CHAPTER 9

Terrestrial Ecosystems of South America

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ABSTRACT

Standardized terrestrial ecosystems of South America were mapped using a biophysical stratification approach, and employing an ecological systems classification recently developed for Latin America and the Caribbean. The classification effort involved the development of diagnostic criteria and names for describing expert-derived ecological systems. The mapping/modeling effort stratified the continent into unique physical environments supporting a variety of land cover types. Ecosystem footprints were delineated by overlaying continental datalayers for elevation class, landform, lithology, bioclimate, and image-derived land cover. Polygonal occurrences of these ecosystem footprints were developed at a working pixel resolution of 450m (20 hectares). The ecosystem footprint polygons were subsequently labeled using the standardized ecosystems. 659 ecosystem types were identified and mapped across the South American continent; by comparison there are 110 World Wildlife Fund (Olson et al., 2001) terrestrial ecoregions. These standardized ecosystems, mapped for the entire continent at a relatively fine scale, are useful for a variety of biodiversity conservation and resource management applications. These data can be used to identify areas deserving of management attention due to their value for biodiversity conservation, as well as the production of ecosystem goods and services (e.g., food, water, fuel, fiber, forage, etc.).

Key words: *biodiversity conservation, biophysical stratification, ecosystems, ecosystem classification, ecosystem management, spatial analysis, spatial planning*

INTRODUCTION

In their seminal work on ecology, the Odum brothers (Odum, 1953) described ecosystems as systems of biotic communities interacting with their physical environment. Since the publication of that early textbook on ecosystem science, ecosystems have largely been recognized as scaleless, varying in size from a whole forest to a small pond, even from the entire biosphere to a small speck of dust. Bounding the area within which organisms interact with their physical environment has always been an interpretive exercise, and depends on the biotic and abiotic components of interest, and the application at hand. As such, various kinds and sizes of ecosystems have been recognized, classified, and mapped. These range from large, coarse scale ecosystems, or ecoregions (Omernik,1987; Bailey, 1996; Olson et al., 2001), to smaller, fine scale environments that support particular biotic assemblages (Franklin, et al., 2002).

Spatial delineation of ecosystems is a difficult undertaking because ecosystems are inherently complex, changing through both space and time. However, recent interest in conserving ecosystems for both biodiversity and ecosystem service values (Millennium Assessment, 2005; Heinz Center 2006) has led to a need for improved knowledge of ecosystem types and distributions on the landscape. Managing the variety of resources within ecosystems (e.g. water, forests, wildlife, etc.) may best be accomplished by an ecosystem-based management approach (Convention on Biological Diversity, 2000), which requires that ecosystems be delineated and their occurrences considered as management or conservation targets (Redford et al, 2003). Ecosystems of regional extent, or ecoregions (Bailey, 1996), are appropriate for use as large (1000s to 10,000s km^2), ecologically meaningful planning units, and have been globally delineated (Bailey, 1996; Olson et al., 2001), but are generally too coarse for on-the-ground management applications. Finer scale ecosystems are more appropriate for local management applications. A conceptual hierarchy relating ecological complexity and scale of management applications is presented in Figure 1, which distinguishes between ecoregions as coarser scale planning units and ecosystems as finer scale management or conservation targets.

There are several applications for which meso-scale ecosystems (10s to 1000s of hectares) are useful. Many conservation priority setting approaches are based on an analysis of the species and

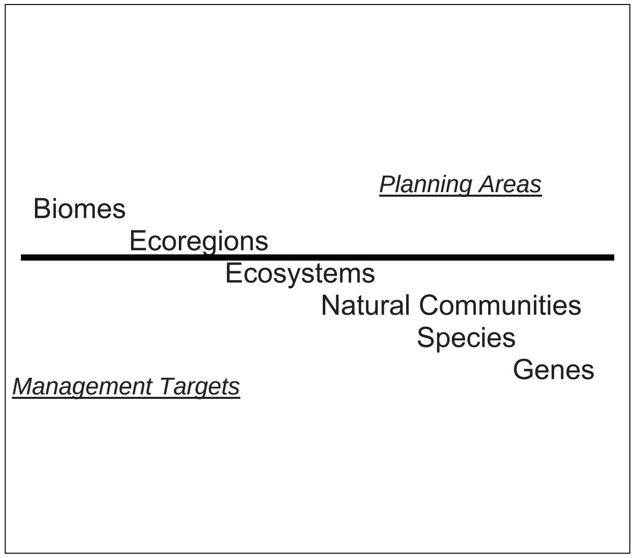

Figure 1 - Ecosystems as conservation targets.

ecosystems occurrences within a particular geography (often an ecoregion) to determine which of these conservation target occurrences merit inclusion in a portfolio of conservation areas or strategies (Groves, 2003). Biodiversity conservation gap analyses (Scott et al., 2001; Rodrigues et al., 2004; Dudley and Parrish, 2006) examine the extent to which species and ecosystems are represented in areas designated for conservation – these gap analyses require good maps and data on the distribution of ecosystems. The Convention on Biological Diversity (CBD) mandates signatory nations to design ecologically representative networks of protected areas, and encourages national and regional gap analyses of ecosystems to identify unrepresented and under-represented ecosystems (Convention on Biological Diversity, 2004). The emerging science of economic and societal valuation of ecosystem goods and services similarly requires a geospatial ecosystems framework to be able to attribute ecosystem service values in a spatially explicit manner to individual ecosystem occurrences on the landscape (Millennium Assessment, 2005).

Although ecosystem classifications and maps exist for several South American countries, there was no single, standardized classification or map of ecosystems for the continent at the start of the 21st century. This lack of critically important conservation and management information was addressed in a collaboration to classify and map standardized, meso-scale ecosystems for South America.

APPROACH

Ecological systems, defined as spatially co-occurring assemblages of vegetation types sharing a common underlying substrate, ecological process, or gradient, have been identified for all of Latin America and the Caribbean (LAC) in a recent classification effort by the conservation non-governmental organization NatureServe (Josse et al., 2003). That classification work, which enlisted the support of several LAC regional vegetation specialists, produced a list and description of 780 ecological system types for the region, but the on-the-ground occurrences of these ecosystems were not mapped as part of the classification effort. Diagnostic classifiers such as climate type, topographic position, and substrate type were developed to differentiate ecosystem types according to the physical environments in which the vegetation assemblages were located.

In addition to lists and descriptions, conservation planners and resource managers need maps of the types and locations of the ecosystems they seek to manage. To extend the utility of the ecosystems classification for South American managers and conservationists, we developed a standardized method to map the on-the-ground occurrences of these terrestrial ecosystems at a relatively fine spatial resolution (450m) for the whole continent.

The mapping method is derived from a fundamental consideration of ecosystem structure. Ecosystems are composed of both physical and biological structural elements. An ecosystem at any point is an integrated expression of these structural components, vertically organized (from top to bottom) as climate, landform, surface and sub-surface waters, soil, and bedrock, with biota occurring essentially throughout (Bailey, 1996). It follows that ecosystems can therefore be spatially delineated by mapping and integrating these structural components in geographic space, and that ecosystem boundaries will represent area-based changes in the structural components.

A continental biophysical stratification approach was adopted to delineate ecosystem footprints as unique physical environments that support a particular land cover type. The resulting ecosystem footprints were subsequently labeled (attributed) using the ecological systems classification described above. This two step process is diagrammed in Figure 2.

The biophysical stratification approach involved the development of continent-wide data surfaces for

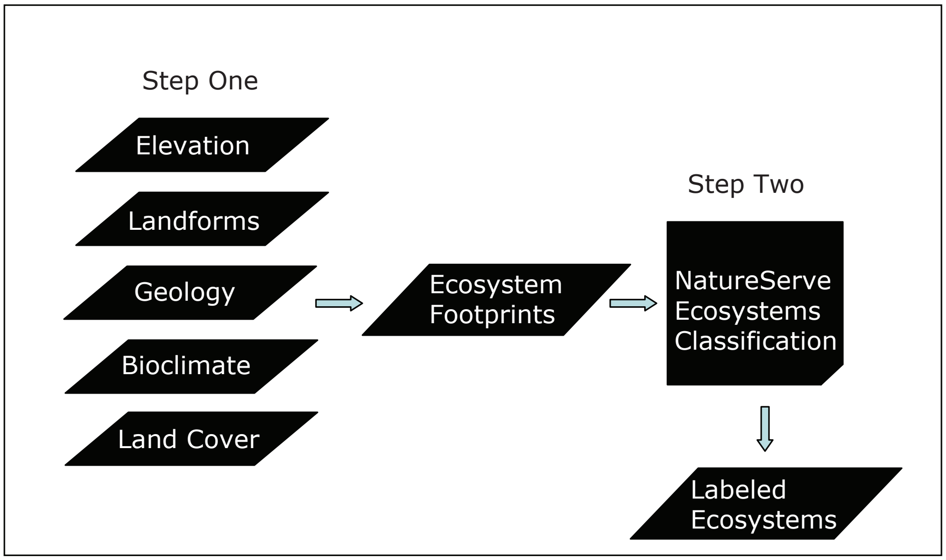

Figure 2 - Biophysical stratification approach to delineate ecosystem footprints as unique physical environment/land cover combinations. Ecosystem footprints were subsequently attributed with NatureServe ecological system labels.

each of four physical environment variables: 1) elevation class, 2) landform, 3) lithology, and 4) bioclimate region. These were combined in a continental, GIS-managed union of the four datalayers to produce a map of the unique physical environments of South America as defined by these four physical environment parameters. Land cover for the continent was also added into the overlay to identify the land cover types located within the abiotic ecosystem footprints. In addition to the general methodological descriptions that follow, detailed procedures for this approach are further characterized in Bow et al. (2005).

METHODS

Historically, terrestrial ecosystems have been defined from a wide variety of perspectives, with emphases on ecosystem function and processes (Bormann and Likens, 1979), physical factors that structure the system (Bailey 1996), and as fundamental elements of biodiversity (Groves, 2003). We incorporate all three of these perspectives in our consideration of terrestrial ecosystems as groups of plant community types that tend to co-occur within landscapes with similar ecological processes, substrates, and/or environmental gradients. Ecological processes include natural disturbances such as fire and flooding. Substrates may include a variety of soil surface and bedrock features, such as shallow soils, alkaline parent materials, sandy soils, or peatlands. Environmental gradients include local climates, hydrologically defined patterns in coastal zones, arid grassland or desert areas, or life zones in mountainous areas. A given terrestrial ecological system will typically manifest itself in a landscape at intermediate geographic scales of 10s to 1000s of hectares and persist for 50 or more years.

The ecological systems of Latin America and the Caribbean were developed by vegetation scientists and landscape ecologists in a series of four regional classification development workshops. In these expert workshops, diagnostic classifiers were developed to explain the spatial co-occurrence of natural communities; diagnostic classifiers included bioclimate, biogeographic history, physiography, landform, physical and chemical substrates, dynamic processes, landscape juxtaposition, and vegetative structure and composition. In these workshops, and with subsequent classification development by additional regional vegetation experts, a total of 780 ecological systems were listed and described for Latin America and the Caribbean. The classification, as with all classifications and maps, is still evolving, with the addition of new ecosystem types as they are described and reviewed. The classification is available at (http://www.natureserve.org/getData/LACecologyData.jsp).

<u>Elevation Class</u> – A 90 m digital elevation model (DEM) for the continent was created from Shuttle Radar Topography Mission (SRTM) data. A seamless, continent-wide dataset was produced and processed to remove no-data values and spurious sinks and spikes. To facilitate processing, the 90 m resolution dataset for the continent was resampled to a 450 m resolution. The following elevation classes were identified and mapped according to their floristic importance in determining South American vegetation distributions: 0-500 m, 500-1000 m, 1000-2000 m, 2000-3300 m, and > 3300 m (Eva et al., 2002; Navarro and Maldonado, 2002).

<u>Landforms</u> – The 450 m continental DEM was also used to produce a continent-wide landforms datalayer, with all pixels assigned into one of the following regional physiographies: plains, rolling plains, hills, mountains, plateaus, valleys, floodplains, and coastal plains. The methodology for the landform class derivation employed a 5 by 5 cell moving neighborhood analysis window to assess relative relief, and followed other regional scale approaches to model macro-landforms (Hammond, 1964; Dikau et al., 1991; True et al., 2000). Four landforms; plains, rolling plains, hills, and mountains

were first modeled for the entire continent; coastal plains, floodplains, valleys, and plateaus were subsequently independently derived and overplotted on the underlying plains/hills/mountains matrix.

Geology – A continental geology dataset was acquired which had been derived from a recent digitization of the geological survey maps of each South American nation by Geologic Data Systems, Denver, Colorado, http://www.geologicdata.com/). This datalayer was developed from 1:500,000 scale sources for all countries except Brazil, which was developed from 1:1,000,000 scale maps. For our ecosystem mapping purposes, the South America geology data were reclassified into the following lithological classes: zonal, sedimentary, limestone/calcareous, alluvium, salt, glacial, and unique. This classification was developed to identify general lithological substrates which give rise to distinct vegetation distributions at regional or continental scales (Kruckeberg, 2002).

Bioclimates- Bioclimate regions were developed using the 1 km^2 resolution WorldClim (Hijmans, et al. 2005) global meteorological raster data and formulas developed by Rivas-Martinez (Rivas-Martinez and Rivas y Saenz, 2007) to delineate isobioclimate regions. The Rivas-Martinez approach quantitatively defines five macroclimate regions for the planet (polar, boreal, temperate, mediterranean, and tropical), and then subdivides these into finer bioclimate regions using meteorological data synthesized into indices of continentality, thermicity, and moisture.

Global Land Cover- The Global Land Cover 2000 (Eva at al., 2002; Mayaux et al., 2006) dataset was acquired for South America. This dataset has a spatial resolution of 1 km^2, and a classification resolution of 73 land cover classes for South America, which were subsequently reclassed into 26 land cover types.

Ecosystem Footprint Generation- Ecosystem footprints were generated by combining each of the raster input datalayers (elevation class, landform, lithology, bioclimate, and land cover) in a continent-wide, non-hierarchical, spatial union. These five input data grids were combined to produce a new continental ecosystems raster data surface where each cell was labeled with a unique grid code. The numeric value of each grid code was designed to be additive, in order to retain the values of the original input classes in the resulting label. For example, the unique grid code 1742020 represented: 1000000 (elevation = 0 to 500 m), + 700000 (landform = floodplain), + 40000 (lithology = alluvium),

+ 2000 (bioclimate = tropical pluvioseasonal), + 20 (land cover = broadleaf deciduous tree cover).

Unique gridcodes were modeled for all parts of South America, except the Galapagos and Falkland Islands, and then evaluated and attributed to one of NatureServe's ecological systems.

Labeling of Ecosystem Footprints – The ecosystem labeling step was an automated matching approach to associate the ecosystem polygons and their grid codes with an ecosystem type from the NatureServe LAC Ecological Systems classification. Independent of the mapping work, the NatureServe ecological systems were characterized and attributed for the elevation class, landform, lithology, and bioclimatic region within which they were expected to occur, and the land cover type they were expected to contain. This information was organized in a matrix of ecosystem types and their attribute classes, and was used as a labeling look-up table in the GIS.

Accuracy Assessment – Ideally, a verification of the mapped ecosystem occurrences would be conducted in an extensive field campaign with stratified random sample points generated and visited to collect information on the elevation, landform type, lithology, bioclimate region, and land cover. Such a field verification effort was not possible within the scope of this project, but a rigorous comparison analysis was conducted. Twenty one mapped representations of vegetation, land cover, habitats, and ecosystems at national and regional scales throughout the continent were acquired and evaluated for suitability in the comparison analysis. Of these, seven sources were judged acceptable for use in a comparison analysis and their classes were crosswalked into the NatureServe classification logic and used as "reference" data for the comparison. A stratified random sampling was conducted for each ecosystem type in nine biome-representative WWF ecoregions (Olson et al., 2001) across the continent. The ecoregions were used as a stratification unit for the assessment, and were not one of the seven comparison datasets. A traditional accuracy assessment analysis was implemented to produce Kappa statistics, user's accuracy, and producer's accuracy on every ecosystem type in each sampled ecoregion. 75-100 twenty hectare hexagon sample units were randomly generated following the sampling adequacy suggestions of Congalton and Green (1999), who suggested a target sample size of 75-100 samples for every class in any classification scheme where the number of classes exceeds twenty. If the number of ecosystem occurrences in the sampled ecoregion was insufficient to meet this target sample

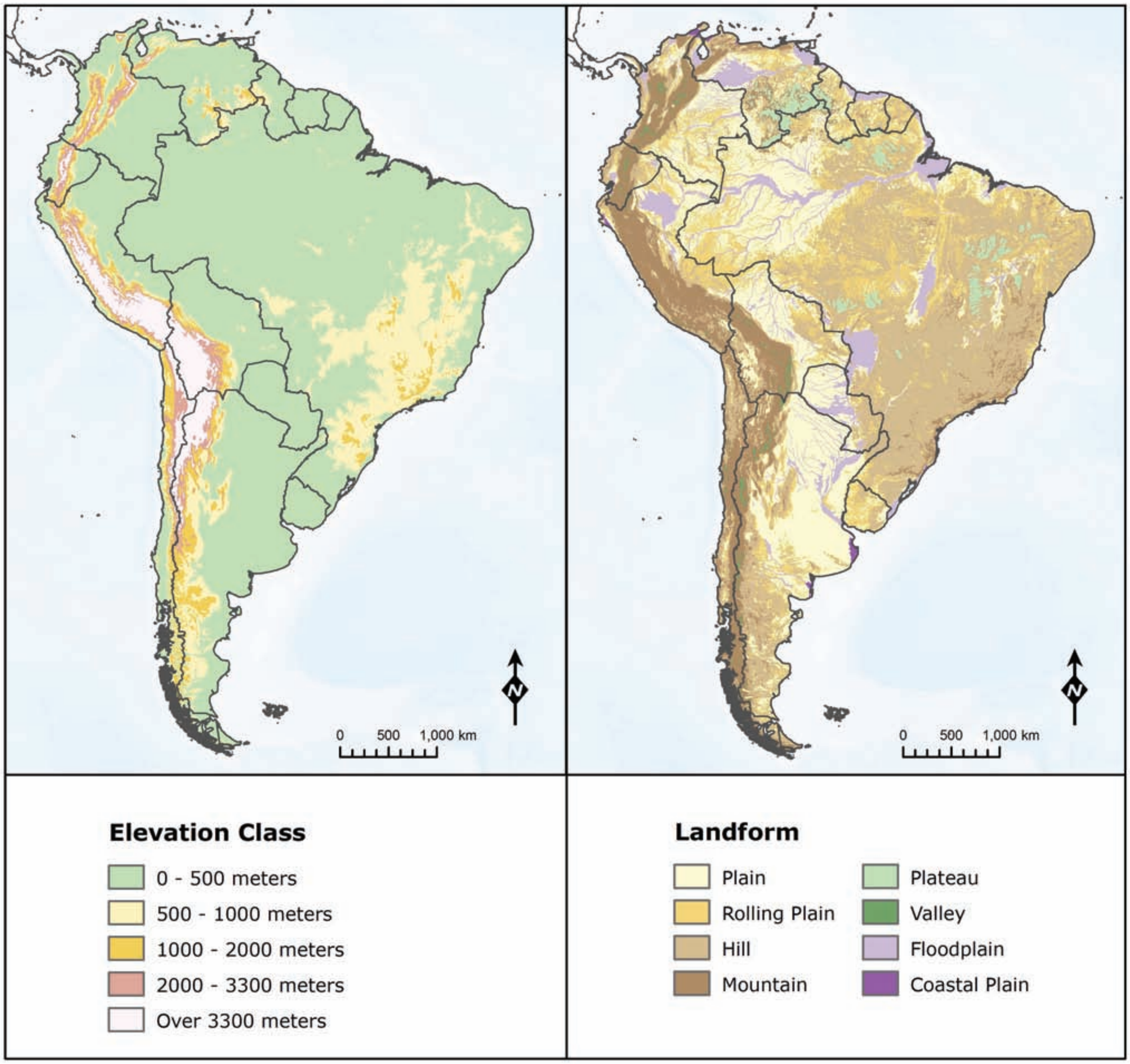

Figure 3 – Elevation classes and landforms of South America, derived from a continental 450 m digital elevation model.

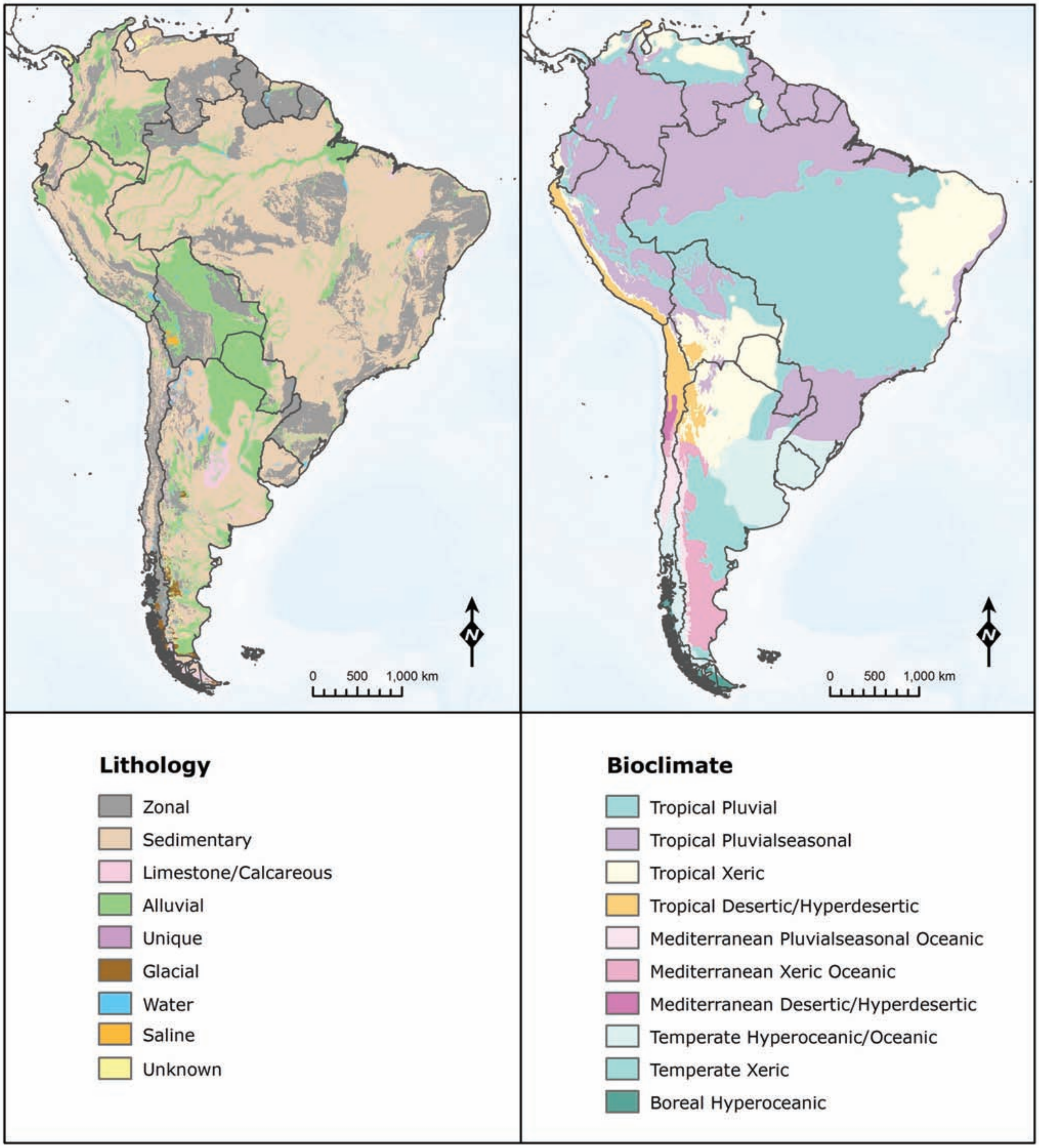

Figure 4 – Lithology and bioclimates of South America. Lithology data were reclassed from a continental geology data-layer of spatially joined national geological maps at generally 1:500,000 scale. The bioclimate regions were modeled from 1 km^2 temperature and precipitation data.

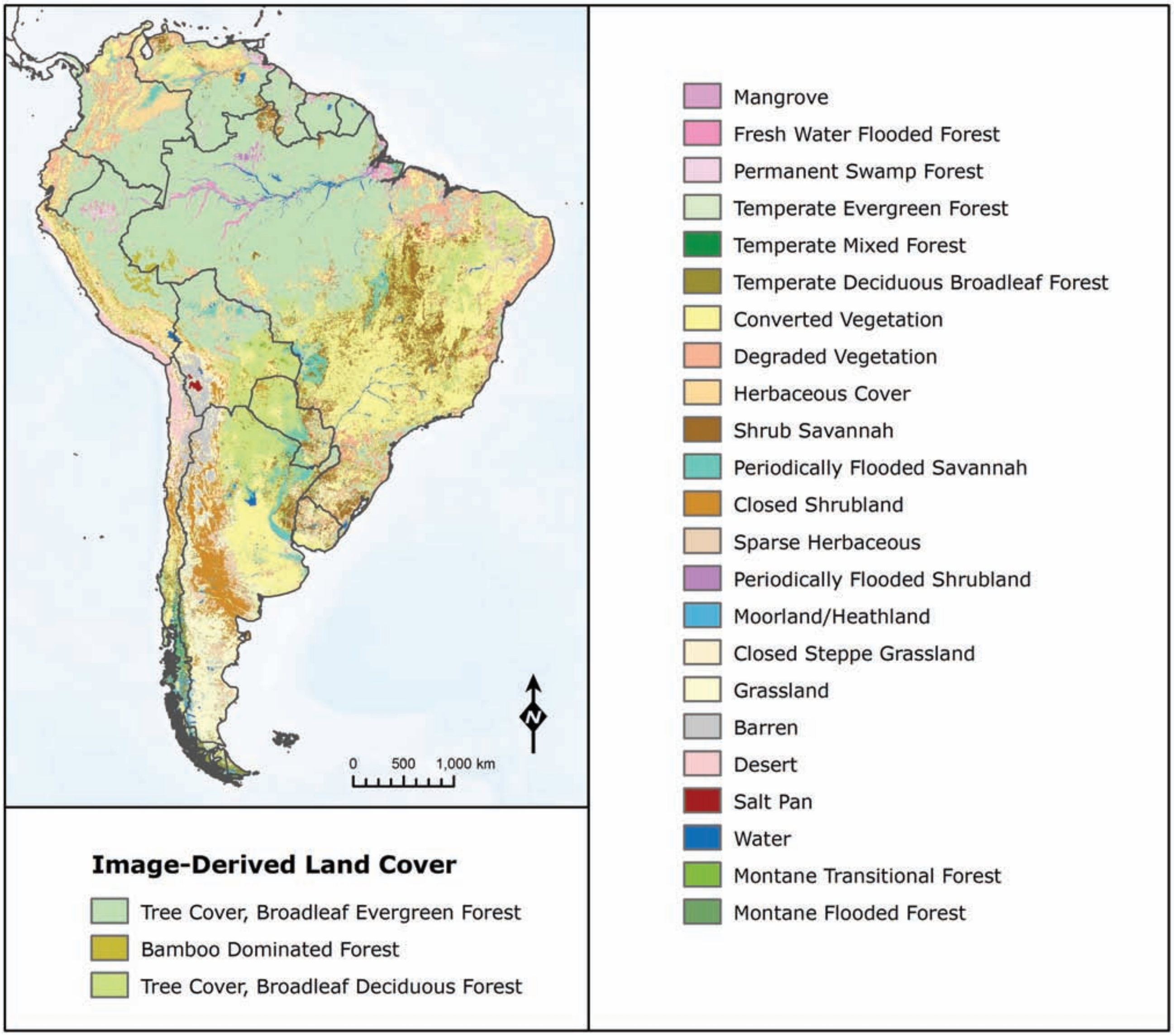

Figure 5 – Land cover of South America, from the 1 km^2 GLC 2000 (Eva et al., 2002) global land cover data, resampled from 76 to 23 classes.

number, all occurrences were sampled. A 500 m buffer and a 2500 m minimum distance between samples were used in the random sample selection process to address the issue of spatial autocorrelation. The minimum sample distance was reduced to 1000 m if the larger sample distance generated fewer than 75 samples. The mapped ecosystems in the hexagon sample units were compared with the reference data, and a crosstabulation matrix, with producer's and user's accuracy, was developed for each sampled ecoregion.

RESULTS

Input Layers – Continental data surfaces were developed for elevation class (Figure 3), landform (Figure 3), bioclimate region (Figure 4), lithology (Figure 4) and land cover (Figure 5). In addition to their use as core data inputs into the ecosystem footprint delineation process, these four continental data surfaces also describe the physical geography of the continent in general. The five elevation bands and the eight landform classes were modeled at a 450 m resolution from a 90 m DEM and characterize the regional physiography of South America in a digital data format heretofore unavailable at any spatial resolution. These "intermediate" products are intrinsically useful for a variety of engineering, land planning, and resource management applications apart from ecosystem delineation and conservation priority setting. The landforms map, in particular, could be useful for much of the infrastructural development planning underway throughout the continent.

Ecosystem Map – The resulting map of standardized, meso-scale terrestrial ecosystems of South America is shown in Figure 6. The combination of input datasets produced a total of 9,352 unique gridcodes, identification codes for each grid cell. Vector polygons were created from contiguous raster cells with the same gridcode in a standard raster-to-polygon conversion, and these ecosystem footprints were labeled to produce a total of 659 unique, mapped, multi-occurrence ecosystems for South America, with a 20 hectare minimum mapping unit. An additional five ecosystem classes (barren, converted, degraded, unknown and water) were also mapped, as identified from the global land cover data. These extensive areas of converted classes are very evident in the Cerrado and Caatinga regions of Brazil, and are likely soy production. Figure 7 shows a subregion of the continental eco-

Figure 6 - Ecosystems of South America. 659 ecosystems were identified and mapped at a 450 m working resolution.

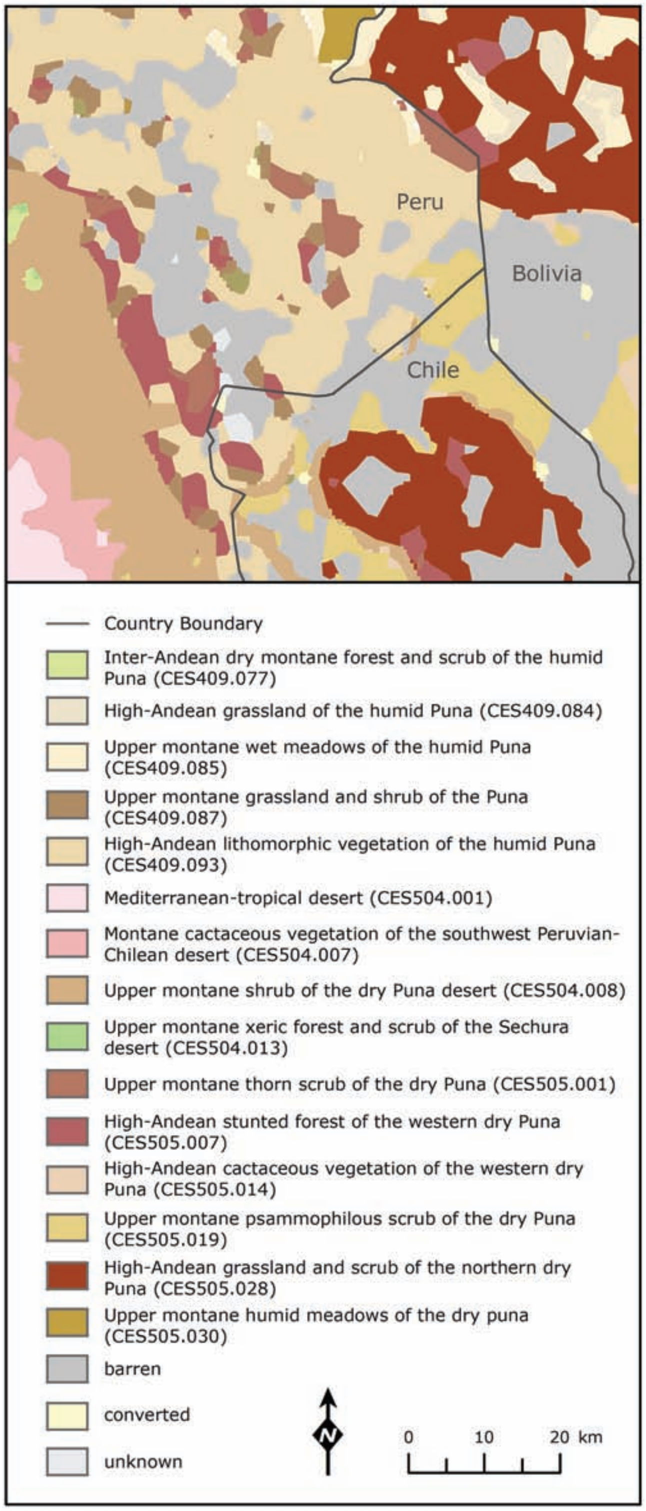

Figure 7 – A subset of the South American ecosystems as they occur near the Peru/Bolivia border, showing the detail in the polygon occurrences and classification resolution.

Ecological System Code	***User's Accuracy***	***Producers's Accuracy***
CES408.523	40.1	85.71
CES409.039	36.1	64.29
CES409.079	12.9	40.1
CES409.095	2.56	6.45
CES409.105	53.33	16.19
CES409.110	61.69	70.31
CES409.112	44.44	69.71
CES409.123	21.21	16.28
CES409.900	79.67	51.49
CES409.903	28.45	62.67
Converted	55.56	34.3

Table 1 – Accuracy assessment results presented for one ecoregion, the Eastern Cordillera Real Montane Forests (Olson et al., 2001). Overall accuracy for this ecoregion was 41.2% (KHAT Value: 0.345377; Variance: 0.00008465; Z Statistic: 37.539). Individual accuracy statistics for the four ecosystems occupying the majority of the area (area data not shown) of the ecoregion were: CES409.110 (61.7%); CES409.112 (44.4%); CES409.900 (79.7%); and CES409.903 (28.5%).

systems map, zoomed in to the area near the intersection of the Bolivia, Peru, and Chile borders. This map provides an illustrative sense of both the classification nomenclature and spatial resolution of the data at an on-the-ground management scale.

The labeling process, although intended to be automated, was complicated due to a strong many-to-one relationship between gridcodes and ecosystem types. The automated search for specific ecosystems based on their expected elevation, landform, geology, bioclimate, and land cover characteristics was confounded by ecosystems with multiple class values in the data input variables (e.g. the same ecosystem could exist in elevation classes 0-500 m, and 500-1000 m). Gridcodes not assigned into an ecosystem class by the automated labeling procedure described above were therefore subsequently labeled in a manual, interpretive process which considered gridcode similarity (i.e. variation in class values in input variables), and in particular, similarity in land cover types. Ancillary maps, usually national vegetation or land cover maps, were also consulted in the interpretive labeling process.

Accuracy Assessment - Kappa statistics, user's accuracy, and producer's accuracies were calculated for every ecosystem in each of the nine sampled ecoregions. These results are presented for one illustrative ecoregion in Table 1. Accuracies for the nine sampled ecoregions ranged from 25% to 49%, and averaging across all ecosystems that met minimum size and distribution requirements, for all sampled ecoregions, the overall accuracy of the mapped ecosystems is 35%.

DISCUSSION

The ecosystems map provides the first comprehensive and consistent delineation of standardized terrestrial ecosystems across South America at such a detailed resolution (450 m minimum mapping unit). The 20 hectare grain size, and the multi-occurrence nature of these ecosystems permits their use as management targets for a variety of on-the-ground conservation and resource management applications. The 659 multi-occurrence ecosystems are considerably finer in spatial and classification resolution than the 110 largely single-occurrence World Wildlife Fund ecoregions of South America (Olson et al., 2001). The ecosystems data are currently being used by The Nature Conservancy in continent-wide ecosystems gap analyses and conservation priority setting.

An overall accuracy of 80-85% has oft been cited as a recommended target accuracy for land cover maps (Foody 2002). However, this level of accuracy is difficult to obtain in evaluations of detailed ecological system, land cover, and/or vegetation maps. Overall accuracies from five recent accuracy assessment studies were 31%, 42%, 50%, 53%, and 59% (Reiners et al., 2000; Laba et al., 2002; Menard et al., 2002, Wickham et al., 2004; and Lowry, et al., 2005). In all of these studies, user and producer accuracies for individual classes varied widely, highlighting the fact that an overall accuracy value, while simple for users to understand, is not reflective of the often great diversity of accuracies between classes. The low overall accuracy results of these studies are not particularly surprising given the complex nature of ecological/land cover/vegetation data (heterogenous complexes and transitional ecotones) and of the unavoidable subjectivity of the accuracy assessment process itself. Several of these studies conducted secondary fuzzy type assessments, where mapped and reference samples were re-evaluated using different fuzzy metrics and similar classes were considered correct, which improved their overall accuracies (Reiners et al., 2000; Laba et al., 2000; Lowry et al., 2005).

Although the best practical alternative to rigorous field sampling across the continent, the use of a comparison analysis with multiple “reference” data sources as an evaluation of data accuracy was problematic, and likely underestimates the true accuracy of the ecosystems map. On the one hand, an inability to field validate the mapped ecosystems, and a lack of a rich set of high resolution aerial photographs to be used for verification, does require the use of a “next best” accuracy assessment method. However, a comparison analysis is an imperfect alternative because our mapped ecosystems were compared against other interpretations, which could themselves have low accuracy, or which could have been highly accurate, but difficult to satisfactorily crosswalk into our classification. It is also likely that several mismatched classes are ecologically similar and should have been classed as matches, given that there is a gradual continuum from absolutely correct to absolutely incorrect in any accuracy assessment. A fuzzy accuracy assessment (Congalton and Green, 1999) might improve the overall project accuracy and individual ecosystem mapping accuracies. Although not within the scope of this project given the size of the continent and available resources, we suggest a randomized field verification analysis where point data can be collected on both the ecosystems and all of their physical and biological structural characteristics.

This conceptual approach to spatial ecosystem delineation follows a classic tradition of ecogeographic regionalization characterized by Bailey (1996) as the science of ecosystem geography. Bailey generally mapped ecoregions at continental scales based on macroclimate regions, but also proposed mapping of finer scale “landscape mosaics” based on geomorphology in addition to bioclimatic partitioning. We consider the 659 ecosystems of South America to be conceptually and scale-equivalent to the landscape mosaics units proposed by Bailey (1996).

It should be emphasized that this approach uses only the physical and biological components (i.e. structure) of ecosystems to model their boundaries, and does not treat ecosystem function in any way. Classical functional definitions of ecosystems (e.g. open systems defined by energy and matter flows, hydrological and nutrient gradients, and complex processes) do not lend themselves to practical, management-oriented, spatial delineation of ecosystems as they are distributed on the landscape. Nonetheless, ecosystem function is a foundational element of basic ecosystem theory, and the ecosystems of South America merit further study from a functional perspective.

Land cover is used as the sole proxy for the biota that are associated with the physical ecosystem footprints. Land cover data are useful because they are generally comprehensively available, fairly current, accurate, and at a moderate spatial resolution. Good data on biotic distributions (flora and fauna, vegetation) would be preferable to land cover, but seldom exist in standardized maps over large areas.

It should also be emphasized that this map of ecosystems is a temporal snapshot of existing ecosystem distribution in the year 2000 era. Three of the physical components of ecosystems that were used in the delineation process (elevation class, landforms, and lithology) are essentially enduring physical features of the environment, and are not expected to change over time. Both bioclimate region and land cover, however, are likely to change as humans continue to dominate the planet. The ecosystems of South America could easily be remodeled using the same methodology when new land cover and climate data become available. A comparison of the two ecosystem maps would then enable a quantitative assessment of land use and climate change impacts to ecosystem distributions. The ecosystems could also be remodeled, if desired, in a sequential, hierarchical fashion using a nested scales approach such as that of Wascher et al., 2007.

The ecosystems map could represent a useful spatial analytical framework for the design of a monitoring system for associating changes in vegetation with changes in land use. In addition to its potential value for ecosystem monitoring, the South America ecosystems map could be quite useful for the spatially explicit calculation of the economic and societal values of ecosystem goods and services. Once formulas exist for the calculation of these values, the ecosystem polygon occurrences could be attributed for multiple ecosystem services values. Knowledge of the ecosystem goods and service values at the level of the polygon occurrences of ecosystems, and their location in space, will be quite useful for resource planning and conservation priority setting.

CONCLUSION

The South America ecosystems map represents the most comprehensive and finest scale characterization of the integrated physical environment of South America ever attempted, and presents the only standardized, meso-scale classification and map of terrestrial ecosystems of the continent available today. The stratification approach to produce ecosystem footprints as unique physical environments and their associated land cover is highly replicable and exportable to other large regions. The ecosystems datalayer is useful for a number of applications, including the economic and societal valuation of ecosystem goods and services. Land planning relies on the accurate delineation of many spatial entities, including property demarcations and ownership, roads, protected areas, and watersheds, and ecosystems are yet another feature of the landscape that can be mapped at management appropriate scales over large areas, as has been demonstrated herein. These ecosystems footprints also represent logical geographic reference units for assessing the impacts of climate change on South American ecosystems.

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