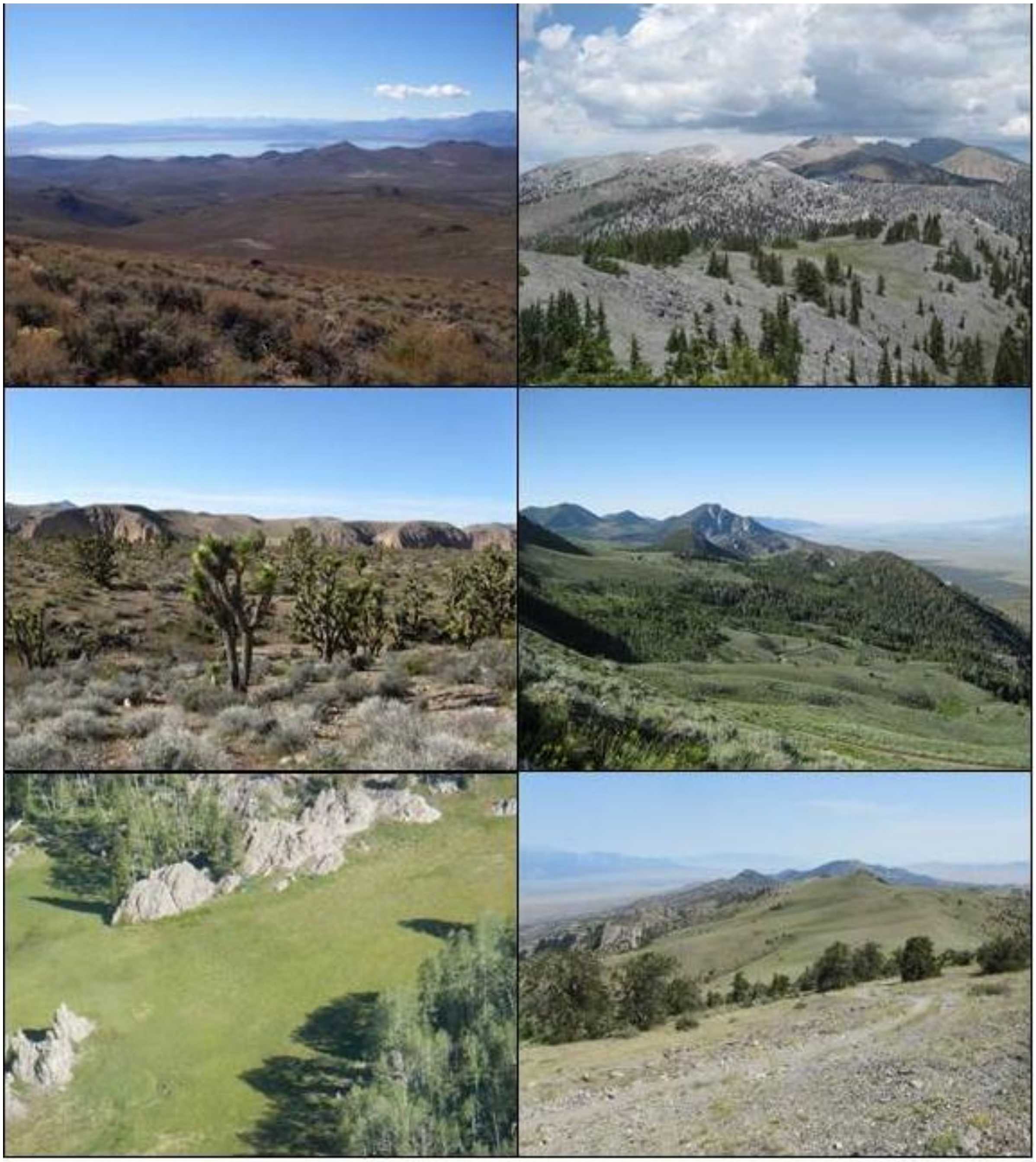
Landscape Conservation Forecasting Handbook



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The cover page features a six-photo collage (left to right, top to bottom): L. Provencher/TNC, Bodie Hills and Mono Lake, CA (2007); Highland Ridge of Great Basin National Park, NV (2010); Beaver Dam Wash National Recreation Area, UT (2011); Upper Terraces of Warm Mountain, NV (2010); Pine Valley Mountains, UT (2012); low-elevation bristlecone pines on the Mountain Home Range, UT (2013).

All sidebar textbox photographs are from LCF projects starting in chronological order in the Introductions and all were taken by Louis Provencher/TNC. Photographs in Preface are picked from pivotal LCF areas.

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Contents

Preface





I wrote this handbook because I did not want to formally teach the Landscape Conservation Forecasting (LCF) method and I wanted to leave something tangible that could be easily used to create new LCF projects. I also wanted to explain the method's origins, conveying its purpose and connections to the regulatory NEPA (National Environmental Policy Act) process.

I am the director of science for The Nature Conservancy in Nevada. By June 2026, I will have worked 32 years for The Nature Conservancy, starting as a research ecologist in longleaf pine forests at Eglin Air Force Base in the panhandle of Florida from 1994 to 2001. LCF was created during my employment in Nevada after a pivotal meeting of the 2003 Fire Learning Network in Sun River, Oregon, where modeling software and remote sensing solutions were identified to develop the method.

This handbook is intended for teams of practitioners that want to map, model, and budget the most cost-effective actions that will inform the management of large landscapes, often done by public or private land managers. A typical team is described in the handbook, and generally it consists of a project manager, an ecologist/modeler, a spatial analyst, and, depending on the remote sensing skills of the spatial analyst, at least one contractor. Another important audience is the funders who have enough conservation science background to understand the cost and practical outcomes of LCF. The method would never have existed without the funders.

I have adopted a more informal style of writing to avoid terse peer-reviewed journal jargon and style. Papers that include LCF are published for those who want more theory and terse prose. While I used "I" in the preface, I will not use "I" in the text because the development of LCF was a team effort involving other Nature Conservancy staff, contractors, and funders.

The handbook took many years to write because it was written during evenings, weekends, and often vacations. I also got stuck in several places. My main obstacle was to explain model building without actually teaching how to build ST-Sim databases. ApexRMS Ltd offers training courses to do the latter (http://www.apexrms.com/stsm). Anyone who wants to create an LCF project will need to be trained in ST-Sim's and Syncrosim's basic and advanced modeling features.

Introduction

Landscape Conservation Forecasting (LCF) was created by staff of The Nature Conservancy in Nevada to help land managers who are responsible for the stewardship of large landscapes. LCF is used to help managers make current and future protection and restoration decisions based on reference conditions, current conditions, desired future conditions, and budget constraints. LCF helps land managers answer the following basic questions:

- What is the current condition of each ecological system in your landscape?
- What is likely to get worse using current management?
- What strategies could improve degraded ecological systems?
- Will strategies work?
- Which strategies produce the highest ecological return-on-investment?

We were motivated to design a new method of conservation action planning to help public land managers overcome the major hurdle of National Environmental Protection Act (NEPA) documentation and litigation for proposed restoration projects. Public land managers from the Bureau of Land Management and US Forest Service identified that the cost of litigation and failure to complete the NEPA process at the point of project implementation were the main reasons preventing conservation on the ground. To reduce these hurdles, LCF was infused with terminology acceptable or at least recognized by federal agency staff, integrated with the tools of range and forest management, couched as status quo and alternative management scenarios as found in NEPA documentation, and assessed with return-on-investment analysis.

LCF can be summarized by "3 Ms": Maps, Models, and Metrics. **Maps** of ecological systems and current vegetation classes for the focal landscape are necessary for LCF. These maps, which are obtained by remote sensing analysis, are the foundation of LCF and, as a result, the adage of "garbage in – garbage out" is apt. **Models** are agent-based models called state-and-transition simulation models (STSMs) constructed in a simulation software platform, more recently ST-Sim in the Syncrosim© platform (Daniel et al. 2016; www.syncrosim.com). STSMs allow stakeholders to explore the future effects of alternative what-if management scenarios on the ecological condition of a landscape experiencing different stochastic futures. **Metrics** reflect the status of the landscape's ecological condition. LCF keeps the number of metrics to a minimum. Basic applications use one unifying metric, whereas more complicated projects involving disparate management objectives, such as wildlife species habitat suitability or carbon accounting, will involve at least two metrics. The performance of scenarios compared to *status quo* management is assessed by calculating the metric's ecological return-on-investment (also termed *cost effectiveness* in the conservation literature). This is an important nuance, LCF tracks success using metrics but recommendations to the land managers are based on the comparative analysis of metrics among scenarios, sometimes using ecological return-on-investment.

The methodological origins of LCF can be traced to one of the first "A to Z" implementations of Fire Regime Condition Class (FRCC) rapid assessment methodology (Hann and Strom 2003). The concept of FRCC measures "ecological system health" by calculating the dissimilarity (0-100%) between the reference condition and current vegetation as expressed by the distribution of succession class proportions (Provencher et al. 2008). Fire Regime Condition (FRC) is the continuous value between 0% dissimilarity and complete dissimilarity of 100% from the reference condition, whereas FRCC breaks the continuum into low departure (0-33%), moderate departure (34-66%), and high departure (67-100%). Shlisky and Hann (2003) proposed that FRC could be partitioned among vegetation classes to determine those classes that should be treated because they were in excess compared to reference conditions and which classes could become "recipients" of treated areas because they were in deficit compared to reference condition (e.g., converting an older, closed-canopy forest class to an older, open-canopy forest class). This is analogous to rebalancing a personal financial investment portfolio. In 2004, using local, high-resolution remote sensing of ecological systems and their vegetation classes, STSMs, and FRC mapping and partitioning, general management actions were identified for different ecological systems on Hawthorne Army Depot's 45,000-acre Mount Grant project area (NV) (**Figure 1**; Provencher et al. 2008). This project, funded by The Nature Conservancy's national Fire Learning Network, was a proof-of-concept project and the start of a collaboration between the remote sensing contractor Spatial Solutions, Inc. and The Nature Conservancy in Nevada. Important lessons were learned through this first project that will be described in this handbook.

Figure 1. Mount Grant (NV) on Hawthorne Army Depot where the first elements of LCF were pioneered.

Based on our recent experience and the unfolding of the massive Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) with its bank of new non-spatial STSMs for the Great Basin ecoregion by 2005 (Rollins 2009, Blankenship et al. 2021), our approach was repeated with local remote sensing for the 1.1-million-acre Grouse Creek Mountains-Raft River Mountains project area (northwestern UT), working in collaboration with The Nature Conservancy in Utah. This project was pre-LCF because it did not use the concept of ecological return-on-investment. However, the project generated key innovations by:

(i) transforming the LANDFIRE STSMs that had been limited to the reference condition to full management models populated by a large number of human-caused vegetation classes and management actions,

(ii) using the now-retired spatial STSM simulator TELSA (Tool for Exploratory Landscape Scale Analysis – Kurz et al. 2000) to model vegetation change over time and space,

(iii) constructing formal management scenarios with associated costs and management action failure rates using an experimental factorial approach to test scenario performance (i.e., lowest FRC), and

(iv) fully incorporating stakeholder workshops and outreach to improve future implementation success (York et al. 2008).

The first complete implementation of LCF with local remote sensing, STSMs for management, and ecological return-on-investment analysis was for the Bodie Hills (eastern CA) (Low et al. 2010). It is also noteworthy that staff of the Bureau of Land Management Bishop Field Office, which funded the project, requested a comparison of management scenarios with and without climate change effects. We had never used climate change projections in our models – figuring it out opened a can of worms that will be covered later as *temporal variability*.

During the Bodie Hills project, it became clear that future LCF projects would become increasingly complex and expensive to implement. Given that the starting cost of LCF projects to date strongly depended on the cost of remote sensing, a specialized analysis, we explored the possibility of conducting projects for clients without large funding by using existing map layers from LANDFIRE that we updated using additional geospatial data. Even updated LANDFIRE map layers do not contain the uncharacteristic vegetation classes present in management models that only local remote sensing can provide. We recognized from a validation study of LANDFIRE products in the Wassuk Range (western NV) that LANDFIRE maps were at best 50% accurate (Provencher et al. 2009); therefore, results from projects using modified LANDFIRE map layers would be coarse scale and not appropriate for project-level management (as stated by LANDFIRE), but could offer land managers general guidance on how to proceed. Subsequently, LCF projects have existed in two versions: 1) using existing and modified map layers, usually from LANDFIRE, generally not appropriate for project-level planning but adequate to guide general management strategies (**Table 1**), or 2) using new local, high-resolution remote sensing designed for project-level implementation (**Table 2**). The former approach has not been used for more than a decade. The greatest improvements to the LCF process after the Bodie Hills project have deployed local remote sensing to create ecological system and vegetation class map layers and allowed managers to engage in more detailed project planning. **Figure 2** shows point locations for projects listed in **Tables 1 & 2**.

Table 1. LCF projects using primarily existing LANDFIRE remote sensing data.

Landscape	Acres	Objectives
Cave Valley-Lake Valley watersheds in the Bureau of Land Management Ely Field Office (NV)	550,000	Developed land management scenarios (a scenario is a group of actions governed by a theme) using LANDFIRE geodata and weed map layers from the NV Natural Heritage Program (Thompson and Provencher 2009).
South Spring and Hamblin Valley Watersheds in the Bureau of Land Management Ely Field Office (NV)	660,000	Developed land management scenarios using LANDFIRE geodata and weed map layers from the NV Natural Heritage Program (Provencher and Anderson 2010).
Fremont River Ranger District in the Fishlake National Forest (UT)	484,060	Developed land management scenarios using LANDFIRE and US Forest Service soil-vegetation correlation maps (Tuhy et al. 2010a).
Powell Ranger District in the Dixie National Forest (UT)	374,110	Developed land management scenarios using LANDFIRE and US Forest Service soil-vegetation correlation maps (Tuhy et al. 2010b).

Northern Sierra Project (CA & NV)	5 million	Modeled climate change effects and tested adaptation strategies using National Forest and National Wetland Inventory map layers (Low et al. 2011).
Steptoe Valley sections B and C in the Bureau of Land Management Ely Field Office (NV)	598,298	Developed land management scenarios using LANDFIRE geodata and weed map layers from the NV Natural Heritage Program (Provencher and Anderson 2012).
Cherokee National Forest (TN)	380,000	Developed land management scenarios using reclassified LANDFIRE geodata and USFS plot data.

Table 2. LCF projects using local high-resolution remote sensing data.

Landscape	Acres	Objectives
Pre-LCF Projects		
2004: Mt. Grant (CA) at Hawthorne Army Depot funded by TNC's Fire Learning Network	45,000	Pioneer the LCF methodology: First time we used high-resolution remote sensing and primitive reference non-spatial state-and-transition simulation models to identify vegetation classes that need management because they are departed from reference conditions (Provencher et al. 2008). No Return-on-Investment tool.
2006-2007: Grouse Creek Mountains-Raft River Mountains (UT) funded by Utah Partners for Conservation and Development	1.1 million	Repeat new methodology pioneered at Mt. Grant at a much larger scale with more advanced spatial management state-and-transition simulation models to find the best set of management actions to restore BLM, US Forest Service and private ranching lands (York et al. 2008). No Return-on-Investment tool.
LCF Projects [including the Return-on-Investment (ROI) tool]		
2007-2009: Bodie Hills (CA) in the Bureau of Land Management Bishop Field Office	192,161	Find cost-effective land management scenarios to reduce ecological departure within the constraints of bi-state greater sage-grouse management (Low et al. 2010).
2010-2011: Great Basin National Park (NV)	77,000	Find cost-effective land management scenarios to reduce ecological departure (Provencher et al. 2013). First use of term "Landscape Conservation Forecasting™."
2010-2011: Ward Mountain (NV) in the US Forest Service Ely Ranger District and Bureau of Land Management Ely Field Office	118,000	Find cost-effective land management scenarios to reduce ecological departure (Abele et al. 2010).
2010-2011: Red Cliffs and Beaver Dam Wash National Conservation Areas in Washington County managed by the Bureau of Land Management St-George Field Office (UT)	Red Cliffs: 45,000 Beaver Dam Wash: 63,500	Test cost-effective experimental land management scenarios for the Mojave Desert to reduce ecological departure and increase desert tortoise habitat suitability (Provencher et al. 2011).
2012-2013, 2025: Pine Valley Ranger District in the Dixie National Forest (UT)	481,000	(a) 2012-2013: Find cost-effective land management scenarios to reduce unified ecological departure and identify areas of higher fire hazard due to greater non-native annual

		Bromus species cover. (b) 2025-2026: Update original map using change detection analysis and quantify sources of changes to different events for US Forest Service reporting (Tuhy et al. 2014).
2013-2014, 2018, 2024-2026: Hamlin Valley and Black Mountains in the Bureau of Land Management Cedar City Field Office (UT)	Hamlin Valley: 220,804 Black Mountains: 311,482	(a) 2015: Find cost-effective land management scenarios to reduce unified ecological departure and increase habitat suitability for greater sage-grouse and Utah prairie dog. (b) 2018: Determine adjustments to restoration action implementation rates simulated under historic climate (as done in 2015) that will maintain greater sage-grouse and Utah prairie dog habitat suitability under two different climate scenarios in the next 60 years. (c) After 12 years, update vegetation maps with higher resolution imagery, analyze changes to vegetation after 12 years, and re-simulate models with new management input. (Provencher et al. 2015, 2018, 2021a).
2013-2015: IL Ranch and TS-Horseshoe Ranch of Newmont Mining Corp. on private and public lands in north central NV	IL Ranch: 503,599 TS-Horseshoe Ranch: 632,834	Find cost-effective land management scenarios to reduce unified ecological departure and increase habitat suitability of greater sage-grouse, mule deer, and golden eagle (Provencher et al. 2016).
Since 2014 and on-going: Barrick-Cortez, Inc. sage-grouse mitigation and mine impact areas on private and public lands in central NV	Mitigation lands: 424,124 Impact lands: 324,885	Finding cost-effective land management scenarios to mitigate loss of sage-grouse habitat suitability credits produced by new mining development on impact lands (Provencher et al. 2017).
2014: Barrick-Cortez, Inc. sage grouse	7H: 12,648 Tumbling JR: 190,201	Conducted remote sensing for sage-grouse mitigation and mine-impact areas on private and public lands. These lands were sold or removed from analysis after maps were completed. TJR landscape used to create a spatially-explicit and stochastic ecological departure metric (Provencher et al. 2024a).
2016-2017: Middle Truckee River Watershed Investment Project (CA & NV)	390,000	Find cost-effective land management scenarios to (a) reduce the likelihood of catastrophic fires that could affect water resources and sedimentation and (b) minimize undesirable effects of climate change on water resources (Badik et al. 2022).
2017-2018, 2019-2020: Pine Valley-Mountain Home Range-Indian Peak Range in the Bureau of Land Management Cedar City Field Office (UT)	284,000	Find cost-effective land management scenarios to reduce unified ecological departure and increase habitat suitability for greater sage-grouse and Utah prairie dog under different climate change projections. In 2025, the mapping area was merged with adjacent Hamlin Valley (remapped in 2024) and the expanded area re-simulated with new management scenarios and carbon modeling (Provencher et al. 2019, 2021b, 2023).
2020-2021: Integrating Bonneville Cutthroat Trout Habitat Suitability into Great Basin National Park's LCF funded by NV Dream Tags (NV Department of Wildlife)	77,000	Spatial re-simulation of 2010 management actions at Great Basin National Park with emphasis on incorporating habitat needs of Bonneville cutthroat trout for restoration of Strawberry Creek.

2021 and 2023: Boulder Mountain (UT) funded by Watershed Restoration Initiative (restoration arm of Utah Partners for Conservation and Development) and US Forest Service	780,000	Find most cost-effective management scenario to restore focal systems in southcentral Utah's Boulder Mountain (Fremont River and Escalante Ranger Districts) with special emphasis on the declining mule deer population (Provencher et al. 2023a).
2021 and 2025: Middle Truckee River Watershed Investment Project (CA & NV)	390,000	Bretzlaff Foundation funded project to re-simulate original Middle Truckee River Watershed project where the primary goal is to couple a socio-political fire management resistance/acceptance R-coded model with STSM models to guide implementation of fuels management actions. Secondary goals are to connect action to pine marten and native non-trout fish habitat suitability indices.
2022-2024: South Snake Range	399,193	Complex project where TNC updated the original 2010 map of Great Basin National Park and the Keyhole Property with change detection remote sensing and conducting new mapping of 316,413 acres of Bureau of Land Management (BLM), US Forest Service, and private lands. The goals of the project were to simulate National Park Service and BLM vegetation management scenarios that would benefit Rocky Mountain bighorn sheep management, fire management, improve ecological condition of ecological systems, and measure the effects of future vegetation management on runoff and recharge using the US Geological Survey's Basin Characterization Model (Flint et al. 2021; Provencher et al. 2024b).

LCF
LCF prototype
Pre-LCF
First-LCF
LCF + Change Detection
LCF using LANDFIRE maps
LCV mapping and NRV

Figure 2. Locations of LCF projects.

Chapter 1 – Choosing the Landscape

Client's General Objectives

Land managers manage legally-defined geographies. Choosing a landscape for any project, especially LCF, is fundamental and is a negotiation between the client's interests and The Nature Conservancy's conservation priorities. The choice of landscape affects the cost of LCF, objectives, and choice of metrics. For The Nature Conservancy in Nevada and Utah, choosing a landscape is determined by the funding source because these chapters cannot afford to implement a project without external funding and, importantly, land managers demonstrate that they may be more willing to implement recommended actions if they have skin (funding) in a project. Conducting an LCF project for which the dominant land managers are not involved is a waste of money and time because results will likely be ignored or rejected.

Figure 3. Staff of the US Forest Service Ely Ranger District (NV) in 2006 for whom concepts of ecological return-on-investment were first developed for application to an aspen restoration project in the North Schell Creek Range (NV).

Managers usually offer funding for conservation action planning because they have a critical management, legal, or political problem to resolve for an area under their jurisdiction. For federal land management agencies, disruptive litigation against proposed actions during the NEPA process is a strong incentive for land managers to rectify an unfavorable situation by bringing new and better science to the next project submission. Successful management of vast landscapes or threatened and endangered species with limited budgets are also powerful incentives for land managers to reach out for help. These issues will probably determine the project's boundaries and primary objectives.

Being clear about the manager's objectives is critical because it should affect the classification of ecological systems and their vegetation classes, which will in turn determine what is mapped by remote sensing, its cost, and what is modeled in STSMs. For example, if a manager is concerned about abating fire hazard caused by varying fuel loadings of non-native cheatgrass (*Bromus tectorum*) in shrublands, then greater resolution of vegetation classes for middle-elevation ecological systems by varying cover of cheatgrass (e.g., 5-15% or >15%) may be called for. If a manager is concerned about increasing habitat suitability for a listed species, then (i) ecological systems and vegetation classes that the species depends on must be mapped at fine resolution (e.g., small wet meadows in herbaceous condition for greater sage-grouse during late brood rearing) and preserved if imagery is resampled to a coarse resolution (e.g., 1.5 m to 15 m) to allow for feasible spatial STSMs, and (ii) modelers need to incorporate a measure of habitat suitability in results.

Area

When choosing the boundary of a landscape, the size of the area needs to be considered because it affects remote sensing cost, spatial resolution to conduct feasible and project-relevant simulated management actions, duration of each simulation, and choice of metrics. LCF was developed for large western US landscapes that do not contain a large fraction of completely anthropogenic land surface (e.g., crop agriculture, cities, and industrial development). Typical LCF projects have been conducted on land managed by the Bureau of Land Management (Low et al. 2010; Abele et al. 2010; Provencher at. 2021), US Forest Service (Abele et al. 2010; Tuhy et al. 2014; Provencher et al. 2023a), and National Park Service (Provencher et al. 2013), although the original pre-LCF development was implemented on a Department of Defense Army installation.

Landscapes need to be sufficiently large to capture the vegetation outcomes of dominant natural disturbances (Keane et al. 2009). If landscapes are too small, the basic metric of ecological condition over-represents the largest vegetation classes and is subject to large variation among alternative simulated futures due to large-scale, uncommon stand-replacing events (e.g., large fires). In systems with slower stand-replacing dynamics, a natural disturbance takes a longer time, such as fire, to create early-development and mid-development classes. Because managers typically think in terms of 20 to 50-year horizons, increasing landscape size is the only substitute to remove small size artifacts for landscapes dominated by slower dynamics. It is problematic, however, that no quantitative rigorous analysis or rules can recommend a project area size; however, area guidance is possible. For example, in the Great Basin ecoregion, where dominant ecological systems have stand-replacing fire events ranging between every 50 to 1,000 years, a minimum project area of 18,211 hectares (45,000 acres) is recommended when the lower ecological systems are at middle elevation (>1,676 m or 5,500 ft). LCF project areas between 80,937-404,686 hectares (200,000-1,000,000 acres) are more common and adequate. Alternatively, in landscapes dominated by ecological systems with faster dynamics, such as longleaf pine (*Pinus palustris*), ponderosa pine (*P. ponderosa*), and tall grass prairie, project area can be as small as 6,070 hectares (15,000 acres).

There are cases when land managers need to assess management scenarios in small areas. In those cases, the LCF methodology still applies but landscape-level metrics of success, such as ecological departure or fire regime condition class (FRCC; Provencher et al. 2008; Rollins 2009) or habitat suitability for wide-ranging species should be avoided and vegetation class percentages (e.g., percentage of exotic species) should instead be used (e.g., Provencher et al. 2007; Frid et al. 2013).

Area affects the cost of remote sensing because satellite imagery is sold by the km^2 and the larger the area, the less likely funders will be able to afford the higher resolution imagery that is often required for better management. Also, analysis cost increases with area, although substantial economies of scale are realized with progressively larger areas. The tradeoff is clear. It is a blessing that many natural resources management objectives do not require the highest resolution (i.e., sub-meter). Fortunately, many multi-spectral satellite platforms are available to the public and price varies considerably among them with resolution and vendors. For The Nature Conservancy in Nevada and Utah, the preferred platforms given prices have been between 1.5- to 5-m resolution, respectively, pricing at $7.00 to $1.80 per km^2 for ortho-rectified multi-spectral imagery extending into the infrared. For imagery at resolution smaller than 1.5 m, prices climb up to >$20 per km^2.

Higher resolution is desired because it helps interpretation of vegetation (increases accuracy of analysis) and identification of small critical vegetation types (dependent on management objectives), while also requiring more work and field interpretation because of the richer spectral characteristics. It is highly recommended that project staff engaging in LCF projects work with an experienced imagery vendor to avoid unnecessary cost and ensure the best choices of satellite platforms and current or archival imagery.

Staffing

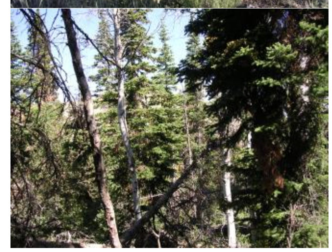
As a landscape is being chosen, it is highly advisable that staff and experts already be hired or available. LCF requires expertise and hiring inexperienced staff or contractors is a prescription for failure or long delays. A coherent team should be formed to handle each LCF project. Each team member is not required to work 100% on a single project, but each brings needed skills (**Table 3**). In our experience, the minimum team size is three people from The Nature Conservancy (again, not 100% full-time employees) plus any contractors. Key roles include lead scientist, remote sensing specialist (usually a contractor), spatial analyst, workshop moderator, and project manager. Required skills are listed in **Table 3**.

Table 3. Staffing LCF projects.

Title	Expertise	FTE* (approximate)
The Nature Conservancy		
Lead Scientist	• Participates in or leads contact with funding entity; • Writes description of ecological systems and their vegetation classes; • Interprets vegetation for remote sensing specialist during field verification; • Develops fully-populated STSMs; • Develops time series of temporal variability for natural disturbances; • Creates alternative management scenarios and conducts simulations; • Leads science component of stakeholder workshops; and • Leads writing of final report.	30-70% depending on experience
Spatial Analyst	• Prepares project's shape files for remote sensing; • Creates initial condition rasters for spatial STSM simulations; • Creates initial condition and final vegetation maps and derivative results maps using either GIS environment or precompiled computer code (e.g., R or Python); • Participates in stakeholder workshops, especially map reviews; and • Creates map results for final report.	20-30%
Project Manager	• Participates in or leads contact with funding entity; • Negotiates and manages award with funding agency; • Organizes stakeholder workshop logistics; and • Moderates stakeholder workshops.	10-20%
Contractor(s)		
Remote Sensing Specialist	• Acquires best satellite imagery to address objectives; • Conducts imagery analysis; • Leads field verification surveys; and • Delivers maps in GeoTIFF format to client.	80-100% during first year; 0% afterwards
Simulation Software Authors	• Provides simulation software support to modelers; and • Upgrades software at modelers' or third-party requests.	1-50%

* Full-Time Employee

All staff positions require that each person performs multi-disciplinary tasks at a high level of competency. For more complex projects, especially those involving spatial modeling and species habitat suitability, more staff with part-time assignments may be needed. The position of lead scientist combines skills/interests that are uncommonly found together: ecology and computer/simulation modeling. Many ecologists do not seem to be proficient with the modeling necessary for LCF. Many modelers have no interest in field work (for remote sensing), cannot describe ecological systems or their vegetation classes, and often do not enjoy stakeholder workshops. For LCF projects, however, it is highly recommended that the modeler participates in remote sensing field verification and vegetation descriptions and must participate in stakeholder workshops. Otherwise, the modeler will not understand ecological dynamics and management opportunities, and the client will not trust the modeler. Similarly, a typical spatial analyst can perform many GIS tasks; however, LCF projects, beyond a basic level of complexity, may require remote sensing training or experience and computer programming skills in Python or R (in the current version of the ST-Sim software). Finally, many project managers do not have workshop moderation skills, which are critical for more complex projects with a potential for litigation or controversy.



Workshops

Choosing a landscape implies choosing stakeholders that live there or have legal responsibilities over management of the land. LCF projects include workshops with local and, sometimes, regional stakeholders. Without stakeholder workshops, there is no transparency, no trust, no acceptance of results, and no implementation.

LCF projects generally consist of anywhere between two and four workshops and the number of workshops depends on the budget (**Table 4**).

Table 4. All possible workshops conducted in previous LCF projects.

Workshop	Objectives	Days
Vegetation Description	Ensure that all relevant ecological systems and their vegetation classes are captured by the draft description created by staff.	1-2
Model Review	Create stakeholder buy-in by reviewing STSM succession and probabilistic processes, and document assumptions.	3-4*
First Management Workshop (most important)	Review ecological system and vegetation class maps, show initial condition map results, show simulated map results from status quo (i.e., custodial) management scenario, define overall management objectives, determine time horizon (number of simulated years), define management scenarios, and establish unit cost of management actions, and establish ballpark management budgets by ownership.	3
Second Management Workshop	Review scenario simulation results of status quo and alternative active management scenarios and recommend modifications to treatment implementation levels.	3

* The model review workshop is especially difficult to conduct as it is abstract and boring to many stakeholders, but it is fundamental to prevent black-box perception of the STSMs and results. In landscapes with >15 distinct ecological systems, a 4-day workshop might be insufficient, but longer workshops are simply too long for most busy professionals.

Chapter 2 – Describing Ecological Systems & Vegetation Classes

An early step in all LCF projects is preparing written descriptions of vegetation. The LCF methodology requires two vegetation layers in GeoTIFF format: ecological systems (e.g., Wyoming big sagebrush-upland in the Great Basin) and all their reference and uncharacteristic vegetation classes (e.g., respectively, mid-development phase and shrubland with an understory of invasive cheatgrass). A GeoTIFF is a TIFF-format raster image file that contains geo-referencing information, allowing it to be positioned in real-world space by embedding metadata about its geographic coordinates, coordinate system, and datum. The format is widely used in remote sensing. Many Nature Conservancy ecologists seem to be familiar with current vegetation types, but not with *potential* vegetation types (i.e., ecological systems) and *current* vegetation classes. The latter two concepts are ingrained in range management training.

Figure 4. Project staff, agency staff, and a remote sensing contractor participating in the review of the vegetation description for the Bodie Hills (CA).

The interpretation of vegetation can have profound management implications. For example, a general ecologist might classify Great Basin loamy soils covered with pinyon or juniper trees at middle elevation as a pinyon-juniper woodland (e.g., vegetation maps from the US Environmental Protection Agency's Southwest ReGAP project), whereas in range management these are considered Wyoming big sagebrush shrublands (ecological system) encroached by conifers (current vegetation class) because trees should not exceed 10% of the system's area before the era of human-caused fire exclusion. The former requires no management, whereas the latter might result in removal of trees and understory restoration to return habitat to greater sage-grouse and other sagebrush-dependent wildlife species. Where this situation is common over a large landscape, total restoration cost can easily exceed $500,000.

The description of ecological systems and current vegetation classes needs to happen early in the LCF process. The remote sensing specialist cannot conduct mapping without this comprehensive description;

therefore, it must precede field verification by several months. Moreover, the description must be approved by project partners.






Data Sources: NRCS Soil Surveys, LANDFIRE, and Others

The two best sources of data for describing vegetation are the US Department of Agriculture Natural Resources Conservation Service's (NRCS) soil surveys and the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE; Rollins 2009; Blakenship et al. 2012) biophysical setting descriptions.

If a project area's soils have been mapped by NRCS, the soil survey geodatabase should be downloaded from http://sdmdataaccess.nrcs.usda.gov/. The NRCS has not made working with soil surveys a user-friendly experience; therefore, it is advisable that the spatial analyst be experienced with these data. Soil surveys are usually for whole counties. The project's spatial analyst will need to extract geodata for the project from the larger geodatabase. In the western US, the three most valuable embedded tables are *Rangeland Productivity and Plant Composition*, *Forestland Productivity and Plant Composition*, *and Ecological Site Descriptions*. The last table is sometimes hard to obtain and the actual written description may need to be requested from the local NRCS staff directly, although these are increasingly available online. An ecological site is similar to an LCF ecological system and is defined as: a distinctive kind of land with specific physical characteristics that differs from other kinds of land in its ability to produce a kind and amount of vegetation (NRCS 1998). These tables allow the team to write an inventory of most ecological systems found in the landscape. From experience, the soil survey's geodata do not allow the mapping of ecological systems as required by LCF standards and cannot be used as an initial stratification for remote sensing.

Nearly all soil surveys downloaded in this manner for conservation project will be of Order III. The order of a survey is important to understand. Order III means that each polygon identified may contain at least one, often 3-7, different ecological sites and the location of ecological sites and their area will not be specified. Moreover, many western polygons can be large (e.g., 2,023 hectares or 5,000 acres). The different ecological sites are presented in decreasing order of importance. The presence of small ecological sites (e.g., wet meadow), called inclusions, are often not specified. Finally, mapping errors can be common in remote areas.

For LCF projects, most *ecological systems* each contain one and usually several *ecological sites*. For example, one can find up to four different ecological sites dominated by mountain big sagebrush (*Artemisia tridendata* spp. *vaseyana*) in a Great Basin mountain range. Although these ecological sites may differ in soil type, slope, aspect, elevation, and dominant grass species, they would be lumped into one ecological system called montane sagebrush steppe with approximately consistent fire regimes in an LCF project. Also, and critically, it is not possible to separate these ecological sites by remote sensing without walking over the entire landscape because spectral characteristics of the sites may not be distinctive, sometimes even between ecological sites with different dominant shrub species. Soil surveys, therefore, are useful to obtain a list of ecological systems and a description of the vegetation, soils and topography. Sometimes information is provided as conceptual state-and-transition models that give some indication of broad succession classes and patterns of degradation.

The other primary source of maps of ecological systems, mostly reference vegetation classes, and simple STSMs for reference vegetation classes is LANDFIRE (https://www.landfire.gov/). LANDFIRE has mapped different vegetation layers of the entire US at 30-m resolution since 2007. To download from LANDFIRE, one uploads a shapefile of the project boundary to an interactive web map and downloads geodata for the project area. This process will reveal the identity of the ecological system (biophysical setting), the current vegetation class (existing vegetation class), and many other vegetation-derived datasets (Rollins 2009). Knowing the region of mapping, one can then download from the LANDFIRE website the comprehensive description of each ecological system and each reference vegetation class, and description of dominant disturbance regimes and the fire return intervals for surface, mixed, and high-severity fires. Moreover, one can download the reference STSMs for each ecological system.

LANDFIRE STSMs only represent the reference condition and have simple dynamics by design. Management models will be created by adding human-caused (uncharacteristic) vegetation classes and disturbances, and more complex dynamics. For example, a LANDFIRE STSM contains at most 5 boxes, whereas many LCF models have >15 boxes and harbor complicated relationships and temporal variability input needed to represent real management and climate variability. For new projects where management STSMs have not already been developed, LANDFIRE geodata and models are perhaps the best way to start a project knowing that modeling enhancements will be required.

Remote Sensing Crib Sheet

The project ecologist's first substantive job is to use NRCS soil surveys, LANDFIRE geodata, existing descriptions, peer-reviewed literature, grey literature, and expert opinion to write a comprehensive description of ecological systems, their vegetation classes, and their numerical and letter codes. Comprehensive, however, does not mean verbose. In addition to the comprehensive vegetation description, the project will also need a vegetation description crib sheet that the remote sensing specialist will use in the field to rapidly identify ecological systems and their classes, and find codes to write on a recording device. Codes must be sufficiently short so that they can be quickly recorded on a tablet computer in a helicopter. In both cases, the ecological systems and vegetation classes match one to one with the classes in the STSMs. Depending on the size and ecological complexity of the landscape, and document formatting, a comprehensive description can be 70 pages long, whereas the crib sheet might be 25 pages.

Some care must be given to the writing of the vegetation description as all stakeholders, including those that could litigate, will rely on the document to understand the maps that underlie the project's metrics and proposed management actions. The summary description of the ecological system must contain species/lifeform group composition, soil, and topographic information that a reader can easily relate to, and the most likely NRCS ecological site names should be stated for crosswalk by range ecologists or foresters. Within an ecological system, vegetation classes must be mutually exclusive in at least one aspect of cover. In shrublands for example, a single breakpoint for shrub cover, native grass cover, tree cover, or non-native grass cover is sufficient to create mutually exclusive classes. Those breakpoints must be clear and listed first in each class description. Class descriptions should preferably contain cover breakpoints for vegetation groups (e.g., native grass cover, conifer cover, sagebrush and mountain shrub cover, and non-native annual species cover) while avoiding species-specific breakpoints (e.g., Thurber needlegrass cover, low sagebrush cover, Russian knapweed cover) unless truly necessary.

Our style for naming vegetation classes has improved in the last 11 years by adopting shorter and more structured codes of class names that alphabetically separate reference classes from uncharacteristic classes. In **Table 5**, we present a few of many classes for Wyoming big sagebrush on upland soil to illustrate coding and mutually exclusive cover characteristics:

Table 5. Example of vegetation class codes and descriptions.

Code	Description	Comment
B 10804022	**Mid-open**: 10-19% cover of big sagebrush and other shrubs; ≥10% herbaceous cover; 20-39 yrs.	Reference class of mid-succession using LANDFIRE terminology. The numerical code 10804 represents big sagebrush shrubland (1080 from LANDFIRE) on upland soils also supporting pinyon and juniper (4). The numerical code 022 is the unique class code for B. Together the code is 10804022.
C 10804030	**Late1-closed**: 20%-39% cover of big sagebrush and other shrubs; 10-20% native herbaceous cover; 40-79 yrs.	Reference class of late-succession using LANDFIRE terminology. The mutually exclusive attribute compared to previous class is primarily the shrub cover.
U-B:Depleted (aka: B DP) 10804203	**Depleted-mid**: 10-19% cover of big sagebrush and rabbitbrush; <5% native grass cover dominated by bottlebrush squirreltail and Sandberg bluegrass; <5% non-native annual species; >20% mineral soil and litter cover.	The mutually exclusive attribute is the loss of the herbaceous understory compared to class B. The shrub cover is identical to that of class B. Because the class is uncharacteristic, the name code starts with the letter U followed by the succession age (-B): therefore, the first part of the code is U-B. The current vegetation is depleted due to the lack of understory, thus U-B:Depleted. In the field, the remote sensing contractor uses the shorthand "B DP."
U-C:Depleted (aka: C DP) 10804303	**Depleted-late**: 20-39% cover of big sagebrush and rabbitbrush; <5% native grass cover dominated by bottlebrush squirreltail and Sandberg bluegrass; <5% non-native annual species; >20% mineral soil and litter cover.	The mutually exclusive attribute is the loss of the herbaceous understory compared to class C. The shrub cover is identical to that of class C and greater than that of class B or U-B:Depleted. As justified above, the code becomes U-C:Depleted. In the field, the remote sensing contractor uses the shorthand "C DP."
U-B:SA (aka: B SA) 10804221	**Shrub-Annual-Species-open**: ≥5% cover non-native annual species; 10%-19% cover of big sagebrush and other shrubs; native grasses rare.	This class is nearly identical to class U-B:Depleted, except in one mutually exclusive attribute: ≥5% annual species cover. Because the class is mainly a shrub canopy ("S") with a non-native annual species understory ("AS"), the current vegetation is "SA."
U-C:SA (aka: C SA) 10804321	**Shrub-Annual-Species-closed**: ≥5% cover non-native annual species; 20%-39% cover of big sagebrush and other shrubs; native grasses rare.	This class differs from U-B:SA by having a greater shrub cover, a mutually exclusive attribute.

Naming and coding ecological systems and classes depend on the individuals involved, but we highly recommend that you build logical and structurally-defined codes and names. Numerical codes need to be of the same length, which are 8-digit numbers in our recent projects (**Appendix 1**).

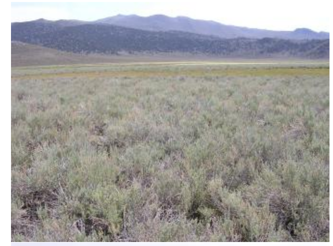
Chapter 3 – Mapping Vegetation Layers

The quality and timely delivery of remote sensing products can make the difference between a good or frustrating, even failed, LCF project. Great care should be taken to select a remote sensing specialist with both field experience, including the use of electronic devices, and interpretation experience that understands the fundamental difference between wall-to-wall mapping of two map layers (i.e., making maps), which LCF requires, and interpretation of repeatable features, which is insufficient for LCF processing. Moreover, it helps tremendously if the remote sensing specialist has experience identifying local vegetation using spectral signatures, even if a local expert is there to assist with field identification.

Figure 5. TNC staff and remote sensing contractor identifying distant ecological systems and vegetation classes using imagery spectral signatures on a tablet computer and binoculars from Mount Washington's summit in Great Basin National Park (NV).

In LCF projects, the models and, therefore, the vegetation descriptions determine what the remote sensing specialist needs to map. Said differently, *a priori* remote sensing classification does not determine what is identified. If a landscape has 25 distinct ecological systems and an average of 10 potential classes per model, then about 250 theoretically possible system-by-class combinations can be classified, although far less are expected to be found. Many remote sensing specialists do not anticipate being responsible for the detection of 250 classes and many of them are not trained to follow this methodology. It is critically important that this key aspect of the work be made crystal clear to candidate remote sensing contractors or staff. Moreover, the candidate remote sensing specialist will need to be informed that identical spectral signatures can represent different system-by-class combinations in different watersheds, including adjacent watersheds, due to geology, and that one system-by-class combination can have very different spectral signatures, again due to soil color and, therefore, geology. All these difficulties imply that LCF remote sensing cannot be adequately completed without extensive field surveys that cover a significant proportion of the entire project area.

Choosing the appropriate imagery will help answer the manager's questions and will affect the project's budget. Imagery can be collected from a satellite or aircraft. LCF projects are completed with satellite imagery because it provides consistent spectral signatures over the entire project area and is cheaper to analyze than aerial imagery. Aerial imagery consists of strips of high-resolution photography taken from a plane; spectral characteristics are not necessarily consistent among strips and thus require more analysis to interpret. Satellite imagery is sold at different resolutions and by the square kilometer. Different corporations access different satellites that have distinct spatial resolutions, typically expressed in meters (e.g., 30 m, 5 m, 4 m, 1.5 m, 1.4 m, or 50 cm).





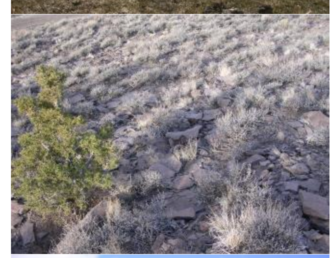

If a project is not well funded, thus requiring free imagery, and if the funder is comfortable with coarse imagery analysis that may not be appropriate for project-level design, then 30-m Landsat or 10-m Sentinel imagery may be satisfactory. Landsat is generally not appropriate for projects attempting to address wildlife objectives because spatial resolution cannot “see” important habitat features that are small, such as wet meadows and narrow riparian corridors. Sentinel imagery is clearly more desirable as more will be seen, but small systems will still be missed; therefore, project objectives should focus on management of common systems.

Since 2016, the sweet spot for LCF projects has been between the Spot 6/7 satellites at 1.5 m for \$7 per km^2. When projects can afford imagery and need to detect small vegetation features and dispersed trees, the Spot 6/7 imagery is ideal and affordable compared to other satellites in the meter range that are priced at >\$20 per km^2. A maximum resolution of 5 m is necessary to address greater sage-grouse management objectives because wet meadows, which are critical to the species during late-brood rearing, would often be undetected at coarser resolution. But detection of encroaching and dispersed trees is difficult at 5-m resolution without use of supporting National Agricultural Imagery Program (NAIP) aerial imagery, which is free, collected every 2 years, and has a spatial resolution ≤1 m. Note the 5-m RapidEye platform is now decommissioned.

LCF remote sensing inexorably follows a timeline. The date of the first field survey sets the pace for all pre- and post-milestone dates. The first field survey comes two to three weeks after satellite imagery is captured and delivered to the remote sensing specialist. The imagery must be captured a few weeks after peak primary productivity (i.e., allow early senescence); otherwise, the infrared reflected light will dominate the entire imagery and not allow separation of system-by-class combinations. For example, in the Great Basin, likely capture dates are from the second to third week of June depending on drought levels and maximum elevation. The first field survey can start as early as the last week of June up to the second week of July, although field work can extend into the first week of August during busy field seasons. Depending on the size of the project area, a field survey lasts from about seven days for small areas (e.g., 16,187 ha or 40,000 acres) to two weeks for larger areas (e.g., 323,749 ha or 800,000 acres). The goal of the field survey is to find reachable examples of each unique spectral signature, preferably a minimum of five examples of each unique spectral signature.








During the development of LCF, the remote sensing contractor gradually changed the field survey methodology to increase the number of dispersed ecological system and current vegetation class observations. Initially, the remote sensing contractor and Nature Conservancy staff visited traditional training plots in areas with unique spectral signatures, where all detailed cover values for cover groups and dominant species were recorded, then supplemented with *ad hoc* road and hike observations. The problem with this approach is that too few training plots can be visited in a reasonable amount of time (<60 plots for the entire landscape) and most of the data collected, except the identity of the ecological system, current vegetation class, and context observations, are unnecessary. Over the years, the remote sensing contractor realized that the number of observation plots, each containing few observations and photographs, was far more valuable than the quantity of data collected in *each* training plot to map vegetation accurately. With this realization and the availability of ruggedized, GPS-enabled tablet computers that could support remote sensing software and imagery, our methodology shifted to accumulating thousands of driving, hiking, and helicopter observations widely dispersed in a landscape. Driving observations are obtained by visiting every passable paved and dirt road, which requires a narrow, short-wheeled base, high-clearance, four-wheel drive truck with at least class C tires (six wheels, including two spares) in the Great Basin. Picking a field truck is an important decision because project objectives and road attributes dictate the equipment needed. For example, working around mines where greater sage-grouse are present means that field trucks must be MSHA (Mine Safety and Health Act) and mining company compliant, thus will need 9-ft flags, DOT reflective tape on three sides, fire extinguishers, and many other enhancements. Over the last 10 years, we have found that light truck tires with as many plies as possible are the most important parts of a four-wheel drive truck. For aerial work, collecting helicopter observations requires that the remote sensing contractor be immune to motion sickness. The new approach allows us to map vegetation more accurately and precisely in a very short amount of time because each group of observations is obtained very rapidly.

The first field trip yields the bulk of observations that will lead to the first draft and incomplete ecological system and vegetation class map layers, from which areas requiring more observations for unique and ambiguous spectral signatures are identified. These draft map layers are not deliverables, but simply tools to lay out more georeferenced points to visit. In our work, the contractor works two to three months on the draft maps before a second field trip is conducted, usually in October or early November (snow risk it too high in the central and southern Great Basin after about November 10th).

The unofficial term to describe this method of remote sensing analysis after field data are collected is “iterative cluster busting,” where a cluster is a group of approximately similar spectral signatures. New field data is used to partition (= busting) subtly different tones of color and textures (= cluster) with increasing number of steps (= iterative). This method is based on the analysis of pixels (of adjacent pixels), which is a traditional approach, whereas other remote sensing experts might choose more recent object-based image analysis. We tried object-based analysis and it failed (50-75% of classified polygons were wrongly assigned) because the complexity of Great Basin vegetation over large areas proved too great, spectrally inconsistent, and irregular to build repeatable search patterns.

The second field survey we conduct resembles the first field trip, except new and specific areas are visited. The duration of the field survey is the same length or a few days shorter than the first one. Following field data acquisition, the remote sensing contractor will use the entire set of observations to finish the map layers. The last step can take three to eight months of intense imagery interpretation.

Although the current ST-Sim software uploads two distinct map layers for ecological systems and vegetation classes (called State Classes in ST-Sim), we prefer the remote sensing contractor deliver a single map layer (GeoTIFF format) where each pixel is attributed by a combination of an ecological system with a vegetation class. Combining both attributes preserves attributes during quality control and resampling of pixels from the original resolution to a coarser resolution. Resampling may be necessary to improve computer performance and to ensure that ST-Sim complete spatial simulations in a reasonable number. After these GIS operations, the single map layers can be split into separate ecological system and vegetation class map layers.






Chapter 4 – Building State-and-Transition Simulation Models

General Concepts

The second "M" of LCF's 3Ms is modeling, which is not a common competency or interest of Nature Conservancy ecologists. Each LCF project team must have at least one state-and-transition modeler, and someone willing to model should learn either from experienced staff using existing models or receive basic and advanced training. For example, ApexRMS Ltd., the creators of ST-Sim software, periodically offers basic and advanced training and provides online documentation and tutorials (http://www.apexrms.com/stsm).

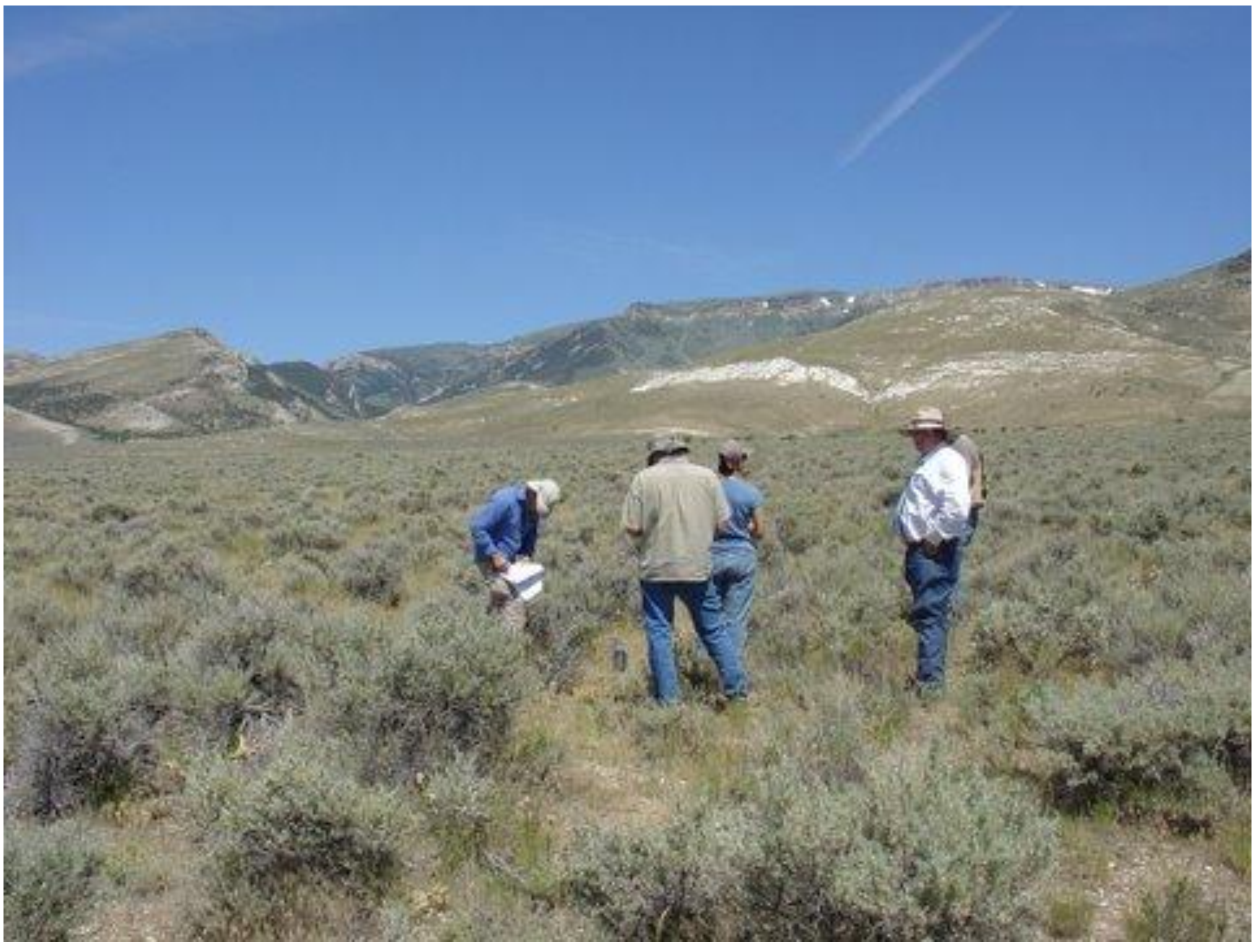
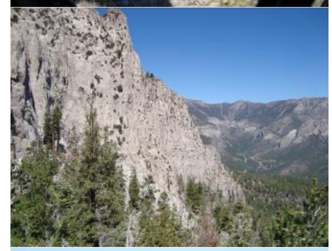


Figure 6. Discussion among Nature Conservancy staff, a remote sensing contractor, and Natural Resources Conservation Service staff at the initiation of remote sensing in the Grouse Creek -Raft River Mountains (UT) in July 2007. ***Credit: E. York/TNC, 2007*****.**

The LCF process includes the simulation of management scenarios using one predictive STSM (state-and-transition model) for each ecological system mapped by remote sensing (reviewed in Daniel et al. 2016 and Provencher et al. 2016b). An STSM is a discrete, box-and-arrow representation of the continuous variation in vegetation composition and structure of an ecological system (Westoby et al. 1989). Examples of STSMs are shown in Forbis et al. (2006) for mountain big sagebrush from eastern Nevada, in Provencher et al. (2016) for Wyoming big sagebrush upland gravelly loam in Utah and buffelgrass (*Cenchus ciliaris*) in Arizona, and below in **Figure 7**. Different boxes in the model belong either to: (a) different *states*, or (b) different *phases* within a state. States are formally defined in rangeland literature (Westoby et al. 1989; Bestelmeyer et al. 2004) as: persistent vegetation and soils per potential ecological sites that can be represented in a diagram with two or more boxes (phases of the same state). Different states are separated by *thresholds*. A threshold implies that substantial management action would be required to restore ecosystem structure and function. Unlike thresholds, relatively reversible changes (e.g., fire, flooding, drought, and insect outbreaks) operate between phases within a state.


Predictive models for ecological systems include multiple different types of vegetation classes: reference and uncharacteristic classes (e.g., see **Figure 7**). The classes of pre-settlement vegetation are each ecological system's succession *reference* classes. At their core, therefore, all models have the reference condition represented by some variation around the A-B-C-D-E reference classes originally developed by LANDFIRE (Rollins 2009). The A-E classes typically represent succession, usually from herbaceous vegetation to increasing dominance by woody species, either shrubs or trees. Said another way, the A-E classes are different (successional) *phases* within a single reference *state* (**Figure 7**). The A-E class naming is often modified, however, to reflect more logical levels of succession age with alternative closed and open canopy structures. For example, we develop models for the Sierra Nevada Jeffrey pine system where A, B, and C represent, respectively, early-, mid-, and late-succession. The B and C succession pathways are further split into open and closed canopy structures (e.g., C-closed and C-open), whereas these same classes are coded as E and D classes in standard LANDFIRE terminology. Use of the exact LANDFIRE terminology in our work ended because it did not separate the concepts of succession and canopy structure.

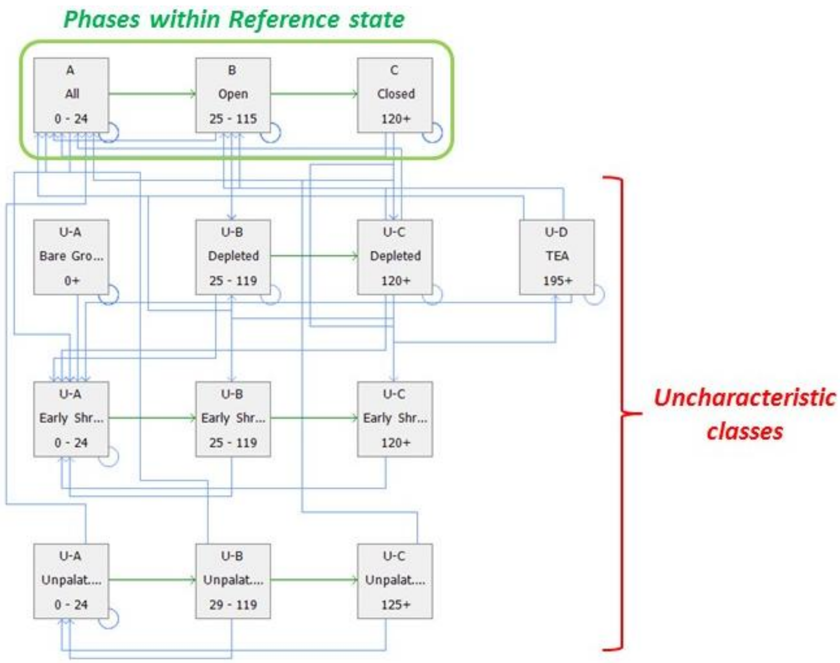


Figure 7. State-and-transition simulation model for subalpine low sagebrush in central NV. In this older version of ST-Sim modeling, succession is deterministic and represented by green arrows originating and ending on sides of boxes.

A current landscape contains native and non-native vegetation classes (in many ecological systems) that would not be expected under natural disturbance regimes, and thus, would not have been present in reference conditions (e.g., a shrubland invaded by non-native annual species). These non-reference classes are termed uncharacteristic ("U") classes. In addition to modeling reference conditions, therefore, predictive models also include the full range of uncharacteristic classes in the project area needed to address objectives. The two main categories of uncharacteristic classes comprise current vegetation that results from:

a. Disturbances beyond what would be considered "natural," whether caused by human actions or not (e.g., invasion or dominance by non-native grasses, depleted understories of shrublands, or incised/entrenched riparian areas); or

b. Purposeful actions by land managers to manipulate or alter vegetation to meet specific management objectives, such as seedings with introduced species to provide forage for livestock or habitat for wildlife.

Predictive models for ecological systems also include arrows (*transitions*) among classes that represent several types of pathways including:

a. Vegetation succession (the passage of time), which is traditionally deterministic (arrows emerging or leaving from sides of boxes in **Figure 7**), but can be modeled probabilistically (arrows originating and ending at top or bottom of boxes) as we have consistently done since

2021; and

b. Disturbances (arrows emerging or leaving from tops or bottoms of boxes in **Figure 7**) that can be represented by:
    i. Natural ecological processes, such as succession, fire, or flooding;
    ii. Uncharacteristic disturbances, such as annual grass invasion or livestock grazing; and
    iii. Active management treatments, such as mechanical thinning or prescribed fire.

Models can be developed by either using and updating existing models (simple and easy approach) or creating new models. Creating new models requires research on disturbance regimes, some of which are described in LANDFIRE model documentation downloads. We have built libraries of management STSMs applicable to different areas of Nevada, western Utah, and eastern California that are recycled for each new project (e.g., Low et al. 2010, Provencher et al. 2013, 2016, 2021a, 2024b). Other parts of the US often do not have such management STSMs.

In past LCF projects, non-spatial modeling was generally conducted because there were few explicit spatial questions that justified the increased difficulty of spatial modeling. Non-spatial modeling means that each virtual pixel behaves independently of others – virtual pixels have no mapped position. Non-spatial and spatial STSMs share the same foundational box-and-arrows models and many peripheral data. Spatial modeling involves additional spatial tables and map rasters that require more work and spatial analysis expertise. In the past, engaging in spatial modeling was substantially more difficult than non-spatial modeling, whereas today the difference in difficulty is less pronounced if one uses software such as ST-Sim. For western practitioners, the need for spatial modeling has increased as managers' questions focus on wildlife species management, (e.g., greater sage-grouse and mule deer), weed invasion and control, and landscape-level fire management. Wildlife management relies on a species habitat suitability, which depends on distance calculations between natural and anthropogenic habitat characteristics. Non-native species invasion and fire management focus on spread of weeds or fire to adjacent areas and successful control or containment is deployed strategically using maps. Only spatial modeling can address such issues because raster maps become the basis for analysis.

Model Building

It is not the goal of this handbook to teach how to create STSMs, as training is available for specific software. Advice, however, is offered on how one may approach model building. Different modelers will likely have varying steps of model building, which reflects the splitter *vs*. lumper preferences based on existing data, viewing the entirety of a system before even adding one box to the model, and manager's need for sufficient detail to direct actions. An experienced modeler competent in the local ecology can complete a model for a new system in one to four hours depending on model complexity. The fastest way to model is to reuse an existing model and update it. Without a model to copy and insufficient data, it can take two days to build a model of moderate complexity. Access to existing models becomes important, e.g., a typical Great Basin valley-to-crest landscape may contain 20-30 ecological systems.






In the Intermountain West where soil moisture is the most limiting factor, ecological system structures and corresponding model structures, fall into several groups that are structurally similar, while having different disturbance regimes. Knowing these groups allows one to build models more rapidly because of repeatable features and ability to copy existing models (a convenient editorial feature of ST-Sim). The groups are:

a. **Grassland/meadow**: Often a simple three-box model (four boxes if water-tolerant subalpine or upper-montane conifers are present later in succession) for successional reference classes consisting of an initial short, post-disturbance phase, followed by a longer graminoid-dominant phase (often the most desirable phase) that transitions to a woodier graminoid-dominant phase without fire or flooding. This model structure has been used for low elevation sandy soils (semi-desert grassland), wet meadows, and subalpine meadows and upland grasslands.
b. **Subxeric shrubland**: There are two major types of general subxeric shrublands: (a) low-elevation mixed salt desert scrub and (b) sagebrush models.
    i. The operative word in mixed salt desert scrub is "mixed" as it best describes the lumping of very different ecological systems found on saline and sodic soils that appear as similar gray-green nondescript vegetation to uninformed visitors. In the Great Basin and Mojave Desert ecoregions, these systems are the dominant vegetation and have not evolved with fire due to the scarcity of fine fuels. In many cases, two to three succession phases form models but it should not be assumed that succession is linear, as in the case of shadscale (*Atriplex confertifolia*)-dominated communities. Soil differences account for the variety of ecological systems. Although succession classes are few, the duration of many classes, especially older ones, can be as long as several hundred years

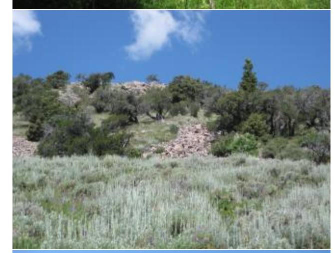
ii. because of the absence of fire (e.g., winterfat (*Krascheninnikovia lanata*)-dominated communities). The most important stand-replacing disturbances in these systems are either flooding in valley bottoms or persistent high soil moisture caused by very wet years.

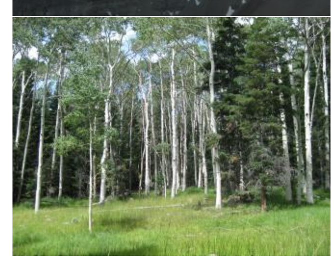
iii. A large class of shrubland models are dominated by a sagebrush species. Subxeric conifer establishment occurs if sufficient soil moisture is present, generally above the 10-inch (25.4-cm) precipitation zone. Models vary from three-box to five-box models with a consistent successional pathway: early-successional vegetation with a mixed herbaceous structure after stand replacing events, mid-successional open structure with plenty of grass and increasing sagebrush cover, and late-successional closed-canopy sagebrush. If trees can find enough moisture, a fourth class will support young trees resembling an often called "Christmas-tree phase," and a wooded closed-canopy class with usually conical trees and a viable understory during the reference phase.

c. **Subxeric woodland**: The classic subxeric woodland is composed of pinyon or juniper with a straight four-box, open-canopy successional pathway ending with old to ancient trees. Juniper savannas with relatively grassy understories found at low elevations on poor soils that experience monsoonal rains can also fit the subxeric woodland model structure. However, curl-leaf mountain mahogany, which is not a conifer, is also a common subxeric woodland that has slightly different structures than pinyon and juniper woodlands in both open and closed-canopy forms. Sometimes pinyon, juniper, and curl-leaf mountain mahogany are intermingled and form a different community type on carbonate (limestone and dolomite) geology.

d. **Riparian**: Riparian systems are found from the subalpine zone, to montane, and bottomland. They are inherently heterogenous and difficult to model because, in reality, they are best represented by multiple parallel successional pathways. Manager's questions will in part determine the simplest structure needed to answer the questions. The simplest model is a three-box model that omits all the ecological complexity, except for a messy early-successional phase resulting from stand-replacing flooding, a shrubby closed-canopy phase dominated by willows with cottonwood (*Populus* spp.) growing through it, and a third phase dominated by riparian trees, generally cottonwood. A more realistic, but complex, riparian structure could be parallel successions for willows (three linear boxes), cottonwoods (three linear boxes), wetlands, and riparian shrubs. Two uncommon

e. hybrid systems between riparian and montane woodland can also be modeled with the three-box riparian structure, although we prefer montane woodland structure, e.g., riparian ponderosa pine and riparian Jeffrey pine.

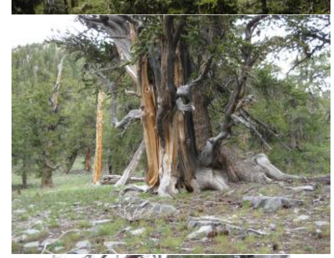




f. **Mountain shrubland**: Mountain shrubs are valued as browse, primarily for mule deer, but are also sought out by greater sage-grouse (*Centrocercus urophasianus*) for nesting. These systems are both difficult to delineate by remote sensing mapping because they may contain mountain shrub species that can resprout post-fire and mountain big sagebrush (*Artemesia tridentata* spp. *vaseyana*) that cannot. The following species can form these systems: Utah serviceberry (*Amelanchier utahensis*), antelope bitterbrush (*Purshia tridentata*), alderleaf (true) mountain mahogany (*Cercocarpus montanus*), Stansbury cliffrose (*Purshia stansburiana*), little-leaf mountain mahogany (*Cercocarpus intricatus*), desert almond (*Prunus fasciculata*), Dixie live oak (*Quercus turbinella*), and Gambel oak (*Quercus gambelii*). Resprouting completely changes model dynamics. The succession pathway we favor consists of four boxes, starting with a rapidly resprouting but short (4-5 years) early-succession class, a closed-canopied mid-successional class (which is always open in sagebrush systems), followed by two classes occupied by increasingly older pinyon or juniper that quite never close the canopy. Three species may not fit the resprouting model. Gambel oak, which is more a small tree than a shrub, is sufficiently distinct to be modeled alone or as riparian vegetation (see above) and usually does not have a pinyon-juniper phase. Stansbury cliffrose and antelope bitterbrush do not generally resprout after fire, but both have a pinyon and juniper wooded late-successional phase. They may need their own distinct models. Unlike for resprouting species, the absence of resprouting after fire does not guarantee that systems invaded by non-native annual species will transition to the mid-successional phase; therefore, they can get “stuck” in an annual species grassland or closed succession forbland.

g. **Aspen**: Aspen is found in three major types: aspen woodland (a.k.a., stable aspen), aspen-conifer (a.k.a., seral aspen), and aspen scrub, which is a stunted form of aspen woodland. Aspen-conifer is a simple linear five-box model where the last two classes are increasingly dominated by various montane conifers, such as white fir and Douglas fir at montane elevations, and limber pine (*Pinus flexilis*) or Engelmann spruce (*Picea engelmannii*) at subalpine elevations (a four-box model may suffice for aspen-subalpine conifer). The first three boxes are identical for aspen-conifer and aspen woodland, whereas the fourth and final box of aspen woodland is more open. Elevation, soil type, and distance from monsoonal precipitation appear to separate aspen-

h. conifer (wetter, more soil moisture and closer to drainages, montane elevations, more monsoonal rain) from aspen woodland (higher elevation, perched off mountain shoulders or at slope breakpoints, less to no monsoonal activity), therefore determining if the fourth box is aspen woodland or the first phase of conifer dominance. Aspen scrub is entirely found where snow accumulates due to wind deposition off mountain ridges and persists into the growing season. Snow persistence and soil saturation due to snowmelt support the water needs of aspen but also stunt growth. The first two boxes of aspen woodland approximate the entire successional chain of aspen scrub, but the second successional box of aspen scrub can be quite old, but not appear old due to the short stature of trees.



i. **Montane conifer**: Montane conifers include common community types such as ponderosa pine (*Pinus ponderosa*; eastern NV and western UT), white fir (*Abies concolor*), Douglas fir, and Jeffrey pine (*Pinus jeffreyi*; western NV and eastern CA). These conifer types all share the same five-box model structure with an early-successional class bifurcating into two parallel open and closed mid- and late-successional classes. In some geographies, such as the Sierra Nevada, the non-serotinous lodgepole pine (*Pinus contorta*) and California red fir (*Abies magnifica*) also follow this structure in the upper-montane to subalpine zone.
j. **Subalpine conifer**: Subalpine conifers represent several community type species that may not have the same model organization: Engelmann spruce, Rocky Mountain lodgepole pine, Sierra Nevada lodgepole pine, limber pine, mountain hemlock (*Tsuga mertensiana*), whitebark pine (*Pinus albicaulis*), and bristlecone pine (*Pinus longaeva*; dry and mesic forms). For many of these species a three-box linear structure works, however, a more general four-box structure addresses the ecology of Engelmann spruce where the fourth box is a mid-successional class of open canopy parallel to the closed-canopied mid-successional class.
k. **Alpine**: Alpine can be deceptively simple because vegetation structure does not appear complex, but various alpine systems range from low sagebrush shrubland, stunted rocky forbland, peat-forming shrubland, and wet stunted willow shrubs. In the Great Basin, low sagebrush alpine expressed as a two-box model is the most common, but alpine is more complex in the Sierra Nevada and Rocky Mountains.

Model structure guidelines presented above are only about reference vegetation classes. A full management model also includes uncharacteristic vegetation classes, which are often the only classes that are treated to reach different management objectives. For example, the Wyoming big sagebrush model that we used for comprehensive management in NV and UT was composed of 53 boxes, of which only five were reference classes. As a rule of thumb for the Intermountain West, systems found at upper-montane and subalpine elevation or found at semi-desert elevations have fewer boxes (thus fewer uncharacteristic classes) than mid-elevation to lower montane elevation systems. The uncharacteristic classes reflect different management legacies (e.g., historic overgrazing and favoring certain reference classes), invasion by non-native species, and intended contemporary management actions (e.g., seedings). Models become large when succession is combined with uncharacteristic classes, such as including non-native annual species invasion (**Figure 8**).

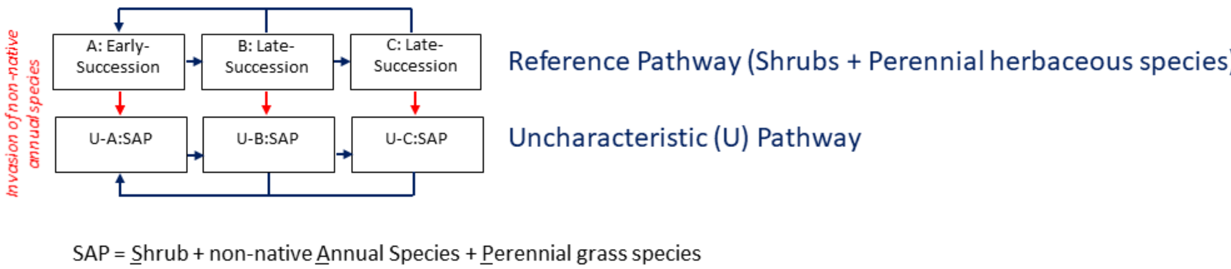


Figure 8. Reference and uncharacteristic pathways illustrating increased model complexity when human-caused processes are added. The uncharacteristic pathway is very similar to the reference pathways except that non-native annual species invaded and occupy >5% of total cover. The presence of non-native fuels shortens the fire-free interval.

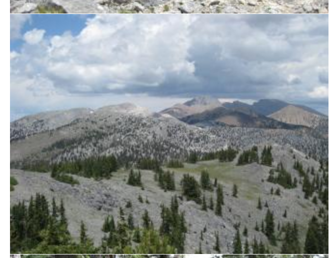
Let's assume a modeler has determined the model structure of ecological systems. Moreover, the model structure should exactly match the systems and classes mapped by remote sensing. The next step is to work on various pathways. A great focus of this step is to first focus on disturbances that account for most of the variability in vegetation dynamics, but that are not management actions (more on that subject later). A typical ecological system rarely has more than six to seven consequential disturbances (**Table 6**).

Table 6. Common influential disturbances in Intermountain West STSMs.

Drought dependent
Annual grass invasion
Severe drought mortality
Insect and disease mortality
Fire (surface, mixed severity, replacement)
Tree establishment in shrublands
Tree encroachment of shrublands
Very wet year mortality
Wet year recruitment
Flooding dependent
Exotic forb and tree invasion
Flash flooding in dry washes
Flood events of different intensities
Livestock grazing
Cattle grazing
Domestic sheep grazing

	Wild or feral# horse grazing
Native herbivory	
	Native browsing
	Native grazing (primarily elk)
Thermal environment	
	Aspen clone mortality from second spring freeze
	Subalpine average temperature
Snow-Water-Equivalent	
	Avalanches
	Snow Depth

Unbranded and unclaimed horses that are not considered federally-managed wild horses from designated Horse Management Areas.



In the western US, fire and flooding, respectively, are generally the most consequential disturbances for upland and riparian systems. Fire and flooding are “natural” disturbances because they existed before European settlement, although both can be altered by human activity. When building models, one needs to differentiate between the disturbances (arrows in the model) that are inherent to the reference condition (e.g., fire, insect outbreaks, and flooding), which generally occurred pre-European settlement in North America (and perhaps in Australia and New Zealand), and the disturbances that only exist because of human activity/accidents after European settlement (e.g., invasion of non-native species, plantations, and livestock grazing). It is noteworthy that reference conditions exist in naturally functioning systems after European settlement.

The first part of adding disturbances to any model is to get the reference condition correct, which usually starts with fire or flooding. Knowing reference parameter values of disturbances is important because one can then guess or adjust the parameter values of the same disturbances in uncharacteristic classes. For example, the reference late-successional class without trees of Wyoming big sagebrush might have a mean fire return interval of 75 years. If this class is only invaded by cheatgrass, thus becoming slightly more flammable, we adjusted the mean fire return interval of the shrub with annual and perennial grasses class to be about 60 years by multiplying the probability per year of the reference class (0.01333 = 75 years^{-1}) by 1.25 (0.01666 = 1.25 × 0.01333 = 60 years^{-1}). In this example, an adjustment factor of 1.25 might reflect field data or expert opinion. Sometimes such adjustments are the only way one can build models in the absence of more data.

Non-spatial and Spatial Questions and Simulations

Before 2013, spatial simulations were hard to conduct (e.g., Provencher et al. 2007) and, as a result, we nearly always conducted simulations with the non-spatial VDDT software from ESSA Technologies (Beukema et al. 2003). In 2012, ApexRMS Ltd made available the ST-Sim software that gave modelers the choice between non-spatial or spatial simulations (Daniel et al. 2016). With the availability of powerful laptops, servers, and cloud computing, spatial simulations became feasible. The ability to upload vegetation raster maps into ST-Sim and run complex spatial simulations was a game changer, but additional data were required to support fire spread, define disturbance size distributions, and spatially constrain disturbances such as livestock grazing within grazing permits and treatments, roadless and wilderness areas, slopes, and so on (Provencher et al. 2021a). Since, we have not conducted non-spatial simulations except to test the models for errors and obtain the non-spatial reference conditions (Provencher et al. 2024a). The types of extra data needed to run spatial simulations are discussed in the following section.

If a project does not have a need for spatial simulations to answer a question, simple non-spatial simulations should provide a good approximation of the real spatial process, while offering less practical output (e.g., charts) compared to frequency maps of treatment implementation. Estimating non-spatial reference conditions is one example (Provencher et al 2008, 2013, 2021; Low et al. 2010; Blankenship et al. 2015). Managers want spatial simulations because they produce probabilistic raster maps of all disturbances, especially where treatments were placed in the project area by ST-Sim given all the constraints for implementation. Spatial simulations are essential when project objectives focus on spatially-explicit processes where the distances to mapped features are required to estimate a value, such as species habitat suitability (Provencher et al. 2021a), hydrologic processes (Provencher et al. 2024b), sedimentation risk after fire (Badik et al. 2022), and social tolerance to local treatments.

Chapter 5 – Basic & Advanced Modeling Features

Scenarios

LCF was created to test alternative management scenarios. The standard template based on the federal NEPA process is to compare a do-nothing (control) scenario to one or more active management scenarios. A scenario is the implementation of treatments over the duration of the simulation expressed in area per treatment and per year (Figure 9). A scenario can represent a theme (e.g., only use prescribed fire) or include all treatments a manager may want to propose.

Figure 9. Examples of prescribed fire and mechanical treatments in sagebrush systems in eastern NV Bureau of Land Management lands and in floodplain restoration on the Truckee River at The Nature Conservancy's McCarran Ranch.

A special scenario is the simulation of Reference Conditions, also called the Natural Range of Variation or Historic Range of Variability (Hann and Strom 2003; Blankenship et al. 2015; Swaty et al. 2022; Provencher et al. 2024a). This scenario is special because there are: (a) no treatments allowed and (b) all post-European Settlement disturbances are excluded from simulations by setting their rates to zero in the Transition Multiplier menu[1] of ST-Sim (if used in a more complex management model). Reference conditions are needed to estimate ecological departure for each ecological system in the current and

[1] The main interface of the simulation software ST-Sim contains tabs with nested options that allow entries and import/export of Microsoft Excel files. These tabs are menus. Simulations are built with the entries in the menus. These menus are no different than any other software's menus.

future (i.e., simulated) years (Hann and Strom 2003; Provencher et al. 2008; Blankenship et al. 2015). Usually, the reference condition scenario is non-spatial, but more complex and interesting spatial versions have been developed (Provencher et al. 2024a).

Management Objectives

To define scenarios, the modeler(s) will need to know the guiding management objectives of project stakeholders, usually land managers. Guiding management objectives are short, general, and should number less than ten (e.g., **Table 7**). They should be concordant with agency objectives from Bureau of Land Management Resource Management Plans, US Forest Service Forest Plans, and National Park Service Natural Resources Management Plans, fire management plans, and state agency Wildlife Management Plans. Guiding management objectives provide project clarity to partners and, as a public domain document, offer transparency about reasonable management intentions to outsiders and potential litigants.

Table 7. Example of joint agency guiding management objectives established by Great Basin National Park (NPS), Bureau of Land Management (BLM), and Nevada Department of Wildlife for south Snake Range's (NV) natural resources.

Guiding Objectives
Map potential and current vegetation, and ecological condition as expressed by ecological departure from reference conditions (formerly Fire Regime Condition Class).
Maintain overall condition of and restore degraded native upland and wetted ecological systems to reference conditions or desired future conditions given climate change.
Maintain and enhance bighorn sheep habitat given climate change.
Treat Wildland-Urban Interface (WUI) areas and reduce fuel loads to help protect human settlements and cultural resources in and around the project area from wildfire.
Meet wilderness area objective of maintaining or enhancing wilderness characteristics using wildland fire for resource benefit and/or targeted prescribed fire.
Help NPS and BLM, and other partners, meet objectives specified in management plans.

Budget Considerations

The total budget per year and its variation over years are the first critical quantitative data we request from project partners, either total or by organization. The total budget is the average ceiling for expenditures that the modeler must respect often achieved through iterative adjustments.

How much money is spent might depend on the number of ecological systems that will be managed. In Intermountain West landscapes distinguished by basin and range geology, we commonly mapped more than 35 small to large ecological systems. Many of these systems will not be managed because they are too low or too high in elevation, are already close to reference conditions and should stay there, are predicted to get worse without special management in the coming decades, or are simply not a priority for managers. It is important that modelers walk partners through the exercise of picking the <12 ecological systems that will be considered focal systems because only they are simulated with management actions. Other systems will be simulated without treatments. Tracking more than 12 systems increases complexity, dilutes the investment in more important systems, and increases the time and staff cost of result analysis and reporting. Another key piece of budget information, which modelers will need to patiently pry from partners, is the money spent per ecological system or the order of importance among managed focal systems. In our management workshop, we can spend a full day on the subject of budget limits and allocations among systems and through time.

Custodial, Status Quo, Minimum, or Baseline Management Scenarios.

The do-nothing scenario is variously named *Status Quo*, Custodial, or Minimum Management. For years we used Minimum Management until a partner told us that their agency certainly did not do the *minimum* amount of management, nor did they *do nothing*. Joel Tuhy from The Nature Conservancy in Utah suggested the term Custodial Management to indicate a maintenance of baseline grazing and fire suppression management, and, maybe, a low level of necessary vegetation treatments. We use that term, although *Status Quo* or *Baseline* are perfectly acceptable.

In the ST-Sim software, the Transition Target menu is where treatment area is specified often by ecological system and, often, land ownership. The custodial management scenario is either created by setting all area values for all treatments to zero in ST-Sim's software Transition Target menu or by specifying a value of zero for all treatments in the Transition Multiplier menu, or by specifying vegetation treatment areas greater than zero for only the truly necessary baseline actions as specified by managers; therefore, active management scenarios will contain treatment areas significantly above the baseline.

Active Alternative Management

We recommend keeping the number of active management scenarios to less than four due to rapid increases in complexity, simulation time, computer memory requirements, and results with each additional scenario. Alternative scenarios can come in different specifications, but listening to federal agency NEPA needs is always a good approach. Also, scenarios are not always about vegetation treatments as we have been asked in the past to simulate custodial management but without any livestock or wild horse grazing. Occasionally, we will define scenarios as progressively increasing budget limits. For example, scenario A might be defined by a budget limit of $1 million per year and scenario B as $5 million per year for the first 10 years of management. Moreover, each scenario can include all treatments most likely used in a landscape.

Active management scenarios are implemented with the Transition Target menu of ST-Sim that is essentially a spreadsheet. There will be as many distinct Transition Targets (expressed as sub-scenarios) as there are scenarios. Each row of a spreadsheet requires a choice of year, ecological system, land ownership, transition (i.e., treatment), and area treated per year. When any entry is left blank, except the annual area treated, the treatment, which must be listed, applies to all levels of that blank entry (for example, all ecological systems if this entry is blank).

To avoid artifacts of implementation, we found the hard way that targets need to be fully balanced and all zero entries entered as such. Being fully balanced means that all the rows of applicable treatments entry for one ecological system and land ownership must be repeated for the other land ownerships and the larger group of all entries must be repeated for every year that treatments are reset, including the zero entries for treatment present in the model but not used. This tedious rigor creates very large treatment implementation files because they are factorially balanced. It is highly recommended to export the file to Excel and reproduce the entries using Excel's copy and paste functions.

A saving grace of the Transition Targets menu is that once targets are specified in a year, those treatment areas persist unchanged until they are reset in a future year; therefore, when one should not reset targets every year. Resetting area per year every year as a form of micromanagement should be avoided. Viewing implementation of treatments over a 5-year period better reflects true land management and the modeler can enter the area treated by simply dividing the total area to treat by the number of years.

Temporal Climate Variability

All natural disturbances can vary annually or monthly around an average rate due to climate and seasons. Fire years versus non-fire years tied to El Niño-La Niña climate cycles is a good example. Different climate change scenarios, each defined by monthly and annual time series, can impose variability around modeled disturbance scenarios. Climate change scenarios can also be the theme for alternative simulation scenarios, sometimes factorially combined with vegetation management scenarios (Provencher et al. 2021a; Badik et al. 2022).

Future climates expressed as precipitation and minimum and maximum temperatures time series can be obtained from websites hosting Global Circulation Model (GCM) results. Past climates can be obtained from PRISM in the US (Daly et al. 2008) or reconstitution of paleo-drought data (Biondi et al. 2008). A few points about using GCMs or paleo-climate are important:

a. There are too many GCMs to use and managers will only want a few contrasting ones for proposed actions. For the southwestern US, about only 12 GCMs have results that are concordant with data (https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Climate-Change-Program/Climate-Program-Activities/Files/Reports/Perspectives-Guidance-Climate-Change-Analysis.pdf). Working with managers, our approach is to select a "control" climate scenario that best emulates recent historic climate, a worst case GCM that is the hottest and driest (often ACCESS1 or HadGEM-ES2), and an intermediate GCM that local land managers believe emulates the changing climate they are already experiencing (e.g., wetter spring and early summer, but drier and hotter fall and winter). Picking the correct GCMs is an art form and depends highly on the partner's objectives. For example, land managers from the Cedar City Bureau of Land Management wanted the intermediate scenario to be one that had a wetter spring and early summer because they were already observing such local trends and, importantly, that period was critical for germination of perennial grass and sagebrush seeds that were aerially spread the previous fall. As a result, the CCSM4 GCM was selected (Provencher et al. 2021a).
b. There are two ways to pick the control climate. (1) Download PRISM data from 1950 to 2010 and extrapolate into the future using a Stochastic Weather Generator (in R script, Verdin et al. 2014). This approach was employed by Provencher et al. (2021a). The drawback of using PRISM is that it should not be used with GCMs for hydrologic analyses because PRISM has precipitation and temperature values that are very different from GCMS in "starting years" (i.e., the amount of precipitation in PRISM in 2012 can be lower than that of GCMs). If hydrologic analyses are not considered, then the SPEI expressed all in deviations from zero and, as a result, are perfectly comparable to deviations from the means of GCM. (2) The control can be selected from the GCM that is most similar to the historic climate using the RCP 4.5. This assumes that the current climate that includes a warming trend is very similar to the GCM with a weak warming trend

(Provencher et al. 2026). This control can be used with other GCMs for hydrologic analyses as they share initial conditions.

c. Downloaded GCM time series cover a 100-year period, often starting in 2012. For STSMs, managers rarely care about the simulation of proposed actions beyond the next 25 years; however, the simulation duration should be longer than 25 years if climate is part of management questions to allow GCMs to strongly diverge (about after 2040-2047) and affect vegetation patterns. Our simulations with climate scenarios are typically between 40 (more recently) and 60 (in older projects from 2007-2015) years.
d. A type of simulation is for the estimation of the reference condition to represent pre-settlement conditions. The reference condition, in turn, is used to measure the departure of current vegetation class distributions from pre-settlement distributions. Ideally, the climate time series would be from paleo-data. Unfortunately, paleo-drought data is reported as one metric, such as the Palmer Drought Severity Index modeled from dendrochronological data or the number of standard deviations obtained from annual tree ring width (Biondi et al. 2008). These time series are limited compared to the SPEI matrices, which offers the ability to tailor different time series to different disturbances. We found that creating a statistical model of the PRISM data from 1950 to 2000 with a Stochastic Weather Generator, generating replicated 1,000-year time series, and estimating SPEI for upload into ST-Sim's External Variables menu was the better approach to obtaining today's reference condition because the 1950-2000 period contains some of the most severe droughts in the mid-1950s and wettest periods in the early-1980s.

Recognizing temporal variability and associated precipitation and temperature time series is accomplishable and important; however, translating this variability into mathematical effects on each disturbance that could be climate-sensitive in a state-and-transition model is difficult and understudied (Provencher et al. 2016b, 2021a). As examples, if annual precipitation is 10 inches (25.4 cm) instead of the average 8 inches (20.32 cm), does that cause twice the amount of area burned in arid rangelands (stimulation of fine fuel growth and assuming the next year being dry) and four times the rate of non-native annual species invasion? In our projects, we obtain and process climate variability time series as an early task because it will be largely independent of remote-sensed maps and STSMs. In ST-Sim, three menus are jointly used to translate climate time series to effects on disturbances: External Variables, Distributions, and Transition Multipliers.

External Variables

The External Variables menu is where time series that contain the temporal variability are hosted. Time series are not the only data that can be entered here, but we upload in this menu replicated time series of Standard Precipitation and Evapotranspiration Index (SPEI; one time series per month of evaluation and months lagged into the past; Hayes et al. 1999 proposed SPI, without evapotranspiration), minimum monthly temperature, CO_2, and so on. SPEI measures soil moisture primarily based on precipitation time series expressed as the number of standard deviations from the mean of the time series (positive values indicate wetter than average precipitation and negative values indicate drier conditions than average). We evaluate SPEI using the free R script R-SPEI (Beguería and Vicente-Serrano 2017). The SPEI is a matrix where the rows are the month of evaluation (e.g., August) and the columns are the lags (e.g., 7 months prior to August, with a maximum value of 72 months). In our work, SPEI by month and lag are the most important external variables in the driest part of the US.

A useful feature of external variables is replication, which is achieved by including different full time series of the same statistical climate (a column of the *External Variables* menu is for replicate number). We upload distinct replicates because we want all disturbances to experience the same replicate of a specific climate by month and lag such that a drought year for fire will also be the drought year for tree invasion. We replicate climate by creating a statistical model of the original precipitation and minimum and maximum temperatures time series (e.g., from 1950 to 2022) using a Stochastic Weather Generator (in R script, Verdin et al. 2014) adapted from daily to monthly output (Provencher et al. 2021a). The climate model allows the production of as many replicates as desired that have the same properties as the original time series. Then, each replicate of precipitation and minimum and maximum temperature are transformed to SPEI as described above.

Distributions

The Distributions menu translates the magnitude of each of the External Variables annual values into positive continuous numbers (multipliers) that will singly or combined with others multiply the average parameter value of a single disturbance across all ecological systems' models. How temporal variability translates into multipliers for a single disturbance is primitive in the Distributions menu because it requires creating a look-up table (rows) that discretely imitates with rows a continuous mathematical function if one wants correlated variability among disturbances. One cannot simply specify a mathematical function (from a list of flexible curve-fitting equations (linear, sigmoid, exponential, negative exponential, parabolic, and so on) that reads the external variable value for the correct year and calculates a value sent to the Transition Multiplier menu. We create heuristic equations that express standard deviations from the mean SPEI or other types of climate time series into multipliers, then tediously build the look-up table in the Distributions menu (e.g., Provencher et al. 2021a; **Figure 10**).

Fire Activity: Greater fire activity occurs in shrub systems if fine fuels first accumulate two years prior to the current year, followed by year with dry fuels. The resulting functions multiplied the historic maximum fire size of each landscape.

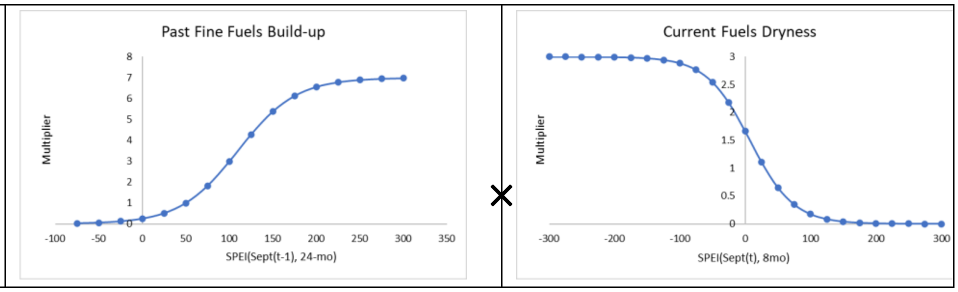


Figure 10. Transition multipliers for fire based on the influence of two multiplied SPEI time series: SPEI in September in year t-1 from a 24-mo lag (curve on the right panel) and SPEI in September of the current year evaluate in the last 8 months (central panel).

The Distributions menu also allows modelers to use common statistical distributions (uniform, normal, gamma, and beta) to add variability to the look-up table values or to completely generate temporal variability multipliers by skipping the External Variables menu. This requires specifying the statistical moments (mean and standard deviation) and minimum and maximum boundary values. The price paid for this convenience is that the variability of all disturbances are uncorrelated because, by random sampling, a dry year for fire and a wet year for flooding could contemporaneously be generated for the same year, which is obviously wrong unless a single disturbance, such as fire, occupies the STSMs.

Transition Multipliers

The Transition Multipliers menu reads the Distributions menu's multipliers that are used in all STSMs. Here, more than one Distribution multiplier can be multiplied, such as for fire (see **Figure 10** from Provencher et al. 2021a), if climate from previous or future years influences the disturbances variability. Values that originate from this menu are absolute in their control of the STSMs base parameter. Transition multipliers can also be statically used to completely or partially suppress or increase any disturbance and assign statistical variability of parameters (as done in the Distributions menu). This menu is versatile and gives modelers great control because it can be applied by replicate, ecological system, vegetation class, or disturbance.

Spatial Modeling

Vegetation Raster Development & Resampling

The remote-sensed GeoTIFF vegetation layers are delivered in their native resolution and coded in the contractor's field codes (like shorthand writing). For older projects, the ecological system and vegetation class map layers were delivered as two separate GeoTIFFs; today the contractor delivers one 8-digit code GeoTIFF that combines the ecological system (five first digits) and the vegetation class (last three digits). The first step is to translate the contractor's field codes to the formal names of ecological systems and vegetation classes and to unique 8-digit codes. Those names and 8-digit codes are exactly as those listed in ST-Sim's library definitions.

This step also allows the first quality control of the remote-sensed vegetation layers. For example, the contractor may have chosen a class in a system that should not exist but will need to be fixed before upload of rasters into ST-Sim. If the contractor delivers one 8-digit GeoTIFF vegetation raster, ST-Sim requires the upload of separate ecological system and vegetation class rasters; therefore, we use GIS software to split the single layer into two rasters.

It is also unlikely that rasters in the native spatial resolution of the satellite imagery (e.g., 1.5 m for Spot 6) will be uploaded because it will exceed the memory limits of hardware or take too long to simulate due to insufficient RAM. Resampling of the native single 8-digit raster to a coarser resolution is necessary. The selection of coarser resolution is a trade-off between achieving greater realism with proposed actions and keeping memory requirements and computing speed reasonable as the size of the area of interest increases. It should be noted that needed memory and computing time increase exponentially with additional pixels in the raster. Using AWS Cloud servers, we currently conduct simulations at 14- to 25-m resolutions (resampled) for landscapes ranging between, respectively, 300,000 to 1,000,000 acres.

Resampling is not the most exciting topic but the choice of resampling method is consequential. Poor resampling can eliminate small but ecologically important systems from the landscape if one simply applies a majority rule algorithm. Because small wet and moist systems are important to wildlife in arid environments and small patches of exotic species draw the attention of managers, we wrote a Python script that retains small patch systems or exotic species (and other small vegetation features) first and then applies the majority rule to larger systems (Provencher et al. 2021a appendices). The script will slightly exaggerate the size of small systems (a 2-m wide elongated wet meadow may become 5 m wide) at the expense of more expansive systems or classes. A spatial analyst writing the Python script will need to create a look-up table with the project's ecologist assigning a resampling pecking order. The pecking order will vary with management objectives or wildlife species of concern.

Supporting Rasters

Different additional rasters support ST-Sim simulations. In the Initial Conditions spatial menu, the modeler can supply a land ownership raster (a secondary stratum to segregate treatments and budgets, for examples), a planning zone raster (a tertiary stratum, for example, to conduct different management types within land ownership), and a vegetation age raster. Land ownership is the only raster added after ecological systems (primary stratum) and vegetation classes in our projects because planning zones complicate treatment and budgeting of simulations and the age of rangeland vegetation classes is rarely known.

Disturbance Size Distributions

All natural disturbances will have a size distribution that assigns a frequency of occurrence to each event size class (**Table 8** from Provencher et al. 2021a's Table 2). While the size distribution of fire is always included in our projects (**Table 8**), we also include distributions for all natural disturbances. If a size distribution is not defined, the software will use a random distribution where the size of any disturbance event is picked from a random number generator with no apparent clumping pattern. ST-Sim will try to simulate fires in the project area of the size and with the frequency specified in the Size Distribution menu.

The size distribution of fire events can be established from downloaded data from federal fire occurrence data recorded since 1980 and the Monitoring Trends in Burn Severity (MTBS; **Table 8**) for the project area or a larger area containing the project area. A modeler will need to determine the number of size intervals that contain enough events to populate the interval. In general, the number of events decreases with the size of fires.

Table 8. Size distribution (acres) of fire events for the Bald Hills (UT) based on federal fire occurrence data from 1980 to 2016 and the Monitoring Trends in Burn Severity (MTBS) data from 1984 to 2016. For example, a size class of "≤10" would indicate fire events were ≤10 acres.

Area of Disturbance (Acres)	Bald Hills Percent Occurrence
≤0.25	64
>0.25 to 10	20
>10 to 100	7
>100 to 300	2
>300 to 1,000	4
>1,000 to 5,000	2
>5,000 to 20,000	1

Spatial Constraints Menu

Spatial constraints control where and the intensity of disturbances (natural ones and treatments) are placed in the project area. Spatial constraint rasters assign to each pixel a value from zero (complete suppression) to one (full implementation). This menu is fundamentally important to address land management regulations, grazing regimes (allotment and pasture use, distance to water sources, season of use), protection of wilderness and sensitive areas, treatment equipment

constraints, and so on:

- Zones in the project area where some treatments cannot be used because mechanical equipment is not allowed due to environmental regulations, cultural exclusion, or topography (e.g., tractor-pulled equipment only used on slope ≤15%). These areas need to be represented by one GeoTIFF raster per treatment disturbance (e.g., masticator and rangeland drill cannot be used in a wilderness area).
- Allotments and their pastures for cattle and domestic sheep, and management areas for wild or feral horses, if applicable. The complexity of grazing regimes can be simple and high depending if season of use and grazing intensity are represented each with raster. This would imply that complexity of grazing is also in the model pathways.
- Representation of livestock grazing can be rendered even more complicated by including a unitless reduction in grazing intensity as a nonlinear function of distance from a water source. Livestock is very dependent on drinking water, especially daily in the summer. We found that distance from water eclipses many other factors. The difficulty with this more realistic approach is mapping all water sources, which are often not all known.

Spatial Controls for Fire Spread

Fire is different than other disturbances in that it spreads with wind direction, slope, and relative humidity. In ST-Sim, modelers can (should) enter the distribution of angles and multipliers (≥ 0) for winds direction, thus capturing such factors as prevailing winds, and use the fire literature to specify how must faster fire spreads up and down slopes relative to wind direction using a US Geological Survey Digital Elevation Model (DEM) raster (e.g., see **Figure 11** for wind direction and **Table 9** for slope effects on fire spread from an example by Provencher et al. 2021a). ST-Sim, however, does not handle relative humidity.

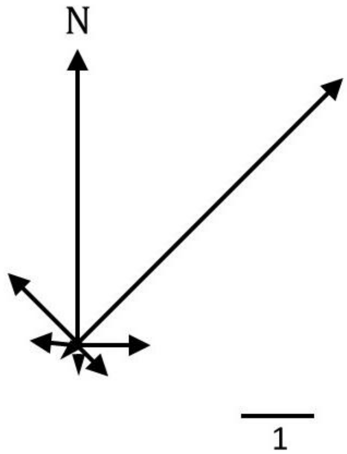
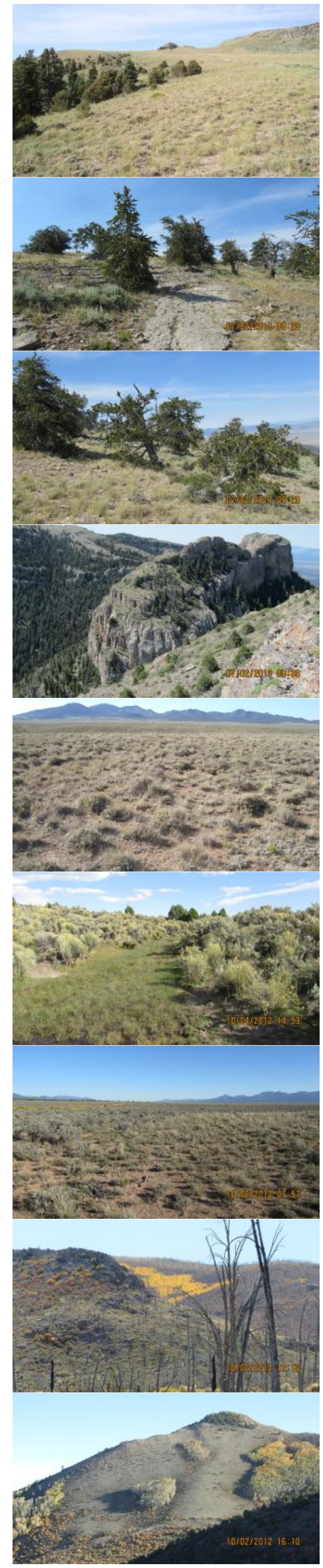


Figure 11. Fire spread direction multiplier imitating prevailing winds. N is north.

Table 9. Fire spread slope multipliers using McArthur's fire danger meter (Weise and Biging 1997). Negative values are against wind direction.

Slope (%)	Multiplier
-16	0.4700
-8	1.1320
0	1.0000
8	0.5600
16	3.9620

Since 2015, modelers can upload a GeoTIFF raster containing non-random fire initiation probabilities in ST-Sim. The default is random initiations weighted by the fire return intervals per pixel (higher initiation probability in a pixel with shorter fire return interval). Random fire initiations are the default in ST-Sim. Lightning strikes are not random and their locations up or downwind from greater sage-grouse leks can have profound effects on the species' population dynamics. Also, human-caused fire is usually along roads and developed areas. We obtain lightning strikes point occurrence data over a 5- or 10-year period from the federally contracted vendor (more recently the Western Regional Drought Center at the Desert Research Institute) that we convert to a probability of fire initiation per pixel and supplemented those with road effects using a moving-window Python script (Provencher et al. 2021a). The density of lightning strikes over a 5-year period is surprisingly dense and distributed everywhere.



External Program Menu

Also in 2015, the External Program menu was added to ST-Sim to allow external scripts in R (now also in Python) to exchange rasters with ST-Sim. For us, this enhancement to ST-Sim was ground-breaking and allowed the incorporation of wildlife habitat suitability and social management tolerance indices to directly influence the model's dynamics (i.e., coupled modeling; Provencher et al. 2021a). The External Program menu allowed us to answer practical questions from managers. The typical exchange between ST-Sim and an external script is: (i) for it to request the annual vegetation layers (ecological systems and vegetation classes) in the timestep simulated from ST-Sim, (ii) calculate a transition constraint multiplier that will affect the realization of disturbances (e.g., treatments to best increase greater sage-grouse habitat suitability), and (iii) and finally return the constraint raster back to ST-Sim to be applied that and, if desired, future years. The external script can be called up annually or at other intervals. The script can also output results, such as habitat suitability for a sensitive species. While we still use the External Program menu, advanced users facile with coding can bypass the External Program menu and more directly exchange rasters for estimation of metrics from their coding platform.

Chapter 6 – Metrics

Metrics are estimated to measure change or success of alternative scenarios. The best metrics of STSMs are those that take advantage of the distribution of vegetation classes per ecological system. Metrics range from simple to complicated (e.g., **Figure 12**).

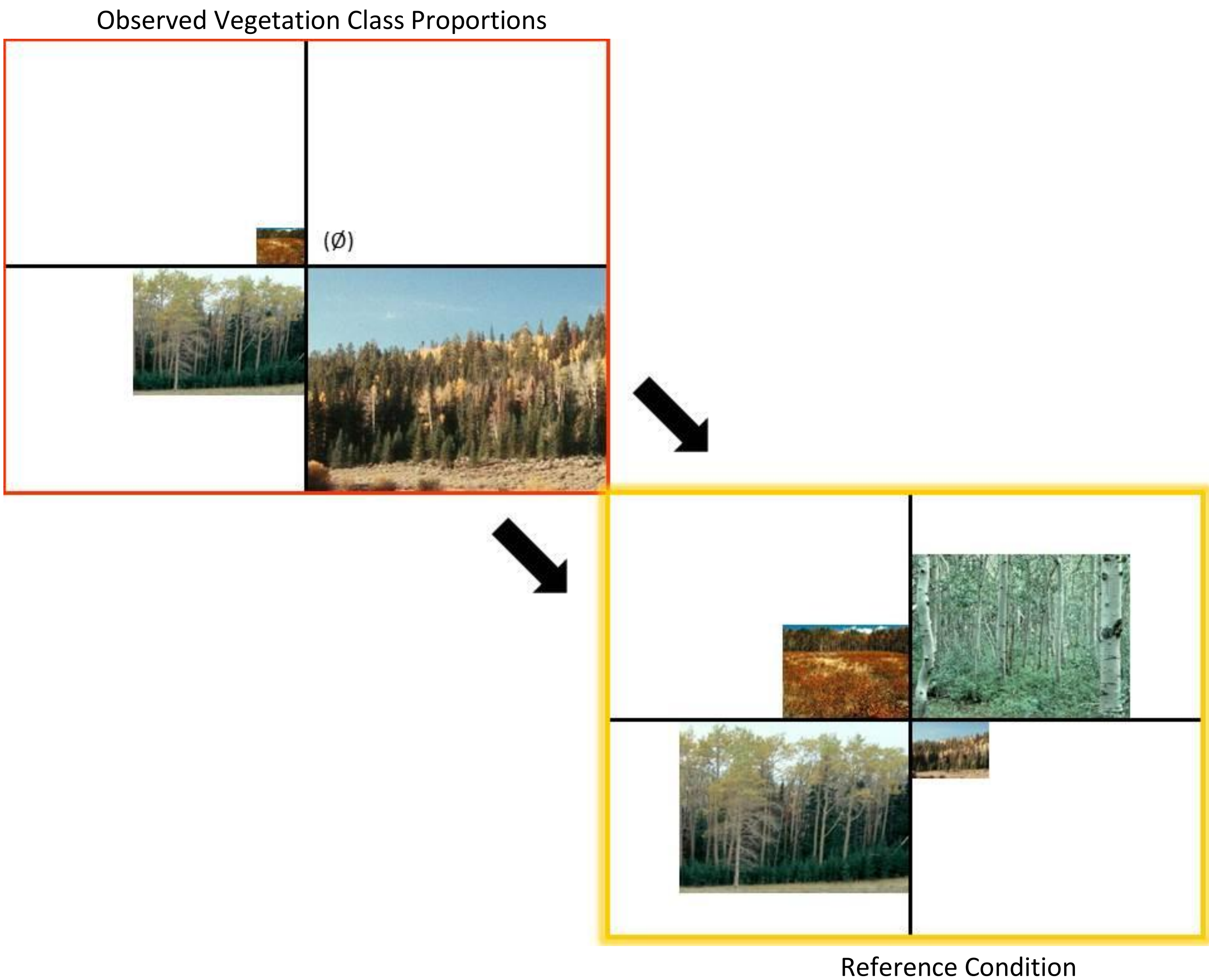


Figure 12. Joel Tuhy (The Nature Conservancy in Utah) presented this figure of aspen-mixed conifer to TNC's Utah Board of Trustees to explain ecological departure. The size of each photograph is proportional to the area of the class shown in the landscape. The upper left panel shows the result of remote sensing where the late-successional class with conifers is dominant. The lower right panel shows what is expected under the reference condition. Ecological departure is the dissimilarity between these groups of proportions.

Vegetation Classes

The simplest metric is an ecological system's vegetation classes of concern. Even when reporting more complicated metrics, the charts of vegetation classes are always shown. But sometimes the more complicated metrics such as ecological departure cannot always be used because the landscape is too small to satisfy metric assumptions (Keane et al. 2009). Regardless of landscape size, the average or median proportion and a measure of error of a vegetation class over time are useful metrics when comparing among scenarios.

Ecological Departure

The oldest and most established metric was originally named *fire regime condition* by Hann and Strom (2003) and carried forward by LANDFIRE and others (Provencher et al. 2008; Low et al. 2010; Rollins 2019; Blankenship et al. 2015). The name was changed as fire regime condition does not analyze fire regime data. We proposed the term *ecological departure* (Provencher et al. 2013, 2024; Furland et al. 2025), whereas LANDFIRE more recently opted for *vegetation condition departure* (Swaty et al. 2022). All these terms refer to the same equation of dissimilarity between observed and expected distribution of vegetation classes by ecological system (Provencher et al. 2008).

The term reference condition or natural range of variation was introduced in the previous chapter. Obtaining the reference condition per ecological system is required to calculate ecological departure. LANDFIRE pioneered the simple methodology of simulating the reference condition of ecological departure. It consists of using non-spatial state-and-transition models to simulate ecological systems without any post-European disturbances or vegetation classes until the proportions of all classes reach equilibrium (Provencher et al. 2008; Blankenship et al. 2015). Typical reference condition simulations are run for 500 to 1,000 years. Long simulations are often needed because some systems with long fire cycles or slow growth (e.g., pinyon- juniper woodland, ponderosa pine woodland, and subalpine conifers) show transient cycles that take time to completely dampen.

In addition to measuring the magnitude of departure between the current or simulated vegetation and the reference condition, ecological departure can be partitioned into its components of dissimilarity per vegetation class such that a manager can identify which class(es) might deserve to be treated (Provencher et al. 2008; Low et al. 2010). The ability to partition dissimilarity is the most important feature of ecological departure because it feeds directly into land management proposed actions. But not all components of departure, especially for the uncharacteristic classes (non-reference), are created equal from the perspective of managers. In 2012, US Forest Service staff from Utah's Pine Valley Ranger District told us that two types of uncharacteristic classes play a disproportionate role in western rangelands, perennial grass seedings and introduced noxious forbs and trees. Ecological departure does not capture the qualitative differences between these classes and all other uncharacteristic classes. The US Forest Service politely "requested" an enhanced ecological departure metric because:

- Perennial grass seedings with introduced species planted from the 1950s to 1980s are beneficial to wildlife today because they have undergone woody succession and resist wildfires. Species such as greater sage-grouse, mule deer, elk, and raptors commonly use them. As a result, seedings should be considered desirable up to a point; thus, a new metric of departure should weigh them less in the partial dissimilarity sum; and
- Introduced noxious forbs and trees are highly detrimental to landscape health even in small areas because the species eventually spread and are difficult to kill. Managers suggested that an enhanced metric should disproportionally increase the weight of introduced species classes in the partial dissimilarity sum.

Unified Ecological Departure

In 2013, we created the *unified ecological departure* metric to exactly address the shortcomings of ecological departure described above (Provencher et al. 2021a). The mathematical equation published in Provencher et al. (2021a) is borderline incomprehensible and the authors never felt satisfied about it because it clumsily uses Min() and Max() functions to imitate computer code. Unified ecological departure allows the condition of the ecological system to not be penalized below a certain management threshold proportion of introduced species seedings in the landscape and made introduced noxious forb and tree species classes weigh twice as much in the metric. The metric of unified ecological departure is in the advanced Reference Condition menu of ST-Sim (an add-on package). Note ecological departure is a special case of unified ecological departure if the seedings threshold is zero or left blank and no “badness” level is assigned to introduced forb and weed classes.

We developed a more elegant and continuous equation for unified ecological departure that will have the general structure of:

$$Unified\ Ecological\ Departure = 100 - \{\textstyle\sum_{i=1}^{N} \mathrm{Min}(O_i, R_i)\} \cdot \prod_{j=1}^{K} S_j \cdot EX \qquad \text{Eq. 1}$$

where O_i, R_i, S_j, and EX are, respectively, the i^{th} observed percentage of vegetation class, the percentage of the i^{th} reference condition vegetation class (equal zero for all uncharacteristic classes), the weight (0 to 1) for the j^{th} introduced species seeding class, and the weight (0 to 1) for all exotic noxious forb and tree classes combined. The numbers of *N* and *K* stand, respectively, for the total number of vegetation classes and the number of introduced species classes. The 100 – {···} terms in **Eq. 1** represent *ecological departure*.

The weights for seeded and introduced noxious forb and tree classes are the most complicated parts of unified ecological departure. Sigmoid curve-fitting equations bounded between zero and one are used to represent the weights:

$$Weight = 1 - \alpha \cdot e^{(\beta \cdot (X-Z))} \div (1 + e^{(\beta \cdot (X-Z))}) \qquad \text{Eq. 2}$$

where α and β are curve fitting parameters, *X* is the percentage of a vegetation class (or a transformation of it), and *Z* is an *X*-axis translation factor. Furthermore, the same curve fitting equation parameters (α = 0.2, β = 0.8, and *Z* = 7) are used for introduced species seeding and introduced noxious forb and tree species to simplify the mathematics.

For introduced species seeding, the entries for X are

$$X_j = O_j - Th_j \qquad \text{Eq. 3}$$

where *Oj* is the observed percentage (from remote sensing) of the j^{th} introduced species seeding class and Th_j is the management chosen threshold (e.g., 20%) for the percentage of the j^{th} seeded class below which dissimilarity is effectively zero and above which the seeded percentage contributes normally to dissimilarity (**Eq. 1**). The multiplication operator Π is in **Eq. 1** to capture the weighted contributions of all K introduced species seeded classes. Therefore, the weight S_j in **Eq. 1** is (**Figure 13**):

$$S_j = 1 - 0.2 \cdot e^{(0.8 \cdot ((O_j - Th_j) - 7)} \div \left(1 + e^{(0.8 \cdot ((O_j - Th_j) - 7))}\right). \qquad \text{Eq. 4}$$

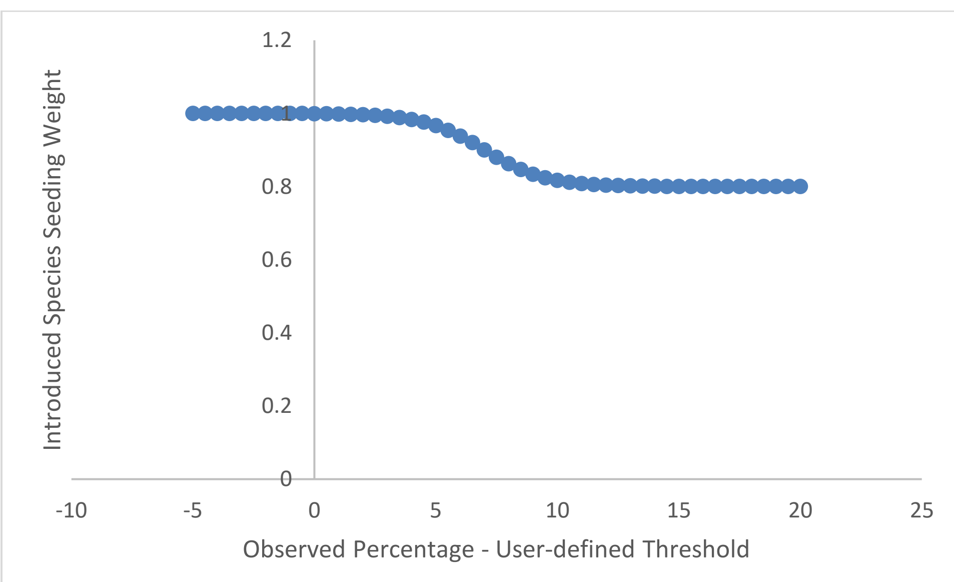


Figure 13. Weight for introduced species seeded class as a function off the observed percentage of the seeded class and the user-defined management threshold for seeded classes. Negative values on the

X-axis represent observed percentages of seeded classes smaller than the management threshold, for which the weight is one and does not increase dissimilarity. Positive values on the X-axis represent percentages of seeding above the threshold where the weight does add to dissimilarity.

For the exotic noxious forb and tree species, the weight *EX* in **Eq. 1** is obtained by summing over the products of exotic noxious forb and tree classes and level of exotic undesirability such that *X* is:

$$X = \sum_{m=1}^{L} O_m \cdot U_m \qquad \text{Eq. 5}$$

where m is the m^{th} uncharacteristic class among a total of L (seeded classes and non-exotic forb and tree species classes all have U = 0), the U factor (0 = no exotic undesirability to 1 = very high exotic detriment) is user-defined and multiplies the observed percentages (O_m) of the uncharacteristic class. We always select U =1 for exotic noxious forbs and trees (worst case scenario) such as knapweed species, tall whitetop, non-native thistles, yellow starthistle, Russian olive, or saltcedar. Classes where the herbaceous understory is dominated by non-native annual species are given a U = 0.5. Otherwise, uncharacteristic classes receive a U = 0. Therefore, weight *EX* in **Eq. 1** becomes (**Figure 14**):

$$EX = 1 - 0.2 \cdot e^{(0.8 \cdot ((\sum_{m=1}^{L} O_m \cdot U_m) - 7)} \div \left(1 + e^{(0.8 \cdot ((\sum_{m=1}^{L} O_m \cdot U_m) - 7)}\right). \qquad \text{Eq. 6}$$

Spatially-explicit and Stochastic Ecological Departure

The estimation of ecological departure has been non-spatial because the observed and reference condition percentages were obtained by summing the area per class per ecological system and dividing each class's sum by the total area of the ecological system in the landscape of interest. The locations of pixels are ignored. All pixels of an ecological system have the same value. Also, the estimation typically has no real variability (or stochasticity) because practitioners always used the average percentages of the reference condition obtained from ST-Sim where random number generation creates minor default software variability; however, Blankenship et al. (2015) pioneered the use of strong variability tied to natural disturbances for non-spatial ecological departure (see *Distributions* sub-section) and expressed variability with a variance transformation.

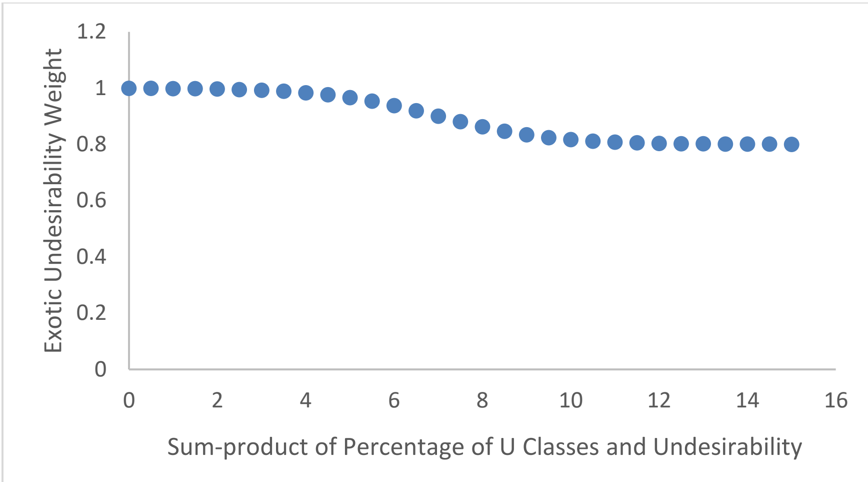


Figure 14. Weight for exotic noxious species classes as a function of the sum-product of the observed percentage of the exotic forb and tree classes and the user-defined undesirability level of the class.

Provencher et al. (2024) reviewed the concept of traditional ecological departure, its management shortcomings, and proposed a new spatially-explicit and stochastic ecological departure from single and multiple ecological systems. The spatially-explicit property of the new metric is based on a user-defined radius of moving-window evaluation around each pixel such that the deliverable is a raster map of ecological departure where its value can change per pixel of the same ecological system. The radius of evaluation should vary among users' objectives; however, we used the maximum daily foraging or perception radius of species of concern (e.g., 1,400 m for bighorn sheep). The reader can read Provencher et al. (2024) for details; however, we wanted to point out two practical points:

a. Estimation of spatially-explicit and stochastic ecological departure is computationally intensive because it uses a moving window algorithm for the observed and each replicate of the spatial reference condition rasters. We wrote a Python script to perform the estimation because Python handles large landscape rasters more efficiently (faster computational speed and less memory needs) than R and employed coding tricks to use less memory and constrain moving window operations.
b. We developed the spatially-explicit and stochastic ecological departure to solve a future smaller problem in the development of the larger challenge of clustered systems. A clustered system is a group of ecologically similar ecological systems often distributed along soil productivity gradients that are represented by a single model. For example, Wyoming big sagebrush on semidesert soil, Wyoming big sagebrush on upland soil, mountain big sagebrush on upland soil, and mountain big sagebrush on mountain soil are found on loamy soil with

increasing precipitation (thus, related to elevation) that we would model as a single *big sagebrush cluster*. By using clustered systems, very large areas of interest can be simulated with less systems and less parameters; however, clustered systems require underlying spatial constraint rasters to selectively modify transitions along soil productivity gradients. Devising the spatial constraints component is the major challenge we are slowly working on.

- Spatially-explicit ecological departure is required to evaluate clustered system work as non-spatial ecological departure would not work because fire return intervals and duration of successional classes change with soil productivity; therefore, the reference condition can vary pixel by pixel. Non-spatial ecological departure assumes spatially invariant reference conditions.

Other Metrics

Many other metrics of varying complexity can be scripted depending on managers' questions. We used wildlife habitat suitability models or indices for greater sage-grouse (Provencher et al. 2021a, *In Review a*), Utah prairie dog (Provencher et al. 2021a), Rocky Mountain bighorn sheep (Provencher et al. *In Review b*) and mule deer, raster-based hydrologic models (Saito et al. 2025), raster-based sedimentation models (Badik et al. 2022), and carbon stocks and flows (Provencher et al. 2023b). Indices can be used to focus treatments by interfacing with the advanced External Programs menu (Provencher et al. 2021a) or calculated *post hoc* from annual vegetation raster outputs (Provencher et al. 2021a; Badik et al. 2022; Saito et al. 2025). For most indices, R, Python, or other coding languages will need to be written by staff who can research the topic and understand it enough to script the index. In other cases, the index is obtained by coupling external and existing software with ST-Sim (Miller and Frid 2022).

Ecological Return on Investment

In 2007, LCF came to maturity in the Bodie Hills (CA) by the addition of Return on Investment (ROI) estimation suggested by Greg Low (MBA) from The Nature Conservancy. ROI allows managers to pick a superior management scenario among more than one alternative active scenario when a custodial management scenario is present (as in NEPA alternative scenarios). There is no gain in calculating ROI when there is only one active scenario, except perhaps to eliminate it if ROI is negative relative to the custodial management scenario.

Traditional ROI is a measure of the net money gained divided by the amount invested. If one invests $1 in a project and it later delivers $2 of revenue, the ROI = 100 × (2 - 1) / 1 = 100%. In ecological projects where revenue is not the currency of interest, ROI is really about Effectiveness Return on Investment (*eROI*), which we represent as:

$$eROI_{i,j} = 100 \cdot Area_j \cdot \left(UED_{c,j} - UED_{i,j}\right) \div \sum_{t=1}^{T} Cost_{i,j,t} \qquad \text{Eq. 7}$$

where *UED* is unified ecological departure at the end of treatments or end of simulation (one can also use *ED* for ecological departure) and *i*, *j*, *Area*, *c, T*, and $Cost_{i,j,t}$ are, respectively, the i^{th} active scenario, the j^{th} ecological system, *Area* is the area of the j^{th} ecological system in the landscape, *c* is the custodial (or control) scenario, and *Cost* is the annual cost of the scenario summed over the duration of treatment implementation (Low et al. 2010; Provencher et al. 2013). The units of *eROI* are acres (or hectares) divided by dollars. The metric can be positive and negative, and ranges between -∞ and ∞. *eROI* is only useful as a relative measure of comparison among active scenarios. Negative *eROI* means that the scenario degraded the ecological system at a cost compared to doing nothing. One can also use other metrics of success, such as wildlife habitat suitability; however, the order of the *UED* terms in **Eq. 7** should be reversed if a higher value of the metric indicates better habitat (*UED* achieves better vegetation condition with lower numbers) because improvement must be a positive value.

An interesting use of *eROI* is to compare among focal ecological systems within the preferred management scenario. A land manager might want to know this information to schedule the treatment of ecological systems in the order of *eROI* magnitude. We found that productive systems with low treatment cost (for example, basin wildrye in loamy bottoms) generally show the highest *eROI.*

Over the years, we found that land managers want to focus on custodial management and one preferred management scenario already comprised of a variety of established treatments chosen on deep experience. In that case, the *eROI* might not be needed or only good to eliminate a scenario causing negative *eROI*.

Chapter 7 – Reporting

Apart from one private foundation, federal or state agencies and one mining company funded our LCF projects. Invariably, such funding leads to writing a final report. We have written at least 20 final reports. These are large and highly detailed documents that are tedious to write. In 2018, the cost of writing one large final report was estimated at about $15,000 (including benefits).

Final reports contain the best information for land managers because they are rich in practical results and lessons learned. Therefore, final reports should be written, and not just for contractual obligations. Few people other than the client and partners read final reports, whereas peer-reviewed publications in scientific journals reach more people and establish stronger credibility for the methodology that can be cited in NEPA documentation. However, peer-reviewed papers often lack practical results (**Figure 15**) because of page limitations and a greater interest in testing hypotheses than solving local problems. We try to write both; however, peer-reviewed publications are only submitted if they contain an innovation.

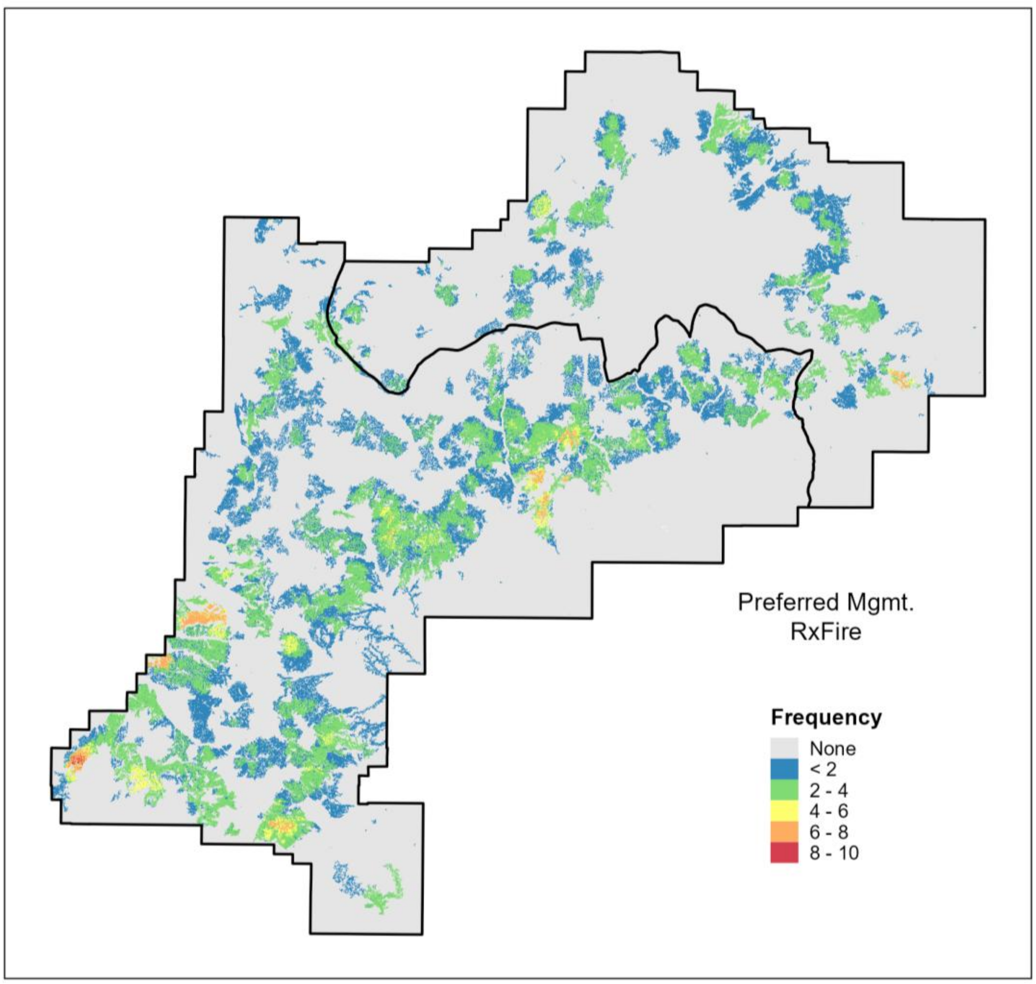


Figure 15. Frequency raster of prescribed fire (RxFire) implementation created by ST-Sim where frequency is evaluated over years and replicates.

Our final reports follow an established structure:

1. Comprehensive methods for:
    a. Presentation of guiding objectives.
    b. Remote sensing, especially a description of its mapping challenges and solutions (often appreciated by managers).
    c. Vegetation map preparation.
    d. Development of state-and-transition simulation models (with details in appendices).
    e. Management scenario development.
    f. Implementation of temporal variability.
    g. Metric(s) of success.
2. Results by only focal ecological system presented in forms:
    a. Area of ecological system.
    b. Current ED or UED.
    c. Table of area and proportions of vegetation classes and reference condition.
    d. Problems to address.
    e. Treatments used to solve problems.
    f. Total cost of scenarios (often in a chart).
    g. ED or UED of each scenario at fixed intervals (e.g., every 10 years) and end of simulations.
    h. If applicable, eROI.
    i. Charts of area of problem vegetation classes over time with all scenarios and error bars.
    j. Charts of area of recipient vegetation classes (e.g., seedings) over time with all scenarios and error bars.
3. Frequency map for fire and all treatments presented in panel with one active management scenario per panel (all scenarios for fire).
4. Discussion and conclusions.
5. Literature cited.
6. Appendix of coding scripts, vegetation descriptions, table of all model transitions, and, if applicable, habitat suitability models.

The modeler might be tempted to describe in words the model dynamics. Such effort is substantial and might rival in number of pages the actual final report. The ST-Sim library contains all that information; therefore, it might more sense to refer the committed reader to the library and suggest model training.

Chapter 8 – Next Steps

The conservation challenges that STSMs might help solve will be different in 5 and 10 years from now. However, note that even the application of traditional STSMs supplemented with non-spatial ecological departure in large complex landscapes does help solve major problems for land managers. Solutions to the three key challenges described below could provide important information for conservation, but we do not yet have those solutions or even prototypes.

Figure 16. Ancient bristlecone pines at Great Basin National Park. Mt Moriah is in the distance. Looking far ahead is important in conservation science.

Clustered Systems for Very Large Landscapes

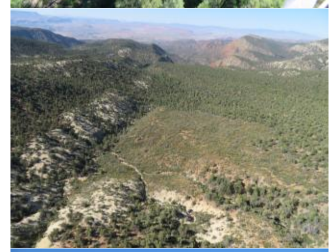
STSMs couched as clustered systems first emerged from our futile effort to model greater sage-grouse habitat management sub-regionally or range wide. The current range of greater sage-grouse touches eleven US states and one Canadian province (USFWS 2013)! In addition to specific wildlife conservation issues, The Nature Conservancy might think of positioning itself to provide spatial forecasting of management products and services to federal land managers at the very time federal agencies are losing scientists that often work at the scale of large landscapes.

The exploration of clustered systems should be important to The Nature Conservancy because we have no spatial tool to forecast over decades the siting of vegetation treatments by land ownership in very large areas of interest (>2 million acres or >809,000 ha) that are, critically, NEPA-ready and will survive litigation. LCF focused on landscapes made of many single systems (the current approach) works well on up to 2 million acres (809,000 ha), but ecological and logistic complexity and limitation of ecological knowledge increase with landscape size. In contrast, producing NEPA-ready deliverables means that modelers maintain high spatial resolution and sufficiently detailed STSMs contain realistic treatments. NEPA readiness and LCF for very large landscapes, therefore, appear incompatible.

We propose that as project complexity increases with landscape size, modelers should strive to simplify the user's experience of STSMs to reduce complexity and reduce project cost. Clustered systems achieve that because fewer systems make remote sensing easier and 20% to 30% cheaper compared to single ecological-system LCF, and the number of systems to model is substantially smaller. These two substantial gains in simplification; however, create new challenges to spatially control transitions along soil productivity gradients (see above in "Spatially-explicit and Stochastic Ecological Departure" sub-section) and handle an enormous number of pixels computationally.

Mapping soil productivity to influence an STSM transition is a difficult undertaking because of the size of the area of interest and the ecological relationships that need to be investigated. Moreover, each of many transitions that respond to soil productivity require a spatial control raster, whereas invariant transitions require none. We suspect that soil productivity mapping will involve a combination of a soil moisture metric, such as vapor pressure deficit (Anderson 1936) corrected for aspect and elevation (such as the HIL index, McCune and Keon 2022), and soil texture and composition data most likely from the US Geological Survey Polaris data (Chaney et al. 2016). Developing different algorithms that convert various pixel attributes of soils combined with soil moisture to create a unique spatial control raster for each transition (e.g., tree invasion) is a huge challenge that needs to be resolved.

The other difficulty of clustered systems is the number of pixels in very large landscapes that exceed the capacity of computer memory or consume most of the memory and render simulations computationally glacial. First, powerful Cloud servers will be needed to handle simulations, but these resources are not free. Second, ApexRMS, the creators of Syncrosim and ST-Sim, might need to make a sub-regional version of ST-Sim that does not debilitatingly task the memory of the software or computer. The Nature Conservancy is not in the business of coding software. Regardless, possible pathways include:



(i) Replacing the two uploaded ecological system and vegetation class rasters with one raster, thus cutting in half the number of pixels to upload and making the software handle the concatenation process that distinguishes between ecological systems and vegetation classes (this will slow simulations but help the limiting factor of insufficient RAM),

(ii) Externally reading initial condition rasters by one large but RAM-acceptable segment (or tertiary strata) at a time that are dynamically self-contained but from which boundary conditions of disturbances that spread at their segment's edge (fire, exotic species) are retained at the boundary of the next zone (fire entering the next segment),

(iii) Parallel processing by tertiary layer (segments) if RAM allows, an existing property of ST-Sim (normally, tertiary stratification with parallel processing would apply *within* a segment as The Nature Conservancy imagines one to be large enough to contain its planning zones),

(iv) Imposing limits on the number of transitions in definitions to keep models compact (i.e., use more generic treatment names where variation in the cost per unit area indicates more complex implementation),

(v) Modernizing the Distributions menu to allow entry of continuous functions that process external variables while not allowing calls to statistical functions (these are only needed when transition variability is *de novo* and not from external variables), and

(vi) Considering the concept of mirroring, a speculative concept, where a subset of values created by internal software operations to simulate transitions in one segment are stored and reasonably used in other segments, thus not requiring new operations. The assumption, perhaps naïve, is that similar regions will share similar dynamics as if there were parallel universes. For example, the number of fires per year in Nevada, southern Idaho, and western Utah's rangelands will be more similar than any of those to forests in the Wasatch Range of Utah.

Accelerating Spatially-explicit and Stochastic Ecological Departure

We have done a nice job of optimizing the Python code to estimate spatially-explicit and stochastic ecological departure, especially the time-consuming moving windows around each pixel of the current vegetation and each of replicate reference condition rasters. Our moving window calculations include *all* pixels in the moving window, which is the elephant in the room to address here. Imagine computational time from extrapolating moving window operations from a taxing 300,000-acre landscape to the entire Great Basin ecoregion.

The number of pixels in a moving window is large, and this number geometrically increases as raster resolution becomes finer or the radius is increased. In statistical jargon, our Python script processes the entire population of pixels of an ecological system. One computational innovation could be to randomly sample a subset of the population of pixels. Instead of the 10,000 pixels in the moving window, sample 1,000, but not 30, to estimate vegetation class proportions. Another trick might be to parallel process each pixel and its moving window, which is possible in R, Python, and Pearl.

Rewriting hydrological models to work with STSMs

We used hydrological models with STSMs in the Middle Truckee River and the south Snake Range (NV). The questions asked are often to investigate the effects of vegetation management or climate change on hydrologic resources or to estimate water quantities for native fish habitat suitability models. ST-Sim is not coupled to the hydrological models through external programs because many hydrological models are coded in Fortran (do not interface with the External Programs menu), require manual entry of parameters at each timestep, or use completely different thematic categorization of vegetation, and often do not respond to variation in vegetation management [except the US Geological Survey's Basin Characterization Model (Flint et al. 2021)]. In other words, modelers of land management and watershed hydrological processes view the world very differently, thus creating near incompatible modeling platforms. We want to remove that barrier because dynamically simulating the effect of land management on water resources is simply too important to not be modeled with high sophistication.

We propose that preferred raster-based hydrological software be recoded in Python (whereas R is too slow and memory intensive), made dynamic, responsive to vegetation classes canopy cover and structure, and able to interact through Syncrosim. We prefer the US Geological Survey's Basin Characterization Model because it is raster based and responds to variation in canopy structure and closure (Flint et al. 2021); however, being a water balance model, it estimates runoff and recharge per pixel (and several other metrics) using process-based physical equations but is only empirical when runoff is calibrated to US Geological Survey water gages.

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