictable likely depends on the dominant seasonal rainfall patter in an area. Section 4.1.2 has been revised to discuss this issue more completely.***

7. Section 4.1.2: Anecdotal evidence from Organ Pipe Cactus National Monument and Cabeza Prieta National Wildlife Refuge support the statement that tropical hurricanes originating in the Pacific Ocean often result in pulses of recruitment of desert perennials. Of note was Hurricane Nora, which delivered a several inches of rain throughout southwestern Arizona in 1998. The rainfall resulted in an abundance of *Ambrosia deltoidea* and *Ambrosia dumosa* seedlings. I have observed similar recruitment events after hurricanes in other years. If these pulses of recruitment are important to the maintenance of some desert plant populations, the review should explain how this is pertinent to grazing management practices. ***We added a subsection on pulse dynamics in arid and semiarid ecosystems to address this comment in part. Other new subsections, such as one on drought, also try to get at these issues and how they affect grazing management practices.***

8. With its emphasis on the floristic origins of the Sonoran Desert flora, the text implies that the phylogenetic origin of a species explains its responses to climate. More directly to the point is the importance of photosynthetic pathway (C3, C4 or CAM) and physiologic tolerances of the species currently growing in the Sonoran Desert, regardless of their origin. Livestock grazing can shift the balance of warm season (C4 and CAM) and cool season (C3) species. ***The reviewer possibly meant biogeographical origin rather than phylogenetic. If so, in general the inference referred to by the first part of the comment is supported by the work of some researchers, such as Mulroy and Rundel (1977. BioScience 27:109–114). These authors also noted that of the 60 summer annuals that occur in Sonora , about 1/3 are C_3s. We agree, however, that the potential for shifts in composition between warm and cool season species as a result of grazing is of interest; however, we did not find specific studies for the Sonoran Desert that addressed this topic other than possibly McAuliffe (1998). We clarified the text and added the Mulroy and Rundel (1977) reference to address the first part of the comment.***

9. Section 4.1.3: The discussion on freezing temperatures should discuss the increasing trend in daytime and nighttime temperatures. The consensus among ecologists is that this trend will have significant but undetermined effects on the composition and relative abundance of species. Extirpations, range expansions or contractions, and population fluctuations are likely. The relative contribution of livestock grazing to these changes will be difficult if not impossible to determine. ***Although global climate change may be a reality, we are not aware that expected regional trends for the Southwest have been identified with much certainty. Specific citations would have helped here, but may be moot (given the last sentence of the comment). We have emphasized throughout this report the variability, as well as the extremes, of the Sonoran Desert's present climate. If flexible grazing strategies can be developed that respond appropriately to this variability, they also should be robust with respect to trends that are occurring over much longer time scales.***

10. Section 4.1.4: Wildland fires require fuel connectivity as well as an ignition and adequate fuel load. Native Sonoran Desert communities generally lack one or more elements of this equation. Invasive species, where sufficiently dense, provide fine fuels that connect coarser native fuels, which has increased not only the frequency but the size of wildland fires in the Sonoran Desert. ***We added information to section 4.1.4 as to the role of invasive non-native species in altering natural fire regimes within the Sonoran Desert.***

11. Although I'm not familiar with the paper by Wilson and others (1996), I suspect the term 'fire tolerance' has been misapplied. Plants can resprout or re-seed after a fire, but the response might not be related to any adaptation to fire. Post-fire establishment success can be explained in terms of response to disturbance, release from competition, or any number of other ecological responses. For example, my observations and unpublished report on wildland fires at Organ Pipe (1995) found that many riparian species could resprout after being top-killed. The likely explanation was not that they had adapted to fire, but that they had adapted to top-kill via scouring floods. ***We deleted the sentence in question and reference to Wilson (1996), as we agree the suggestion of fire tolerance was misapplied.***

12. Section 4.1.5: See my comments on section 4.1.2 regarding production of summer and winter annuals. ***See our response to that comment.***

13. Plant Responses to Herbivory (page 4.8): The Belsky (1986) paper was a controversial one that triggered a series of responses in the journals and bulletins of the Ecological Society of America. These papers and rebuttals should be addressed in this review. ***We agree that the discussion of Belsky's opinion needed better balance. The relevant material was extensively revised and expanded and included a number of the rebuttal articles.***

14. Page 4.9: The section introduces the concept that the evolutionary history of a system with grazing can explain grazing tolerances. Your review, then, should briefly explain the grazing history of the Sonoran Desert. The Sonoran Desert is less than 5,000 years old and very little history with large herbivores. ***We added material to address this topic.***

15. Section 4.2 Impacts of Grazing: See comments on including studies that have occurred outside the Sonoran Desert. ***See our previous response to this comment.***

16. Section 4.2.1: Dr. Joe McAuliffe has produced an influential body of work explaining the relationship between surficial geology, vegetation patterns and site potential. His work should be reviewed in this section (see 1991 J. of Arid Environments, also chapter 8 **[should be chapter 4]**, The Desert Grassland**; complete citations for both papers are provided in section E.4.3**). I believe a

surficial geology map would be critical to managing grazing or studying the effects of grazing on the SDNM. Did Hovorka (1996) account for the effects of surficial geology on vegetation? ***As this section addresses the literature on the impacts of livestock grazing on community composition, the papers by McAuliffe are not appropriately included here. We did incorporate information from these papers in sections 4.1.2 and 7.1. We could find no indication that Hovorka (1996) accounted for the effects of surficial geology on vegetation***.

17. Page 4.13, Warren and Anderson (1992) study: The review should provide information regarding stocking rates and grazing management so that the effects of grazing and post-grazing impacts can be fairly evaluated. In this case, the herd size was several times the recommended stocking rate and grazing was year-long. Range analyses (1966 and 1972) that were completed while livestock use was ongoing indicated that the range condition was so poor in most areas that livestock were traveling up to 8 miles from water sources. Recovery from the extreme degradation that was present in some of Warren and Anderson's study areas will take much longer than the decade or so that was included in their study. Some of the permanent plots in the study occurred next to grazing exclosures, which were used as control plots. While excluding cattle and burros, these plots did not exclude the overarching effect of accelerated soil erosion that was causing the loss of soils from within the exclosures. More than 10 inches of soil has been lost at some sites. Due to these confounding factors, it is difficult to draw any conclusions about the effects of exclosures or distance from livestock waters. These same issues apply to some of the grazing exclosures located within the SDNM. ***Added grazing history and stocking rate information. Also added caveats about range condition that may affect interpretation of the study's results.***

18. Page 4.14, regarding the application of the word 'suffrutescent': A suffrutescent plant is a perennial that has a much smaller amount of above-ground biomass during its dormancy than it does during its growing season. McAuliffe distinguishes the suffrutescent *Hilaria rigida, Hilaria mutica* and *Muhlenbergia porteri* from other perennial grasses, which store nutrients in their below-ground biomass. Suffrutescent species, therefore, are more damaged by grazing than other perennials. ***We expanded the text to incorporate McAuliffe's (1997b) discussion of the topic and its relevance to management.***

19. Page 4.17: This section should address the effect of livestock trails going to and from stationary water sources. Livestock trails on easily-deflated soils can be several inches deep, and much deeper in extreme cases. Organ Pipe Cactus National Monument had livestock trails that were more than 18 inches deep. These trails re-distributed runoff and created channels which, combined with the loss of plant cover, created large gully networks in accelerated erosion areas. ***Livestock trails may indeed be problematic; however, for us to include such specific information about their effects it should be documented in a published paper or report. We did not incorporate the comment.***

20. Conclusions, page 4.18: The first paragraph needs to do a better job of synthesizing the more complex ecosystem painted in the preceding text. Also, the influence of soils on all elements of the ecosystem (plant and animal) is at least as important as precipitation, yet it is poorly represented. ***We revised the Conclusions section and in a new section 4.3.1 summarized our findings relative to Sonoran Desert ecosystem dynamics.***

21. Page 4.19: The paragraph on community function and invasive species is poorly supported. A review of the literature is needed before these conclusions can be made. ***This paragraph was deleted in the revised Conclusions section. The information about livestock interactions with non-native plants is now split between section 4.1.4 (which addresses fire as an ecological process) and the piosphere studies subsection of section 4.2.2.***

22. Page 4.19: The time needed for site recovery from livestock grazing depends on many factors, including former and current stocking rates and grazing management history, condition (and sometimes presence) of surface soils, condition of the seed pool, status of herbivore populations, and rainfall. ***We agree. We eliminated mention of specific time periods related to recovery and broadly dealt with only the generalities of recovery.***

23. [In the interest of time, I did not review the chapters on saguaro recruitment and survival and other plant species. However, you should look for and review papers on whether or not livestock grazing causes the loss of rare species from a flora.] ***Waser and Price (1981), which we reviewed in Chapter 4, seems to be the most applicable study relative to the comment. In Chapter 6, we were concerned with whether studies existed relative to specific rare plants.***

24. Page 7.2: My observation is that the greatest soil crust cover occurs on flat or low-angle surfaces on Organ Pipe but I would expect to see the opposite trend in grazed areas. ***We incorporated the first part of this observation.***

25. Page 7.2: Dr. Belnap has measured disturbed and undisturbed soil crusts on Organ Pipe. She has reported significant changes in chlorophyll (photosynthetic activity) after a single tire track. Her work seems directly applicable to this review. ***We checked with Dr. Belnap on whether this work had been published. It was; however, the relevant paper—Belnap (2002)—was already included in our review. Moreover, the paper addresses impacts on nitrogenase activity and photosynthetic activity. We clarified in the text that the research was accomplished at Organ Pipe Cactus National Monument.***

26. Page 7.9. At Organ Pipe, livestock grazing reduced not only perennial grass cover but also reduced woody perennial plant cover. The link between reduced plant cover and accelerated erosion is a well-established one. ***We added the observation about woody perennial plant cover.***

27. At the 2004 Ecological Society meeting, the USDA NRCS presented a paper regarding soil erosion at Big Bend National Park. Their study site had a nearly identical setting to Organ Pipe and McAuliffe's study areas, and their conclusions regarding the causes and recovery potential were the same as ours. Livestock concentration at a water source placed on a susceptible soil led to localized devegetation, which triggered accelerated erosion. The site remains unstable and recovery will be long term. ***No response needed as the information remains to be published.***

28. Section 7.3.6 Albedo: Balling and others (1997**; complete citation provided in section E.4.1**) compared grazed sites in Sonora with ungrazed sites in Organ Pipe and reported significant differences in albedo, infrared surface and near-surface air temperatures. Plant cover in Sonora was about 50% less than on a nearby site in Organ Pipe. Daytime temperatures in August were more than ten degrees Fahrenheit higher on grazed sites in Sonora versus ungrazed sites in Arizona. These alterations cause a positive feedback that will continue to desertify the area. ***The Balling and others (1997) citation was from a conference proceedings. This work was subsequently published, in a slightly modified and expanded form, as Balling and others (1998. Climatic Change 40:669–681.). The information from this latter paper was incorporated into the text; however, the published numbers differ from what was cited by the reviewer.***

Comments on Chapter 11:

29. Immediate Considerations (page 11.3): I recommend being more pragmatic about your recommendations. I agree, for example, that BLM should avoid managing to average conditions. The questions remain: How does that affect their current method of year-to-year decision making?

How should it change? Is the current method of monitoring utilization inappropriate? Why? Should it change? ***Per BLM's request we removed explicit recommendations from the final report; however, we did draw general conclusions regarding livestock grazing management strategies appropriate to the Sonoran Desert that in part address some of your questions (see Chapters 10 and 11).***

30. The recommendation regarding productivity and utilization should be more clear and pragmatic. TNC's emphasis should shift away from annual and perennial species and focus on cool season and warm season species. The BLM should monitor the grazing pressure on warm season or cool season palatable species or both, depending on the permitted season(s) of use. The most palatable species in a pasture can be depleted long before less palatable species are used. ***See the response to comment No. 29 above.***

31. I recommend changing the decision recommendation regarding accelerated erosion (page 11.4). The recommendation should read: Decisions should prevent accelerated erosion by 1) limiting percent utilization to a conservative 25% or less of the most palatable species, 2) not developing water sources on soils that are resistant to accelerated erosion, 3) removing water developments on soils that are susceptible to erosion, and 4) removing water developments where livestock trails have become or are becoming deeply imbedded. ***See the response to comment No. 29 above.***

32. The second-last recommendation, while scientifically justified, is not realistic. Funding for these types of studies is almost never available, particularly in a reasonable timeframe. How, then, can the BLM best gather and apply information? ***See the response to comment No. 29 above.***

33. I would add additional considerations. Many BLM grazing allotments have no recent (less than ten years old) production/utilization studies. I suggest that grazing permits be issued only if the BLM has actually measured the variability of plant productivity in an allotment and has determined the appropriate stocking rate. Permits should not be issued if this information is not available. ***See the response to comment No. 29 above.***

34. A second recommendation is to avoid the modern tendency to develop water sources to improve economic profitability of rangelands. The BLM should consider allowing some areas to receive little or no livestock grazing by virtue of their distance from water. ***See the response to comment No. 29 above.***

35. The research recommendations need to be more focused on applied research that will produce results that will contribute directly to management decisions. It is not necessary to conduct research to determine, for example, if cattle are browsers in the Sonoran Desert. Cattle will eat the most palatable and nutritious plants they can find. If they can't find enough grass, they will eat the next best thing, across any weather gradient. It is unlikely that anyone will 'prove' that broad-scale reductions in cover and density of native perennial grasses has occurred. It is possible, however, to develop appropriate ecological site descriptions and manage towards those goals. ***See the response to comment No. 29 above.***

E.3.14 Dr. George Ruyle, College of Agriculture and Life Sciences, School of Natural Resources, University of Arizona

General Comments

As requested I have reviewed the draft manuscript "The Impacts of Livestock Grazing in the Sonoran Desert: A Literature Review" prepared by The Nature Conservancy in Arizona (TNC) for the Bureau of

Land Management (BLM), Phoenix Field Office, hereafter referred to as the manuscript or TNC manuscript. Evidently, the review was contracted to TNC by the BLM in order to help the BLM rule on whether or not livestock grazing will continue to be permitted on parts of the Sonoran Desert National Monument (SDNM) where it is not already scheduled to be eliminated, and if allowed to continue, under what regulatory criteria. It is my opinion that a literature review of this sort is of limited relevance in this situation. I believe the decision to continue or eliminate grazing on the SDNM should and will be largely related to political and social norms rather than the limited and highly equivocal ecological research available on the subject. Additionally, if grazing is to continue in the SDNM it should be based on the accumulated experience of the 120 years of grazing history and the experience of those working in the field applied on an allotment by allotment basis. ***Experience may help to some extent; however, we suggest that much more is involved here, as little guidance can be presently gleaned from the literature on how to set appropriate stocking rates for the Sonoran Desert. Our analysis of the literature on Sonoran Desert ecosystem dynamics also indicates that numerous ecological factors that characterize the Sonoran Desert have been under-appreciated in how they may affect implementing an appropriate grazing management strategy and setting appropriate stocking rates for the Sonoran Desert. Our conclusions are broadly applicable to the Arizona Upland and Lower Colorado River Valley subdivisions of the Sonoran Desert and not just to the Sonoran Desert National Monument.***

General Observations: My general opinion is that the TNC manuscript presents an excellent description and overview of vegetation dynamics and precipitation patterns in the Sonoran Desert. The document falls well short, however, of a comprehensive analysis of the literature related to managed grazing influences. It seems to focus on negative impacts at the small plot scale, while dismissing conflicting views or contradictory or inconclusive evidence, which comprises most of the literature reviewed. Grazing is not well defined either by the TNC authors or in reviews of the literature. This omission negates much potential contribution of the review as grazing must be defined in terms of intensity, frequency and timing for research or observations to be useful to managers. Large grazing animals cause localized site perturbations, especially when compared to areas where they are not present. The question for resource managers is what are the implications of these disturbances on a landscape basis and how do they influence the long term productivity of the system? ***The main problem is, as we discuss at length in the report, that studies of "managed" grazing in the Sonoran Desert do not exist in the literature. We note this as a serious shortcoming. We have attempted to better define "grazing terminology" to clarify our meanings, but note that most studies we reviewed failed to do this.***

I offer the following primary points of criticism for you to consider:

1. From my perspective, I do feel that the review presents a biased view against livestock grazing as a legitimate use of the SDNM. I suspect the authors believe that this is merely representing a conservative approach to livestock grazing but that is not how it came through to me. ***Obviously we disagree with the first part of the comment but respect the reviewer's right to offer his opinion.***

2. The literature cited from systems other than the Sonoran Desert seemed to be very selective and designed to represent an ideology rather then an overall conceptual model of potential grazing impacts. ***We contend that this is an inaccurate characterization of our work, but acknowledge that it has been through addressing the varied comments of our 16 reviewers and incorporating our resolution of these comments into the final report that we have approached developing an overall more robust conceptual model of livestock grazing impacts and appropriate management responses for the Sonoran Desert.***

3. Chapter 7 is most speculative and needs a complete rewrite. ***The chapter was extensively revised.***

4. Chapter 10 is the weakest and as it exists lends nothing to the document. ***The chapter was extensively revised. It now includes discussions of the relevance of particular grazing management strategies to the Sonoran Desert and a discussion of the equilibrium-non-equilibrium paradigm debate.***

Specific Comments

Chapter 1 Purpose and Scope

1. The tone of the manuscript is depicted on page 1.1 when the authors imply that livestock grazing on rangelands is not compatible with "resource conservation." In my opinion, this view permeates the entire literature review, especially the conclusion section of each chapter. ***We do not agree that the referred to sentence implies what the reviewer contends and unfortunately we infer from the comment itself a polarization of the opposite point-of-view: namely that livestock grazing in all cases is assumed compatible with resource conservation. Our sentence, on the other hand, we contend is balanced, as it avoids taking one side of the issue versus the other. The sentence simply implies that land managers must demonstrate compatibility through their grazing management practices. It does not say that grazing is in all cases incompatible with resource conservation, as it also does not say that grazing is in all cases compatible. Other than some edits unrelated to the comment, we retained the sentence as is.***

Chapter 2 Approach

2. While the manuscript is a literature review, an attempt was made to focus on papers specific to the Sonoran Desert, and distinguish between peer reviewed or not and those based on empirical data or reviews. Unfortunately, this approach encounters significant limitations as actually applied in the manuscript. These distinctions are not always evident in the body of the text and experimental research papers are not necessarily given greater credence than gray literature or reviews in either the discussion sections or the conclusions. Additionally, when reviews are cited, there appears to be no attempt to check the source of those reviews to determine which category the cited papers fit. ***We do not agree that the distinctions between primary and grey literature need to be made explicit in the text. For the most part technical readers can ascertain by looking at the literature citation information (Chapter 12) whether a reference is primary or grey. This is the standard approach for a scientific article. When we reviewed an "unusual" source, such as an Environmental Impact Statement, we did describe the nature of the source in the text.***

3. In section 2.1.4, the question is posed "If a plant community shows enormous turnover in composition and structure in the absence of grazing how are we to know livestock grazing could impact such an ecosystem?" This is a highly pertinent question, especially at a landscape scale, and can be directly applied to the Sonoran Desert as reported in sections 4.1.1 and 4.2.2, yet no further discussion was found. ***We agree that the question is pertinent, but it was premature to include it in this section. We deleted the question, but we expanded the introductory sentence of the paragraph to broaden the scope of what we were trying to address. We address the underlying intent of the question in both Chapter 4 and section 10.3.***

Chapter 3 The Sonoran Desert National Monument in an Ecological Context

4. This is an excellent general description of the SDNM and its physiography, geology, soils, natural communities, and especially the variable and limited precipitation.

Chapter 4 Community Composition, Structure, and Function

5. The statement in section 4.1.5, page 4.6 "In comparison, consumption of ANPP by non-native domestic mammalian grazers ranged from 5 to 75%" is attributed to a review by Hadley and Szarek (1981). This statement raises red flags on two accounts. First, it indicates that there is no agreement or generalizable relationship on consumption of AAPP by non-native domestic mammalian grazers in the literature. Secondly, in my experience, I believe that the high levels of that range would be unobtainable on any realistic scale in the Sonoran Desert. Upon checking the reference, I found that this quote was taken directly from the Hadley and Szarek manuscript but that they cite Noy-Meir (1974). Noy-Meir (1974) offers no data or reference for this claim. ***We added appropriate caveats to Noy-Meir's (1974) reported values. Moreover, we eliminated the comparative nature of the original remark as a true comparison did not exist.***

6. The discussion of "Plant Responses to Herbivory" is too focused on the herbivore optimization debate. The TNC manuscript relies heavily on the Blesky arguments to refute claims of "overcompensation" in plant growth due to grazing (see Briske and Richards 1995, Gold and Caldwell 1989a,b,c**; complete citations provided in sections E.4.1 or E.4.3, as appropriate**) but only does a cursory job of identifying studies on individual species response to herbivory. For example, detailed studies on desert grasses such as cotton top, black grama, tobosa and galleta are available in the literature but not reviewed (for example see Cable 1979 [should be 1971], Anderson 1988**; complete citations provided in section E.4.3**). Additionally, the argument that the evolutionary history of the Sonoran Desert does not include large herbivores and therefore is somehow pre-programmed to unravel with livestock grazing is fundamentally flawed. These systems may have not had large herds of grazing animals since the Pleistocene, but they have supported pronghorn and desert bighorn in unknown numbers. Also and significantly, other herbivores have likely shaped evolutionary response of Sonoran Desert plants. Secondary compounds in plants such as creosote are known to deter herbivory. Finally, many Sonoran Desert plant species are tolerant of defoliation. They are not, however, tolerant of heavy and repeated defoliation. Even studies involving bush muhly have shown neutral or positive responses to grazing, depending upon site specific influences (see Hayes 2004**; complete citations provided in section E.4.1**). ***We agree that the discussion of Belsky's opinion needed better balance. The relevant material was extensively revised and expanded. We also tried to make the topic more relevant to livestock management issues. We added the Briske and Richards (1995) and Gold and Cadwell (1989a) citations and appropriate discussion. We do not agree that pronghorn or desert bighorn sheep would have the same ecological impact or selection pressure on Sonoran Desert plants and plant communities as would large, hooved mammalian herbivores. We do agree that other herbivores may have acted as selection agents that favored certain plants evolving avoidance or tolerance mechanisms to herbivory; however, those selection pressures may differ by herbivore. Upon review, the other references were found to be not relevant to the topic of overcompensation or in some cases not even responses to herbivory (for example, the Cable [1971] paper on Arizona cotton top). As we noted in our revised discussion, the fact that "many plants can at least partially compensate for the loss of tissue resulting from herbivory by regrowing tissue does not seem to be in dispute." So in consideration of the topic addressed by this section, we didn't see the value in incorporating these other references. We did incorporate the findings of Hayes (2004) into section 4.2.1.***

7. Section 4.2.1 indicates just how equivocal plant community composition response is on a landscape scale. Section 4.2.2 provides an even greater stretch in the discussion of the Bowers and Turner (2002) paper which "speculated" livestock grazing "may have indirectly benefited paloverde populations by reducing small mammal populations via competition for forage." See Martin and Turner (1977**; complete citations provided in section E.4.1**). ***Because the Bowers and Turner (2002) speculations about the effects of grazing were included among a suite of other hypotheses***

regarding foothill paloverde population dynamics, we decided it was not an appropriate study to include as part of our detailed analysis. We decided to use the study instead to illustrate the additional complexity involved when biotic interactions in addition to livestock grazing are considered. We also referenced the Martin and Turner (1977) paper in a similar context. Section 4.2 was extensively revised and reorganized.

8. While the state and transition model of vegetation change is described and evidently adopted later in the review, section 4.2.3 Community Function, begins with a clearly Clementsian description of vegetation dynamics. Such equilibrium-based paradigms of plant community dynamics are not consistent with modern ecology, especially for arid systems. The statement “Livestock affect community function by altering the ecological processes that are necessary for the formation and long-term maintenance of the plant communities” suggests that plant communities cannot exist if they are grazed. The paragraph goes on the describe all of the bad things livestock grazing does to biological and physical processes. While all of this may be true in some circumstances, there is no discussion of resistance or resilience of ecosystems to disturbances such as grazing or any possible amelioration such as controlling intensity, frequency or timing of grazing. In fact, the review seems to provide further unsubstantiated and/or contradictory statements in this section. For example, “Livestock grazing also increases dominance of unpalatable plants, a measure that indicates lower biodiversity.” There is no reference for this statement. Moreover, the same paragraph contains the statement “ Most of the literature did not show differences in perennial plant species richness in comparisons of grazed and ungrazed areas.” ***Section 4.2.3 was deleted and only its information related to piosphere studies was retained as part of a reorganized section 4.2. The Conclusions section, from which the last quote was taken, also was extensively revised. We acknowledge that the quoted sentences were not appropriately crafted and deleted them. We suggest that the revised Conclusions section accurately reflects the literature reviewed.***

Chapter 5 Saguaro Recruitment and Survival

9. Research and anecdotal evidence cited in this chapter is clearly inconclusive. The conclusion to the chapter should be the last sentence in section 5.2 “The regional trends in saguaro demographics suggest that factors other than the presence or absence of livestock grazing account for current saguaro declines, but the causes are yet unknown.” However the Saguaro National Park East example is highlighted in the conclusion even though it is “unique in the literature” and no indication of the kind or amount of grazing involved is given to help clarify the account. ***We deleted the last paragraph of the Conclusions section and revised the remainder to better reflect the literature review. The changes are more a matter of proper emphasis.***

Chapter 6 Other Plant Species

10. No studies are available to document livestock grazing impacts on rare species. ***In regard to the specific rare plants we discuss, we agree.***

Chapter 7 Soils and Biological Soil Crusts

11. This chapter is almost entirely speculative, based on generalizations and extrapolation from research in other ecosystems, especially cold deserts which have biologically and physically different biological crusts. Based on the information in Chapter 2 it appears that there was only 1 peer reviewed article reviewed, which was evidently a review article. Additionally, the relevance of the soil compaction discussion is unclear and, as stated, none of the soil compaction studies took place in the Sonoran Desert. ***The entire chapter has been extensively revised to rely more on Sonoran Desert-specific empirical studies rather than just review articles and extrapolations from cool***

desert ecosystems. The number of peer-reviewed articles cited changed as a result, though many of these were identified through other reviewer comments or by additional literature searches focused on obtaining articles specific to the ecological characteristics of Sonoran Desert biological soil crusts. The soil compaction section was revised, so hopefully its relevance is clearer.

12. The first sentence in Section 7.3.3 states "Because biological crusts are the primary source of nitrogen in desert soils, livestock grazing or other disturbance activities affects nitrogen fixation rates, soil nitrogen content, and nitrogen availability to vascular plants." This statement just does not necessarily follow logic because the influence of degree and scale of disturbance and recovery rates are not known. ***This sentence and subsequent text were revised to reflect a less definitive position consistent with current knowledge. We agree that the degree of impact is in large measure a scale-dependent phenomenon.***

13. In Section 7.3.5 it is not clear to me how the anecdotal descriptions of past grazing abuses relate to current grazing management in the Sonoran Desert. ***The descriptions provide baseline information and potential benchmarks for grazing management practices to avoid in the future. In addition, we do not rule out the possibility that overgrazing may be occurring currently at some locales within the Sonoran Desert or that the lessons learned from the cited studies may be especially applicable during periods of extended drought.***

Chapter 8 Wildlife

14. The statement "Therefore livestock compete with native wildlife by removing biomass at times when native wildlife are most reliant on it for forage, nesting materials, shade, and so on" imply that for the purposes of the TNC review, any level of livestock grazing is viewed as competition with wildlife for the various resources provided by forage plants. This is a naïve and incorrect view of competition. Even if livestock and whatever wildlife species is meant by "native wildlife" consume exactly the same forage plants, competition is not necessarily the ecological interaction. The first statement in the conclusion section "Whether livestock grazing has a positive or negative effect on wildlife depends on the species under consideration—including their preferred forage and foraging habitat, the season of grazing and its intensity, and other site-specific factors" better depicts the potential interactions among livestock and various wildlife species. ***Added the word "potentially" between "livestock" and "compete" in the referenced statement to better reflect the intended meaning of the statement.***

15. While the TNC review was "unable to locate any papers that directly studied the effect of livestock grazing on the endangered cactus ferruginous pygmy-owl" in his MS thesis, Flesch (2003**; complete citations provided in section E.4.1**) found a well distributed population of the owl throughout Sonora and no correlation between owl densities and areas where livestock utilization was considered slight, moderate or extreme. ***We incorporated the findings of Flesch (2003) and note that he drew mixed conclusions about the impacts of livestock grazing on pygmy-owl habitat suitability. The impacts may be habitat-specific.***

16. The discussion of the Bostic (1990) paper on page 8.6, which was determined to have "a strong pro-grazing bias" deserves comment. The authors cite "many unsubstantiated claims" and the "greatest mistake is in attributing correlational patterns as causality." I agree with this assessment. The TNC review authors should apply that same level of critique throughout their manuscript. ***We appreciate the comment, but contend we have been consistent in objectively and critically reviewing each piece of literature that purports to describe the impacts of livestock grazing by not only pointing out its findings, but also by describing its caveats and scope of applicability. We also modified our language relative to the critique of Bostic (1990) to reflect a more neutral tone.***

17. Why aren't the Warren and Anderson (1987 and 1992) findings discussed in the plant community changes section? ***Warren and Anderson (1992) is discussed in Chapter 4. Because Warren and Anderson (1987) applies to a spring system, we decided not to review it as part of this report.***

Chapter 9 Cultural Sites

18. No comments.

Chapter 10 Livestock Grazing Strategies

19. The discussion of grazing systems is simplistic, incomplete and has limited direct application to the Sonoran Desert. ***We revised our overview of grazing systems (or other grazing management approaches such as continuous grazing) to make it more relevant to the discussion of appropriate grazing strategies for the Sonoran Desert.***

20. The discussion of continuous grazing is misleading both in application and theory. Under current recommended stocking levels (either BLM or NRCS) much of the range is not grazed under continuous grazing. Livestock pick favored grazing and resting areas however and these locations are repeatedly grazed, resulting in very uneven utilization patterns with varying degrees of grazing influence evident across the landscape. ***We agree and have revised our description accordingly. Please note that at least one of the references we used (Howery and others 2000) can be interpreted to imply that continuous grazing leaves no portion of the range ungrazed.***

21. Section 10.1.1. The idea that stored carbohydrates play a major role in the influence of grazing on grasses has been in doubt for over 25 years (see Caldwell 1984, Briske and Richards 1995**; complete citations provided in section E.4.1**). ***We decided the point about carbohydrate storage was not germane to the discussion of continuous grazing and deleted it. We address the carbohydrate storage question in section 4.2.2.***

22. Section 10.1.2. The definition of season-long grazing is not correct in the claim that "season long grazing is when an area is grazed for an entire growing season, but not during the dormant period." Seasonal use can be restricted to winter grazing, or any other season. ***The various references we checked differ in their definition of season-long grazing. We pointed this out in our description of season-long grazing.***

23. Section 10.1.4. Rest rotation grazing schemes do not promote "severe defoliation" as implied. The severity of defoliation at the individual plant level is a function of the size of the plant and the size of the bite at a particular defoliation event. "Severe defoliation" at a pasture scale is a function of the available forage, number of animals and the length of the grazing period. These are management decisions linked to selection of grazing schemes. ***We removed the implication about "severe defoliation" and changed the phrase to read: "…benefits of rest (even for multiple years) can be easily offset if previously rested pastures are overgrazed…."***

24. Section 10.1.5. The concept of short duration grazing is not necessarily tied to radial pasture design and, depending on how it is calculated, high intensity grazing is not necessarily the same as high stocking rates as implied. The concepts of stocking rate, stocking density and grazing have technical definitions to help describe these relationships. ***We agree and made the necessary text changes to reflect a correct description of the system and the correct use of terminology.***

25. Section 10.2.1. In my opinion, an EIS is an inappropriate reference for a technical literature review of this nature. A thorough review of grazing studies conducted on the Santa Rita and Jornada Experimental Ranges, as well as research stations in Mexico, should be included. Many of the plant species which occur on these ranges also occur on the SDNM. It appears that the authors were quite selective throughout the review in deciding whether or not to include research done outside the Sonoran Desert. ***In this section we were evaluating the available literature that attempted to assess grazing management strategies as applied in the Sonoran Desert. Despite the co-occurrence of some forage species, we do not agree that studies conducted at the Santa Rita and Jornada Experimental Stations are suitable for evaluating the specific performance of a grazing strategy within the Sonoran Desert. Our review of the ecosystem dynamics literature drew us to the conclusion that the Sonoran Desert ecosystem has fundamental characteristics that distinguish it from semidesert grasslands when evaluating livestock grazing impacts and management strategies. We evaluated the Kofa NWR EIS and also added a review of Hayes (2004) as frankly these were the only two documents that specifically evaluated grazing management approaches for the Sonoran Desert. This is more a reflection of the paucity of such studies rather than some bias in our selection criteria. Throughout the document we tried to make our selection criteria transparent for those studies we evaluated from outside the Sonoran Desert.***

26. The statement "In most arid lands, including the Sonoran Desert, livestock are incompatible with ecosystems in which biological soil crusts predominate in the late successional stages because these systems did not evolve with abundant large ungulates that continually break up biological crusts" is not supported by the research reviewed and expresses the distinct bias of the authors, in my opinion. The evolution argument, especially tied to the equilibrium-based paradigm of plant communities, is purely academic with little application to realistic resource management objectives. ***Although we removed this sentence from the final report because we concluded the entire paragraph was out of place, we disagree that the evolutionary argument in general is purely academic. Chapter 7, where this issue relative to biological soil crusts is more appropriately addressed, has been revised to address this topic in a more balanced and appropriate way. In our opinion, it is incorrect to associate any evolutionary argument with solely an equilibrium view of vegetation dynamics.***

27. Section 10.4. The statement in the conclusion section "Furthermore, regardless of what grazing system is in use, no system can counteract the negative impacts of long-term overstocking" is confusing to me. Is long-term overstocking one of the management objectives the BLM is considering? Or, does this imply that past overgrazing necessitates complete removal of livestock from the SDNM and no other options exist to offset such "negative impacts?" ***As part of the revision to the conclusion section, this sentence was removed. We agree that the sentence was somewhat confusing. The point was that if overstocking occurred in the past, recovery will be slow (or perhaps not possible if the ecosystem has transitioned to a new state) and may be hampered by continued grazing under any management approach.***

Chapter 11 General Conclusions and Recommendations

28. The conclusions seem to be more of a summary of some of the major findings, than actual conclusions from the research review. I believe this is because the research results presented regarding managed livestock grazing in the Sonoran Desert are not conclusive. On the other hand, I strongly agree with the statements listed as "specific characteristics of Sonoran Desert ecosystem dynamics that place limits on the potential for livestock grazing in the Sonoran Desert, especially in regard to the SDNM and its objects." Additionally, I support section 11.2 "Immediate Considerations…" and would hope that BLM managers routinely make these considerations. ***Per BLM's request we have removed explicit recommendations from the final report. Otherwise, Chapter 11 has been extensively revised and now reflects three sets of general conclusions:***

ecological context of livestock grazing in the Sonoran Desert, grazing impact literature, and grazing management strategy literature.

29. Section 11.3. The BLM is not a research agency and cannot base day to day management decisions, or even management planning, on a research wish list. A more relevant section on "Monitoring Recommendations" should be included. ***See the response to comment No. 28 above. Specific monitoring recommendations are beyond the scope of this report; however, we suggest we have included information in this report that should be considered when developing an appropriate monitoring strategy.***

30. The general tone of conclusions in Chapter 11 implies that the current impacts of livestock grazing are similar and can be compared to the impacts of historic grazing. Unfortunately, without specific knowledge of intensity, frequency, timing, class of livestock, season of use, ecological sites, precipitation patterns and other variables not available from the majority of the literature reviewed it is difficult to make meaningful interpretations. The impacts of historical overgrazing are not in doubt. What is questionable and not elucidated by the review is whether or not current livestock grazing is compatible with SDNM object protection. Only by site-specific assessment and monitoring will this be determined. ***We agree a number of confounding factors can influence whether present-day grazing has adverse impacts on natural and cultural resources. We have tried to point these confounding factors out throughout the report. We suggest the final report provides BLM the information needed to make a more informed decision relative to the compatibility question. As we concluded in Chapter 10, grazing impacts and grazing management strategies must consider multiple spatial (and temporal) scales.***

31. Suggested Literature. This is a brief list but along with the 400 publications that report research done on the Santa Rita Experimental Range should be a start (**list includes the complete citations to the literature referenced in the individual comments; these citations are included in section E.4**). ***We evaluated all of the specific literature suggested for its applicability to this review. We do not agree, however, that by default all studies conducted on the Santa Rita Experimental Range are of relevance to livestock grazing management in the Sonoran Desert. The Santa Rita Experimental Range is located in semidesert grassland and as we have made abundantly clear in this report fundamental ecological differences exist between this ecosystem type and the Sonoran Desert that preclude the assumption grazing strategies and impacts evaluated in semidesert grasslands are immediately applicable to the Sonoran Desert. That case has yet to be made.***

E.3.15 Dr. Raymond Turner, U.S. Geological Survey and Desert Laboratory (Retired)

General Comments

This livestock grazing literature review is quite remarkable because of its thoroughness. It is objective and well written. The few points I would add or change are noted below.

Specific Comments

1. Page 1.1. "… is managed by the BLM out of their Phoenix Field Office." Change "their" to "its." ***Corrected.***

2. Page 2.1. "… of the how the remainder …" ???? ***Corrected.***

3. Page 4.7. "Cattle avoid eating shrubs that are high in volatile oils because they lack mechanisms for dealing with the toxicity." Rephrase to avoid the teleological implications. As written, the cattle are

seen to avoid eating the shrubs because they know they don't have the mechanisms to deal with the toxicity. ***Recast the sentence to correct.***

4. Pages 4.13, 4.17, and 4.18. No reference to Burgess, Bowers and Turner (1991; **complete citation provided in section E.4.1**). Findings in this paper would fit into the discussion on these pages. ***Incorporated information from this citation.***

5. Page 4.15. Include reference to Glinski, R. L. 1977 (**complete citation provided in section E.4.1)**. Also, page 262 in Turner, Webb, Bowers, and Hastings 2003 (**complete citation provided in section E.4.1**). ***Our focus in this report is not on intermittent or perennial stream-associated communities. We have limited our discussion to only xeroriparian (dry wash or ephemeral stream) habitats. As a result, we did not incorporate either reference in regard to this section.***

6. Page 4.15. Change "foothills paloverde" to foothill paloverde." ***Corrected spelling.***

7. Pages 5.3 and 5.4. Turner (1966) should be Turner and others (1966). ***Corrected.***

8. Page 6.1. "Acuña cactus only been found . . ." Something missing? ***Corrected.***

9. Page 7.6. Should cite Robert Webb's work on ORV effects in the Mohave Desert. See list at end of [these comments]. **Recommended literature is identified in section E.4.2.** ***We did not cite or discuss any of this literature in the text as it is focused on Mojave Desert and OHV-related research. We will, however, try to make as much of the recommended literature available to the Bureau of Land Management for their use.***

10. Page 8.1. "dessication" change to "desiccation." ***Corrected spelling.***

11. Page 12.2. Humphrey, H. H. 1957 should read Humphrey, R. H. 1957. ***Actually, it should be "R.R." Corrected.***

E.3.16 Dr. Robert Unnasch, Senior Ecologist, The Nature Conservancy

General Comment

This document provides a reasonably complete review of existing literature on the impacts of livestock (primarily cattle) on six key components of the recently designated Sonoran Desert National Monument. These components are: (1) native plant communities, (2) saguaro populations, (3) rare plants, (4) wildlife, (5) soils and soil crusts, and (6) cultural sites. Unfortunately, as the authors make clear, the existing literature is spotty at best, and provides a shaky foundation for making management decisions. For example, the authors found no literature addressing the impacts of different grazing systems on Sonoran communities. Similarly, they only found a single study examining the impacts of domestic livestock on wildlife. This paucity of information has led the authors to be justifiably cautious in their recommendations to the BLM. While this caution is appropriate when considering specific actions, I believe there can be more stridency about what is necessary to manage in the face of such uncertainty. Below, I address some of these issues.

Specific Comments

1. The Sonoran Desert National Monument Proclamation charges the BLM to manage the Monument's lands in a manner that "protects" the objects identified as being important. The Agency must rise to the challenge of defining "protection" for each of the objects within the monument, and I strongly

suggest they set measurable goals for each by which progress, and success, can be measured. A call to set measurable goals is often met with resistance from managers who believe our ignorance of pre-Columbian conditions precludes our ability to envision final success. Often it is simpler to define a trend toward improvement of key ecological attributes – increased recruitment of annuals, decreased soil crust disturbance – associated with each object. Measuring changes in these key attributes will help guide an adaptive management program for the Monument. ***Per BLM's request we removed explicit recommendations from the final report.***

2. This literature review is very clear that the most important ecological process driving this desert ecosystem is precipitation. Within the Sonoran desert, the patterns of precipitation are highly variable both over time, and over space. Most grazing management plans ignore this variation, and 'manage to the mean'. The authors point out that in the Sonoran Desert this virtually assures overgrazing because it does not build in the flexibility to expand or contract stocking rates to meet current forage production. From an ecosystem management perspective, this flexibility must occur at the same geographic scale as the patterns of rainfall, which is certainly larger than the grazing allotment, and likely at the scale of the monument. While necessary, management at this scale may require the BLM to redefine, or eliminate its livestock management unit boundaries and change its management prescriptions. Current remote sensing technologies may prove to be very useful to manage livestock at this scale. NDVI data, for example, might be used to differentiate areas that have received precipitation from those that have not. This information could then be used to determine stocking rates. ***In the final report we attempted to deal with the flexibility issue more directly by drawing specific conclusions relative to appropriate grazing management strategies for the Sonoran Desert (see Chapters 10 and 11).***

3. The monument finds itself in a unique and exciting situation from a scientific perspective. It has the Sand Tank Mountains which have had no domestic grazing for over 60 years, the area south of Interstate 8 that is slated to have livestock removed, and the area north of the Interstate in which livestock management is to continue. Well designed monitoring, at the appropriate scales, across all three areas would provide more information about the impacts of domestic livestock on Sonoran ecosystems than currently exists in the scientific literature. I would strongly recommend that the Monument take advantage of this opportunity. ***Although we agree obvious opportunities exist regarding monitoring, per BLM's request we removed explicit recommendations from the final report.***

4. This current literature review provides Monument managers a remarkably complete assessment of our notably incomplete understanding of the impacts of domestic livestock on Sonoran systems. This document should be a touchstone for all Agency planners and managers. I believe that the major take-home lessons from this review are (1) that these systems are not resilient and they recover slowly, and episodically, from disturbance, (2) caution and conservative management will be required to improve the condition of the objects within the Monument, and (3) our lack of understanding of these systems calls for a well designed, consistently implemented monitoring program across the entire Monument. ***In the final report our conclusions are broadly applicable to the Arizona Upland and Lower Colorado River Valley subdivisions of the Sonoran Desert and not to just the Sonoran Desert National Monument.***

E.4 ADDITIONAL LITERATURE RECOMMENDED BY REVIEWERS AND ITS DISPOSITION

Reviewers recommended literature of four types. First, recommendations included literature that may address additional studies on the impacts of livestock grazing that we did not consider in the draft report (section E.4.1). We evaluated each of these recommended pieces of literature for its relevance to the scope of our review, in which our primary focus was on literature that was directly applicable to grazing in the Sonoran Desert or on literature that at least had significant applicability to the Sonoran Desert when the reported study was conducted outside the Sonoran Desert. If the recommended literature met either of the preceding criteria, we incorporated its findings into the final report. At a minimum, these citations were entered into the Access database and hard copies provided to the Bureau of Land Management (BLM).

Second, some reviewers recommended literature that addressed non-grazing impacts to natural resources in the Sonoran Desert. These generally were not incorporated into the final report, but were entered into the Access database and copies provided to BLM.

Third, some of the recommended literature was meant to bolster our analysis of Sonoran Desert ecosystem dynamics but did not address either grazing or non-grazing impacts. We may have incorporated this type of literature into the final report, when appropriate, but we did not enter this literature into the Access database nor make copies for BLM.

Fourth, occasionally reviewers recommended literature that was meant to clarify certain implications in the test, a figure, or a table that was tangential to the purposes of the review. For example, one reviewer suggested that Figure 2.1 might give the wrong impression of the extent of shortgrass steppe grassland, the historic distribution of bison, and by implication the geographic extent to which an area had an evolutionary history of grazing by native large herbivores. We addressed these types of comments indirectly: that is, we did not try to clarify the extent of shortgrass steppe grassland by citing additional references, but instead clarified the purpose of the figure and ecoregional boundary determinations in general.

E.4.1 Potential Additional Livestock Grazing Impact Literature Relevant to the Sonoran Desert

An “*” before the citation indicates a paper that we incorporated and cited in the final report.

Angell, D.L., and M.P. McClaran. 2001. Long-term influences of livestock management and a non-native grass on grass dynamics in the desert grassland. Journal of Arid Environments 49:507–520. ***Not really germane to this review. Did not incorporate into the final report.***

*Averill-Murray, A., and R.C. Averill-Murray. 2002. Distribution and density of desert tortoises at Ironwood Forest National Monument, with notes on other vertebrates. Nongame and Endangered Wildlife Program Technical Report 193. Arizona Game and Fish Department, Phoenix. ***Addressed biological characteristics rather than grazing impacts per se. Incorporated and cited in the final report.***

*Averill-Murray, R.C. 2002. Reproduction of *Gopherus agassizii* in the Sonoran Desert, Arizona. Chelonian Conservation and Biology 4:295–301. ***Addressed biological characteristics rather than grazing impacts per se. Incorporated and cited in the final report.***

*Balling, R.C., Jr., M.L. Hildebrandt, J.M. Klopatek, C.K. Moritz, and C.J. Watts. 1997. Impacts of land degradation on the temperature records of Northwest Sonoran, Mexico. 10th Conference on Applied Climatology, 20–23 October 1997. American Meteorological Society, Boston, Massachusetts. ***This paper was subsequently revised and published as: Balling, R.C., Jr., J.M. Klopatek, M.L. Hildebrandt, C.K. Moritz, and C.J. Watts. 1998. Impacts of land degradation on historical temperature records from the Sonoran Desert. Climatic Change 40:669–681. We incorporated and cited this latter reference in the final report.***

*Barrett, S.L., and T.B. Johnson. 1990. Status Summary for the Desert Tortoise in the Sonoran Desert. Report to the U.S. Fish and Wildlife Service, Albuquerque. 115 p. ***Incorporated and cited in the final report.***

Brady, W.W., M.R. Stromberg, E.F. Aldon, C.D. Bonham, and S.H. Henry. 1989. Response of a semidesert grassland to 16 years of rest from grazing. Journal of Range Management 42:284–288. ***Not really germane to this review. Did not incorporate into the final report.***

*Briske, D.D., and J.H. Richards. 1995. Plant responses to defoliation: a physiological, morphological and demographic evaluation. Pages 635–710 in D.J. Bedunah and R.E. Sosebee (eds.), Wildland Plants: Physiological Ecology and Developmental Morphology. Society for Range Management, Denver, Colorado. 710 p. ***Review article that identifies the general effects of herbivory and summarizes the literature on compensatory growth. Incorporated and cited in the final report.***

Bristow, K.D., and R.A. Ockenfels. 2000. Effects of human activity and habitat conditions on Mearns quail populations. Technical Guidance Bulletin No. 4. Arizona Game and Fish Department, Research Branch, Phoenix. ***Subspecies does not occur within the Sonoran Desert as we identified its geographic extent in this document. As a result, we did not incorporate the citation.***

*Brooks, M.L., and D. Pyke. 2001. Invasive plants and fire in the deserts of North America. Pages 1–14 in K. Galley and T. Wilson (eds.), Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: The First National Congress on Fire, Ecology, Prevention and Management. Miscellaneous Publications No. 11, Tall Timbers Research Station, Tallahassee, Florida. ***Citation encapsulates some information on the interaction of livestock grazing, invasive non-native plants, and fire. Incorporated and cited in the final report.***

Brown, R.L. 1982. Effects of livestock grazing on Mearns quail in southeastern Arizona. Journal of Range Management 35:727–732. ***Subspecies does not occur within the Sonoran Desert as we identified its geographic extent in this document. As a result, we did not incorporate the citation.***

*Burgess, T.L., J.E. Bowers, and R.M. Turner. 1991. Exotic plants at the Desert Laboratory, Tucson, Arizona. Madroño 38:96–114. ***Hypothesizes a relationship between historic livestock grazing and non-native plant invasion at the Desert laboratory. Incorporated and cited in the final report.***

*Caldwell, M.M. 1984. Plant requirements for prudent grazing. Pages 117–152 in Developing Strategies for Rangeland Management: A report Prepared by the Committee on Developing Strategies for Rangeland Management. National Research Council/National Academy of Sciences. Westview Press, Boulder, Colorado. ***Incorporated and cited in the final report.***

Clary, W.P. 1999. Stream channel and vegetation responses to late spring cattle grazing. Journal of Range Management 52:218–227. ***Citation applies to riparian systems that we specifically excluded from our review. Did not incorporate into the final report.***

Eckert, R.E., F.F. Peterson, M.S. Meurrise, and J.L. Stevens. 1986. Effects of soil surface morphology on emergence and survival of seedlings in big sagebrush communities. Journal of Range Management 39:414–420. ***Citation applies to the Great Basin Desert. As a result, we did not incorporate the citation.***

*Flesch, A. 2003. Distribution, Abundance, Habitat of Cactus Ferruginous Pygmy-Owls in Sonora, Mexico. Unpublished master's thesis, School of Natural Resources, University of Arizona, Tucson.

Discusses potential impacts of livestock grazing on pygmy-owl habitat suitability. Incorporated and cited in the final report.

Fuhlendorf, S.D., and D.M. Engle. 2001. Restoring heterogeneity on rangelands: ecosystem management based on evolutionary grazing patterns. Bioscience 51:625–632. ***Citation was suggested as a commentary on short-duration grazing; however, we did not address the aspect considered (landscape heterogeneity) as part of our review. Did not incorporate into the final report.***

Glinski, R.L. 1977. Regeneration and distribution of sycamore and cottonwood trees along Sonoita Creek, Arizona. Pages 116–123 in R.R. Johnson and D.A. Jones (technical coordinators), Importance, Preservation and Management of Riparian Habitat: A Symposium. July 9, 1977, Tucson, Arizona. General Technical Report RM-43. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. ***Citation applies to species associated with riparian systems that we specifically excluded from our review. Did not incorporate into the final report.***

*Hayes, J.U., Jr. 2004. Perennial Grass Abundance and Livestock Management in the Arid Rangelands of the Sif-Oidak District, T.O. Nation. Unpublished master's thesis, School of Natural Resources, University of Arizona, Tucson. ***Incorporated and cited in the final report.***

Herbel, C.H. and R.P. Gibbens. 1996. Post-drought vegetation dynamics on arid rangelands of New Mexico. Agricultural Experiment Station, Bulletin. 776. New Mexico State University, College of Agriculture and Range Sciences, Department of Animal and Range Sciences, Las Cruces. ***Citation applies to plant communities outside of the Sonoran Desert. Did not incorporate into the final report.***

*Krausman, P.R. (ed.). 2000. Special Issue: Bighorn Sheep Restoration. Restoration Ecology 8(4S):1–94. ***Incorporated and cited an included paper by Krausman in the final report.***

*Krausman, P.R., B.D. Jansen, J.R. Heffelfinger, C.R. Anderson, J.C. deVos, Jr., and T.H. Noon, T.H. In Press. Desert bighorn sheep, disease, and urbanization. International Game Ranching Congress 6. ***Incorporated and cited in the final report.***

*Krausman, P.R., A.J. Kuenzi, R.C. Etchberger, K.R. Rautenstrauch, L.L. Ordway, and J.J. Hervert. 1997. Diets of desert mule deer. Journal of Range Management 50:513–522. ***Addressed biological characteristics rather than grazing impacts per se. Incorporated and cited in the final report.***

Krausman, P.R., and M.L. Morrison. 2003. Wildlife ecology and management, Santa Rita Experimental Range (1903 to 2002). Pages 59–67 in M.P. McClaran, P.F. Ffolliott, and C.B. Edminster (tech. coords.), Santa Rita Experimental Range: 100 Years (1903 to 2003) of Accomplishments and Contributions. Conference Proceedings October 30–November 1, 2003, Tucson, Arizona. Proceedings RMRS-P-30. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, Utah. ***Reviewer indicated other material in this report also may be of interest. We further evaluated only specifically recommended literature, but we also found that several of the citations included in this reference we had already included as part of our review. We did not incorporate or cite Morrison and Krausman (2003) in the final report.***

*Krausman, P.R., K.R. Rautenstrauch, and B.D. Leopold. 1985. Xeroriparian systems used by desert mule deer in Texas and Arizona. Pages 144–149 in R.R. Johnson, C.D. Ziebell, D.R. Patton, P.F. Ffolliott, and R. H. Hamre (tech. coords.), Riparian Ecosystems and their Management: Reconciling Conflicting Uses. First North American Riparian Conference, April 16–18, 1985, Tucson, Arizona. General Technical Report RM-120. U.S. Department of Agriculture, Forest Service, Rocky Mountain

Forest and Range Experiment Station, Fort Collins, Colorado. ***Addressed biological characteristics rather than grazing impacts per se. Incorporated and cited in the final report.***

*Krausman, P.R., A.V. Sandoval, and R.C. Etchberger. 1999. Natural history of desert bighorn sheep. Pages 139–191 in R. Valdez and P.R. Krausman (eds.), Mountain Sheep of North America. The University of Arizona Press, Tucson. ***Addressed biological characteristics rather than grazing impacts per se. Incorporated and cited in the final report.***

*Mack, R.N. 1981. Invasion of *Bromus tectorum* into western North America: an ecological chronicle. Agro-Ecosystems 7: 145–165. ***Incorporated and cited in the final report.***

*Martin, S.C., and R.M. Turner. 1977. Vegetation change in the Sonoran Desert region, Arizona and Sonora. Journal Arizona Academy of Sciences 12:59–69. ***Already was cited in the report.***

*McAuliffe, J.R. 1984. Prey refugia and the distributions of two Sonoran Desert cacti. Oecologia 65:82–85. ***Does not address livestock grazing impacts, but still incorporated and cited in the final report.***

McClaran, M.P., P.F. Ffolliott, and C.B. Edminster. (tech. coords.). 2003. Santa Rita Experimental Range: 100 Years (1903 to 2003) of Accomplishments and Contributions. Conference Proceedings October 30–November 1, 2003, Tucson, Arizona. Proceedings RMRS-P-30. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, Utah. ***Studies generally not applicable to the Sonoran Desert, as the Santa Rita Experimental Range is a semidesert grassland site. Did not incorporate into the final report.***

Navarro, J., D. Galt, J. Holechek, J. McCormick, and F. Molinar. 2002. Long term impacts of livestock grazing on Chihuahuan Desert rangelands. Journal of Range Management 55:400–405. ***Citation applies to plant communities outside of the Sonoran Desert. Did not incorporate into the final report.***

*Nelson, T., J.L. Holechek, R. Valdez, and M. Cardenas. 1997. Wildlife numbers on late and mid seral Chihuahuan Desert rangelands. Journal of Range Management 50:593–599. ***Incorporated and cited in the final report.***

Paulsen, H.A., Jr., and F.N. Ares. 1962. Grazing values and management of black grama and tobosa grasslands and associated shrub ranges of the Southwest. Technical Bulletin No. 1270. U.S. Department of Agriculture, Forest Service, Washington, D.C. ***Citation applies to environmental conditions or plant communities that occur outside of the Sonoran Desert. Did not incorporate into the final report.***

*Price, M.V. and J.H. Brown. 1983. Patterns of morphology and resource use in North American desert rodent communities. Great Basin Naturalist Memoirs 7: 117–134. ***Addressed ecological characteristics rather than grazing impacts per se. Incorporated and cited in the final report.***

*Rebollo, S., D.G. Milchunas, I. Noy-Meir, and P.L. Chapman. 2002. The role of a spiny plant refuge in structuring grazed shortgrass steppe plant communities. Oikos 98:53–64. ***Incorporated and cited in the final report.***

*Reichman, O.J. and M.V. Price. 1993. Ecological aspects of heteromyid foraging. Pages 539–568 in H.H. Genoways and J.H. Brown (eds.), Biology of Heteromyid Rodents. Special Publication No. 10. The American Society of Mammalogists. ***Addressed ecological characteristics rather than grazing impacts per se. Incorporated and cited in the final report.***

*Senft, R.L. 1983. The Redistribution of Nitrogen by Cattle. Unpublished doctoral dissertation. Colorado State University, Fort Collins. ***Incorporated and cited in the final report.***

Schmutz, E.M., and D.A. Smith. 1976. Successional classification of plants on a desert grassland site in Arizona. Journal of Range Management 29:476–479. ***Not really germane to this review. Did not incorporate into the final report.***

Shaw, N.L. and W.P. Clary. 1996. Willow establishment in relation to cattle grazing on an eastern Oregon stream. Pages 148–153 in D.W. Shaw and D.M. Finch (tech. coords.), Desired Future Conditions for Southwestern Riparian Ecosystems: Bringing Interests and Concerns Together. September 18-22, 1995, Albuquerque, New Mexico. General Technical Report RM-GTR-272. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. ***Citation applies to species associated with riparian systems that we specifically excluded from our review. Did not incorporate into the final report.***

*Smith, G., J.L. Holechek, and M. Cardenas. 1996. Wildlife numbers on excellent and good condition Chihuahuan Desert rangelands: an observation. Journal of Range Management 49:489–493. ***Incorporated and cited in the final report.***

Stebbins, R.C. 2003. Western Reptiles and Amphibians. 3rd edition. Houghton Mifflin, Boston. ***Did not incorporate into the final report.***

Tisdale, E.W. and M. Hironaka. 1981. The sagebrush-grass region: a review of the ecological literature. Bulletin 33. Idaho Forestry, Range, and Wildlife Experiment Station, Moscow. 31 p. ***Citation applies to the Great Basin Desert. As a result, we did not incorporate the citation.***

Walker, B., and N. Abel. 2002. Chapter 11. Resilient Rangelands—Adaptation in Complex Systems. Pages 293–313 in L.H. Gunderson and C.S. Holling (eds.), Panarchy: Understanding Transformations in Human and Natural Systems. Island Press, Washington, DC. ***Did not incorporate into the final report.***

Webb, R.H. 1980. An Annotated Bibliography on the Effects of Livestock Grazing on Soils, Vegetation, and Wildlife. Report to the Bureau of Land Management, Desert Plan Staff, Riverside, California. 63 p. ***Did not incorporate into the final report.***

Webb, R.H., and S.S. Stielstra. 1979. Sheep grazing effects on Mojave Desert vegetation and soils Environmental Management 3:517–529. ***Did not incorporate into the final report.***

*Witham, J.H. 1983. Desert bighorn sheep in southwestern Arizona. Unpublished doctoral dissertation, Colorado State University, Fort Collins. ***Addressed biological characteristics rather than grazing impacts per se. Incorporated and cited in the final report.***

E.4.2 Non-Grazing Impact Literature

None of the following citations were incorporated and cited in the final report, but they are included in the literature database that we constructed as part of this project.

Bowers, J.E., R.H. Webb and R.J. Rondeau. 1995. Longevity, recruitment, and mortality of desert plants in Grand Canyon, Arizona, U.S.A. Journal of Vegetation Science 6:551–564.

Griffiths, P.G., R.H. Webb, N. Lancaster, C.A. Kaehler, and S.C. Lundstrom. 2002. Long-Term Sand Supply to Coachella Valley Fringe-Toed Lizard (*Uma inornata*) Habitat in the Northern Coachella

Valley, California. Water-Resources Investigations Report 02-4013. U.S. Department of the Interior, U.S. Geological Survey, Tucson, Arizona. 49 p.

Iverson, R.M., B.S. Hinckley, R.H. Webb, and B. Hallet. 1981. Physical effects of vehicular disturbances on arid landscapes. Science 212:915–917.

Steiger, J.W., and R.H. Webb. 2000. Recovery of Perennial Vegetation in Military Target Sites in the Eastern Mojave Desert, Arizona. Open-File Report OF 00-355. U.S. Department of the Interior, U.S. Geological Survey. 28 p.

Webb, R.H. 1982. Off-road motorcycle effects on a desert soil. Environmental Conservation 9(3):197–208.

Webb, R.H. 1983. Compaction of desert soils by off-road vehicles. Pages 51–79 in R.H. Webb and H.G. Wilshire (eds.), Environmental Effects of Off-Road Vehicles. Springer-Verlag Publishers, New York.

Webb, R.H. 2002. Recovery of severely compacted soils in the Mojave Desert, California, USA. Arid Lands Research and Management 16:291–305.

Webb, R.H., T.C. Esque, P.A. Medica, L.A. DeFalco, and M.A. Murov. 2001. Monitoring of ecosystem dynamics in the Mojave Desert: the Beatley permanent plots. U.S. Geological Survey Fact Sheet FS-040-01. 4 p.

Webb, R.H., M.B. Murov, T.C. Esque, D.E. Boyer, L.A. DeFalco, D.F. Haines, D. Oldershaw, S.J. Scoles, K.A. Thomas, J.B. Blainey, and P.A. Medica. 2003. Perennial Vegetation Data from Permanent Plots on the Nevada Test Site, Nye County, Nevada. Open-File Report 03-336. U.S. Deaprtement fo the Interior, U.S. Geological Survey. 251 p.

Webb, R.H., and E.B. Newman. 1982. Recovery of soils and vegetation in Mojave Desert ghost towns. Environmental Conservation 9:245–248.

Webb, R.H., H.C. Ragland, W.H. Godwin, and D. Jenkins. 1978. Environmental effects of soil property changes with off-road vehicle use. Environmental Management 2:219–233.

Webb, R.H., J.W. Steiger, and E.B. Newman. 1988. The Response of Vegetation to Disturbance in Death Valley National Monument, California. U.S. Geological Survey Bulletin 1793. 103 p.

Webb, R.H., J.W. Steiger, and R.M. Turner. 1987. Dynamics of Mojave Desert shrub vegetation in the Panamint Mountains. Ecology 50:478–490.

Webb, R.H., J.W. Steiger, and H.G. Wilshire. 1986. Recovery of compacted soils in Mojave Desert ghost towns. Soil Science Society of America Journal 50:1341–1344.

Webb, R.H., and K.A. Thomas. 2003. Recoverability of severely disturbed soils and vegetation in the Mojave Desert, California, USA. Pages 283–290 in A.S. Alsharhan, W.W. Wood, A.S. Goudie, A. Fowler, and E.M. Abdellatif (eds.), Desertification in the Third Millennium. Proceedings of an International Conference, Dubai, 12–15 February 2000. Swets & Zeitlinger (Balkema) Publishers, The Netherlands.

Webb, R.H., and H.G. Wilshire. 1978. An annotated bibliography on the effects of off-road vehicles on the environment. Open-file Report 78–149. U.S. Department of the Interior, U.S. Geological Survey 21 p.

Webb, R.H., and H.G. Wilshire. 1979. Recovery of soils and vegetation in a Mojave Desert ghost town, Nevada, U.S.A. Journal of Arid Environments 3:291–303.

Webb, R.H., and H.G. Wilshire. (eds.). 1983. Environmental Effects of Off-Road Vehicles. Springer Verlag Publishers, New York. 534 p.

Webb, R.H., H.G. Wilshire, and M.A. Henry. 1983. Natural recovery of soil and vegetation following human disturbance. Pages 279–302 in R.H. Webb and H.G. Wilshire (eds.), Environmental Effects of Off-Road Vehicles: Sprinter-Verlag Publishers, New York.

E.4.3 Sonoran Desert Ecosystem Dynamics (and Miscellaneous Recommended) Literature

An “*” before the citation indicates a paper that we incorporated and cited in the final report.

Anderson, D. M. 1988. Seasonal stocking of tobosa managed under continuous and rotation grazing. Journal of Range Management 41:78–83. ***Citation did not address the overcompensation issue. Did not incorporate into the final report.***

Anderson, E. 1984. Who's Who in the Pleistocene: a mammalian bestiary. Pages 40−89 in P.S. Martin and R.G. Klein (eds.), Quaternary Extinctions: A Prehistoric Revolution. University of Arizona Press, Tucson. ***Used a different reference to address the reviewer comment. Did not incorporate into the final report.***

*Brooks, M.L., C.M. D’Antonio, D.M. Richardson, J. Grace, J.J. Keeley, J. DiTomaso, R. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of invasive alien plants on fire regimes. BioScience 54:677–688. ***Incorporated and cited in the final report.***

Brooks, M.L., T.C. Esque, and T. Duck. 2003. Fuels and fire regimes in creosotebush, blackbrush, and interior chaparral shrublands. Report for the Southern Utah Demonstration Fuels Project, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Science Lab, Missoula, Montana. 18 p. ***Citation applies to plant communities outside the Sonoran Desert. Did not incorporate into the final report.***

*Brooks, M.L., and T.C. Esque. 2002. Alien annual plants and wildfire in desert tortoise habitat: status, ecological effects, and management. Chelonian Conservation and Biology 4:330–340. ***Incorporated and cited in the final report.***

Brown, D.P., and A.C. Comrie. 2002: Spatial modeling of winter temperature and precipitation in Arizona and New Mexico, U.S.A. Climate Research 22:115–128. ***Not relevant to precipitation discussion. Did not incorporate into the final report.***

Brown, J.H., T.J. Valone, and C.G. Curtin. 1997. Reorganization of an arid ecosystem in response to recent climate change. Proceedings National Academy of Sciences USA 94:9729–9733. ***Applies to plant communities that occur outside of the Sonoran Desert. Did not incorporate into the final report.***

*Burgess, T.L. 1995. Desert grassland, mixed shrub savanna, shrub steppe, or semidesert scrub?: The dilemma of coexisting growth forms. Pages 31−67 in M. McClaran and T.R. V. Devender (eds.), The Desert Grassland. University of Arizona Press, Tucson. ***Incorporated and cited in the final report.***

Cable, D.R. 1971. Growth and development of Arizona cottontop. Botanical Gazette 132:119–145. ***Citation did not address the overcompensation issue. Did not incorporate into the final report.***

*Comrie, A. C., and E.C. Glenn. 1998. Principal components-based regionalization of precipitation regimes across the southwest United States and northern Mexico, with an application to monsoon precipitation variability. Climate Research 10:201–215. ***Incorporated and cited in the final report.***

*Cooke, R.U., and R.W. Reeves. 1976. Arroyos and Environmental Change in the American South-West. Oxford University Press, London. ***Incorporated and cited in the final report.***

*Curtin, C.G., and J.H. Brown. 2001. Climate and herbivory in structuring the vegetation of the Malpai borderlands. Pages 84–94 in C.J. Bahre and G. Webster (eds.), Changing Plant Life of La Frontera: Observations of Vegetation Change in the United States/Mexico Borderlands. University of New Mexico Press, Albuquerque. ***Applies to plant communities that occur outside of the Sonoran Desert. Did not incorporate into the final report.***

Curtin, C.G., D.A. Kelt, T.C. Frey, and J.H. Brown. 1999. On the role of small mammals in mediating climatically driven vegetation change. Ecology Letters 2:309–317. ***Applies to plant communities that occur outside of the Sonoran Desert. Did not incorporate into the final report.***

Curtin, C.G., N.F. Sayre, and B.D. Lane. 2002. Transformations of the Chihuahuan borderlands: grazing, fragmentation, and biodiversity conservation in desert grasslands. Environmental Science Policy 5:55–68. ***Applies to plant communities that occur outside of the Sonoran Desert. Did not incorporate into the final report.***

Gill, R.A., H.W. Polly, H.B. Johnson, L.J. Anderson, H. Maherall, and R.B. Jackson. 2002. Nonlinear grassland responses to past and future atmospheric CO_2. Nature 417:279–282. ***Study conducted on grasslands in Texas. Did not incorporate into the final report.***

*Gold, W.G., and M.M. Caldwell. 1989a. The effects of spatial pattern of defoliation on regrowth of a tussock grass. I. Growth responses. Oecologia 80:289–296. ***Incorporated and cited in the final report.***

Gold, W.G., and M.M. Caldwell. 1989b. The effects of spatial pattern of defoliation on regrowth of a tussock grass. II. Canopy gas exchange . Oecologia 81:437–442. ***Citation did not address the overcompensation issue. Did not incorporate into the final report.***

Gold, W.G., and M.M. Caldwell. 1989c. The effects of spatial pattern of defoliation on regrowth of a tussock grass. III. Photosynthesis, canopy structure and light interception. Oecologia 82:12–17. ***Citation did not address the overcompensation issue. Did not incorporate into the final report.***

Holling, C.S. 1995. What barriers? What bridges? Pages 3−34 in L.H. Gunderson, C.S. Holling, and S.S. Light (eds.), Barriers and Bridges to the Renewal of Ecosystems and Institutions. Columbia University Press, New York. ***Did not incorporate into the final report.***

Laurenroth, W.K., and D.G. Milchunas. 1991. The shortgrass steppe. Pages 183–226 in R.T. Coupland (ed.), Natural Grasslands, Introduction and Western Hemisphere. Ecosystems of the World 8A. Elsevier, Amsterdam. ***Not relevant to this report. Did not incorporate into the final report.***

*McAuliffe, J.R. 1991. Demographic shifts and plant succession along a late Holocene soil chronosequence in the Sonoran Desert of Baja California. Journal of Arid Environments. 20:165–178. ***Incorporated and cited in the final report.***

*McAuliffe, S.P. 1995. Landscape evolution, soil formation, and Arizona's desert grasslands. Pages 100–129 in M.P. McClaran and T.R. Van Devender (eds.), The Desert Grassland. The University of Arizona Press, Tucson. ***Incorporated and cited in the final report.***

*McLaughlin, S.P. 1986. Floristic analysis of the southwestern United States. Great Basin Naturalist 46:46–65. ***Incorporated and cited in the final report.***

*Neilson, R.P. 1986. High-resolution climatic analysis and southwest biogeography. Science 232:27–34. ***Addresses how changes in seasonal precipitation can affect the competitive interactions between C_3 and C_4 plants. Incorporated and cited in the final report.***

Peterson, F.F. 1981. Landforms of the Basin and Range Province: Defined for Soil Survey. Technical Bulletin 28. Nevada Agricultural Experiment Station, Max C. Fleischmann College of Agriculture, University of Nevada, Reno. ***Incorporated use of terminology and cited in the final report.***

Phillips, A.M., III. 1984. Shasta ground sloth extinction: fossil packrat midden evidence from the western Grand Canyon. Pages 148−158 in P.S. Martin and R.G. Klein (eds.), Quaternary Extinctions: A Prehistoric Revolution. University of Arizona Press, Tucson. ***Used a different reference to address the reviewer comment. Did not incorporate into the final report.***

Polley, H.W., H.B. Johnson, and C.R. Tischler. 2002. Woody invasion of grasslands: evidence that CO_2 enrichment indirectly promotes establishment of *Prosopis glandulosa*. Plant Ecology 164:85–94. ***Study conducted on grasslands in Texas. Did not incorporate into the final report.***

*[SRM] Society for Range Management. 1989. A Glossary of Terms Used in Range Management. 3rd edition. Compiled and edited by the Glossary Revision Special Committee (P.W. Jacoby, Chairman), Publications Committee, Society for Range Management, Denver, Colorado. iv + 20 p. ***Incorporated and cited in the final report.***

*Turner, R.M., J.E. Bowers, and T.L. Burgess. 1995. Sonoran Desert Plants: An Ecological Atlas. The University of Arizona Press, Tucson. ***Incorporated and cited in the final report.***

Walker, B.H., D. Ludwig, C.S. Holling, and R.M. Peterman. 1981. Stability of semi-arid savanna grazing systems. Journal of Ecology 69:473−498. ***Citation applies to savanna habitats and tree-grass interactions uncertain to occur in the Sonoran Desert unless under specific circumstances. As a result, we did not incorporate the citation.***

*Westoby, M., B. Walker and I. Noy-Meir. 1989. Opportunistic management for rangelands not at equilibrium. Journal of Range Management 42:266–274. ***Incorporated and cited in the final report.***