A National Approach for Mapping and Quantifying Habitat-based Biodiversity Metrics across Multiple Spatial Scales

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Abstract

Ecosystem services, i.e., "services provided to humans from natural systems," have become a key issue of this century in resource management, conservation planning, and environmental decision analysis. Mapping and quantifying ecosystem services have become strategic national interests for integrating ecology with economics to help understand the effects of human policies and actions and their subsequent impacts on both ecosystem function and human well-being. Some characteristics of biodiversity are valued by humans in varied ways, and thus are important to include in any assessment that seeks to identify and quantify the benefits of ecosystems to humans. Some biodiversity metrics clearly reflect ecosystem services (e.g., abundance and diversity of game species), whereas others reflect indirect and difficult to quantify relationships to services (e.g., relevance of species diversity to ecosystem resilience, cultural value of native species). Wildlife habitat has been modeled at broad spatial scales and can be used to map a number of biodiversity metrics. In the present study, we map 20 metrics reflecting ecosystem services or biodiversity features derived from US Geological Survey Gap Analysis Program data for land cover and habitat models for terrestrial vertebrate species (i.e., amphibians, birds, mammals, reptiles). Metrics include species richness for all vertebrates, specific taxon groups, harvestable species (i.e., upland game, waterfowl, furbearers, small game, and big game), threatened and endangered species, and state-designated species of greatest conservation need, and for ecosystem (i.e., land cover) diversity. The project is being conducted at multiple scales in a phased approach, starting with place-based studies, then multi-state regional areas, culminating into a national-level atlas. As an example of this incremental approach, we provide results for the southwestern United States (i.e., states of Arizona, New Mexico, Nevada, Utah, and Colorado) and portions of two watersheds within this region: the San Pedro River (Arizona) and Rio Grande River (New Mexico). Geographic patterns differed considerably among metrics across the southwestern study area, but metric values for the two watershed study areas were generally greater than those for the southwestern region as a whole.

Keywords: Biodiversity, Ecosystem Services, Habitat Modeling, Terrestrial Vertebrates, San Pedro River, Rio Grande River, Western United States

1. Introduction

The discussion for formal maintenance and conservation of biological diversity (biodiversity) was first organized in a cohesive fashion by the United Nations Environment Programme in 1992 at the Rio Earth Summit. A year following, 168 countries signed the Convention of Biological Diversity (CBD)[1] to protect and ensure conservation and sustainable use of biodiversity. The CBD recognized that the Earth's biological resources are essential to human well-being and economic and social development and thus constitute a global asset of crucial value to both present and future generations (Secretariat of the Convention on Biological Diversity, 2005). More recently the United Nations Secretary-General initiated and completed the Millennium Ecosystem Assessment to assess the consequences of ecosystem change for human well-being and the scientific basis for action needed to enhance the conservation and sustainable use of ecosystems. The assessment provided a reaffirmation that sustainable societies are dependent on the goods and services provided by ecosystems, including clean air and water, productive soils, and the production of food and fiber and more importantly, it propagated the ecosystem services paradigm upon which to assess and value biotic resources throughout the world (Millennium Ecosystem Assessment, 2005; Farber et al., 2006). Ecosystem services have been defined in a variety of ways; however, in the end they reflect the basic outputs of ecological function or process that directly or indirectly contribute to human well-being, economy, health, and a sense of security. The central premise

[1] Abbreviations: BIP (Biodiversity Indicators Partnership); CBD (Convention of Biological Diversity); IPBES (Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services); GEO BON (Group on Earth Observatory Biodiversity Observation Network); MEA (Millennium Ecosystem Assessment); GAP (Gap Analysis Program); SGCN (Species of Greatest Conservation Need); ICLUS (Integrated Climate and Land Use Scenarios); IPCC (Intergovernmental Panel on Climate Change); SWReGAP (Southwest Regional Gap Analysis Project); T&E (Threatened and Endangered); TEEB (The Economics of Ecosystems and Biodiversity); UNEP-WCMC (United Nations Environment Programme World Conservation Monitoring Centre); US (United States).

of the ecosystem services framework is that all forms of life on earth (i.e., biodiversity) provide the core benefits that humans derive from their environment and thus are responsible for sustaining human culture throughout the world.

Following the Millennium Ecosystem Assessment, an Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) was formed to conduct periodic assessments of biodiversity and ecosystem services at global, regional, and sub-regional scales. The purpose is to address policy relevant questions, identify emerging issues and research gaps, and identify consistent tools and methodologies that can be operationalized on various scales, regardless of geography (IPBES, 2011). A key part of IPBES is a call for the development of scalable indicators and metrics that could provide thematic assessments and monitor status and trends of biodiversity and ecosystem services across multiple geographies at multiple scales. Other existing international biodiversity initiatives and recently created communities of practice, e.g., DIVERSITAS (Larigauderie et al., 2012), The Economics of Ecosystems and Biodiversity (TEEB, 2010), and Group on Earth Observatory Biodiversity Observation Network (GEO BON, 2010a and 2010b) have engaged in similar calls for action.

Within the US, a National Atlas for Sustainability that relates directly to ecosystem services is currently under development by US Environmental Protection Agency , United States Geological Survey, and other partner organizations. Communities and other decision-making bodies do not have adequate spatially explicit information to fully account for costs, benefits, and trade-offs of ecosystem services. The Atlas is being developed to help fill this information gap. This national effort will include measures of ecosystem services including clean air and water; water supply and timing; flood protection; climate stabilization; food, fiber, and fuels; cultural, recreation, and aesthetic amenities; and habitat to support wildlife of concern (the approach described herein). The National Atlas for Sustainability will be an online decision support tool that allows users to view and analyze the geographical distribution of the supply and demand for ecosystem services as well as drivers of change. This paper focuses only on biodiversity related metrics

Recent approaches to conservation planning have identified land acquisition and conservation for wildlife in response to the decline of biological diversity (Wilson and Peter, 1988; Wilson, 1992; Langner and Flather, 1994; Meffe and Carroll, 1994; Noss et al., 1995), including adaptive management (Ridder, 2008). Coupling biodiversity perspectives with geographical approaches to conservation planning has existed for many years (Burley, 1988; Goldman and Tallis, 2009). This concept was first applied to locating management areas for sensitive Hawaiian birds (Scott et al., 1986) and more recently has been developed broadly for biodiversity conservation purposes (i.e., US Geological Survey Gap Analysis Program) in the continental United States (Scott et al., 1993, 1996; Prior-Magee et al., 2007). Within the Gap Analysis Program (GAP), habitat suitability for terrestrial vertebrates is used to identify gaps in long-term maintenance of elements of biodiversity. The analysis is an approximation of the geographic distribution of natural diversity and the degree to which diverse areas are managed for their natural values to endure. The baseline datasets within GAP, particularly the individual species habitat models, are well-suited for use with the concept of ecosystem services at broad multiple scales.

Regional GAP efforts have progressed to the point that the current emphasis is to finalize national datasets and provide the ability to conduct analysis at local, regional, and national scales (Aycrigg et al., 2011). These efforts provide contemporary methods and data to evaluate the distribution of biotic elements and their conservation status in an ecoregional context without concern for political boundaries, and thus are now focused on providing policy-relevant tools and methodologies that can be easily assimilated into the environmental decision-making processes, regardless of scale or institutional responsibility (see Boykin et al., 2011).

The objectives of the ongoing project reported herein were: (1) to identify mappable biodiversity metrics that reflect ecosystem services (e.g., harvestable species representing recreation and subsistence value) or resources of conservation concern; (2) to map the metrics identified throughout the conterminous United States beginning with selected regions and watersheds; and (3) to compare metric values obtained for multiple areas of various extents, i.e., selected watersheds, regions, and the entire continental US. Herein, we illustrate progress to date by comparing values for 20 biodiversity metrics derived from GAP data for three areas: the southwestern US (5 states) and two areas within this region.

2. Material and Methods

The three study areas were the southwestern US comprising the states of Arizona, Colorado, Nevada, New Mexico, and Utah, and portions of two watersheds within this region along the San Pedro River (Arizona) and the Rio Grande River (New Mexico; Fig. 1). The southwestern US was selected because the Southwest Regional Gap Analysis Project (SWReGAP; Prior-Magee et al., 2007) provided datasets for land cover and predicted suitable habitat models for 817 terrestrial vertebrate species for this region. The other two study areas were selected because they are known areas of high biodiversity and ecological importance (Simpson, 1964; Finch and Tainter, 1995).

The southwestern US (hereafter, Southwest) study area represents approximately 20% of the conterminous United States, encompassing 1,389,000 km^2. SWReGAP mapped 125 land cover types within this region consisting of 109 ecological systems and 16 anthropogenic land cover types (Lowry et al., 2007b). Comer et al. (2003) described ecological systems as “groups of plant community types that tend to co-occur within landscapes with similar ecological processes, substrates, and/or environmental gradients.” The area includes portions of the four North American Deserts, i.e., the Chihuahuan, Great Basin, Mojave, and Sonoran Deserts. The region includes the western portion of the short grass prairies of the American Great Plains, portions of the Rocky and Sierra Nevada Mountains, and the entirety of the

Colorado Plateau. Vegetation types range from alpine tundra in the Rocky Mountains to arid desert scrublands in the south.

The San Pedro study area was delineated by two 8-digit Hydrologic Unit Code units from the National Hydrography Dataset (http://nhd.usgs.gov) comprising the San Pedro River watershed from the Arizona/Mexico border to the river's confluence with the Gila River near Winkelman, Arizona (9,723 km^2 or 0.7 % of the Southwest study area). The San Pedro River flows 230 km from its headwaters in Sonora, Mexico to its confluence with the Gila River. It is one of the last free-flowing rivers in the Southwest (Kepner et al., 2004). It has significant ecological value, supporting one of the highest numbers of mammal species in the world and providing critical habitat and a migration corridor to several hundred bird species (Simpson, 1964; Miller et al., 2002). SWReGAP mapped 34 land cover types within the study area. Vegetation types range from primarily semi-desert grassland and Chihuahuan desert scrub in the southern portions of the watershed to primarily Sonoran desert scrub and semi-desert grassland in the northern portions. This area is home to the San Pedro Riparian National Conservation Area, the first Riparian National Conservation Area designated by US Congress to protect approximately 64 km of river and administered by the US Department of the Interior, Bureau of Land Management.

The Rio Grande study area was delineated by two 8-digit Hydrologic Unit Code units comprising a segment of the Rio Grande River watershed in central New Mexico (8,317 km^2 or 0.6 % of the Southwest study area). The Rio Grande River flows 1,350 km from its headwaters in Colorado to the Gulf of Mexico. The river has multiple impoundments that provide water and recreation to large populations in both the US and Mexico. The study area has significant ecological value, providing critical habitat and a migration corridor to many bird species. SWReGAP mapped 54 land cover types within this area. Vegetation types range from primarily semi-desert grassland and Chihuahuan desert scrub in the lowlands to pinyon-juniper forests in the surrounding mountains. The study area is home to the Bosque del Apache and Sevilleta National Wildlife Refuges.

To develop metrics for biodiversity, we used all the deductive habitat models for terrestrial vertebrates (i.e., amphibians, birds, mammals, reptiles; Boykin et al., 2007) and the digital land cover map (Lowry et al., 2007a; Lowry et al., 2007b) from SWReGAP. These data (http://fws-nmcfwru.nmsu.edu/swregap/) are Imagine (ERDAS, Atlanta, Georgia, US) grid files that utilize predictive environmental variables (e.g., land cover, elevation, distance to water) to derive deductive habitat models for each species. Deductive models use expert knowledge and literature to identify wildlife habitat relationships that are then depicted spatially. SWReGAP modeled habitat for 817 terrestrial vertebrate species that reside, breed, or use the habitat within the 5-state Southwest study area for a significant portion of their life history. Vertebrate models identified presence/absence of suitable habitat for each 30-m pixel (i.e., a binary dataset) with coding reflecting seasonal occurrence (breeding, wintering, migratory). In field validation, deductive model processes were shown to be accurate for modeling species habitat (Boykin et al. 2010).

We used species richness for selected species groups and ecosystem diversity (primarily reflected by vegetation diversity) as metrics that we considered to represent ecosystem services or biodiversity aspects of conservation concern. For example, metrics reflecting harvestable species and high bird species richness provide economic, recreational, and aesthetic value. Species richness and vegetation diversity have been used in prior ecosystem services studies (Egoh et al., 2009). We selected 20 species richness metrics including all species modeled by SWReGAP, and the individual taxa of amphibians, birds, mammals, reptiles; we also included bats as a subset of mammals (Table 1). Federally threatened or endangered species (T&E) also represented a metric. We also included metrics for species regulated by state wildlife agencies, specifically all harvestable species and the designated harvestable subgroups of big game, upland game, furbearers, small game, and waterfowl. Metrics also included Species of Greatest Conservation Need (SGCN) as designated in the Comprehensive Wildlife Conservation Strategies or state Wildlife Action Plans completed by each of the five southwestern states in 2005. The metrics represented all SGCN combined and the individual SGCN taxa of amphibians, birds, mammals, reptiles, and bats. To compute each of the species richness metrics, we combined the binary SWReGAP habitat datasets for the individual species included in a given metric and identified the number of species with predicted suitable habitat for each pixel using ArcGIS 10.1 (ESRI, Redlands, California, US).

To calculate ecosystem diversity, we analyzed the SWReGAP land cover map using a moving window to identify the number of land cover types within a 1-km square centered on each pixel. We consulted with federal and state agencies and non-governmental organizations in stakeholder meetings and scientific presentations to obtain feedback concerning the above metrics (Table 1) and to identify additional metrics for consideration (e.g., climate vulnerable species, economic or recreationally important species, and common but declining species).

Metric values for the three study areas are represented as maps, summary statistics, and frequency histograms. Because data could not be presented for all metrics in some figures, we feature vertebrate species richness, T&E species richness, harvestable species richness, and ecosystem diversity. To facilitate comparison of metric values among the three study areas, we normalized the mean value for each metric for a given study area relative to the maximum value among all pixels in the Southwest study area. Thus, normalized metric values ranged from 0 to 1. For example, a value of 0.5 for a given metric in one of the study areas indicates that the mean metric value is half the maximum value for the metric among all pixels in the Southwest study area. These normalized values are represented for all 20 metrics in a radar graph to provide a single means of comparison (Tallis et al., 2008).

3. Results

Maps of biodiversity metric values reveal conspicuous geographic patterns across the Southwest study area. For example, vertebrate species richness is generally greatest in southeastern Arizona and southern New Mexico, and decreases toward the northwest (Fig. 2 A). Such patterns, however, differ considerably among metrics. For example, in contrast to the pattern for vertebrate species richness, T&E and harvestable species richness are generally greatest in the eastern part of the region, decreasing toward the west (Fig. 2 B, Fig. 2 C), and ecosystem diversity is generally greatest in the central northern part of the region (Fig. 2 D). The shape of the frequency distributions of metric values also differs among the four mapped metrics, and the frequencies of pixels with high values are relatively rare in comparison to the frequencies of pixels with low values (Fig. 3). For example, for T&E species the extent of area in the highest map category (7-11 species) represents 6.1% of the region whereas the extent of area in the lowest map category (1-2 species) comprises 17.5% of the region (Figs. 2 B and 3 B). Similarly, corresponding values for ecosystem diversity for the highest and lowest map categories are approximately 0.3% and 39.4 %, respectively (Figs. 2 D and 3 D). Differences among the three study areas are also apparent. For example, vertebrate species richness appears to be generally greater for both the San Pedro and Rio Grande study areas in comparison to the southwestern region as a whole (Fig. 2 A).

Characteristics of biodiversity metrics are provided in Table 2. For example, of the 817 vertebrate species represented in the Southwest study area, a maximum of 271 are represented in one pixel, and the mean species richness per pixel is 110. Similarly, of the 21 T&E species in the region, a maximum of 11 are represented in one pixel and the mean is 3.8 species. Mean metric values obviously differ among metrics (Table 2, Fig. 4). Birds dominate species richness values, whereas few amphibian species are represented (Table 2, Fig. 4 A). Within the harvestable category, mean species richness is similar for four of the five subgroups (i.e., big game, furbearers, small game, and upland game), whereas mean waterfowl richness is extremely low (Table 2, Fig. 4 B). Variation in metric values among pixels is relatively large for all metrics. For example, coefficients of variation for the metrics featured in Fig. 4 other than waterfowl range between 20 and 61% (i.e., standard deviations represent these percentages of the mean values; Table 2; Fig. 4).

Although comparison of diversity metrics among the three study areas can be made using descriptive statistics (i.e., Table 2, Fig. 4), such comparisons are facilitated by normalizing metric values to the maximum pixel value (Fig. 5). In general, the normalized diversity metrics average greater for the two watershed study areas in comparison to the southwestern region as a whole. Also, most diversity metrics for the San Pedro study area average greater than for the Rio Grande study area. Among the four featured major metrics (i.e., total species, T&E species, harvestable, and ecosystem diversity), however, values for the latter three are similar among the three study areas. Among the harvestable subgroups, metric values for big game, small game, and upland game are greater in the San Pedro study area than the Rio Grande, whereas the reverse is true for furbearers.

4. Discussion

Currently, there is keen interest in developing common processes and methodologies to monitor the status and trends of ecosystem services, especially scalable metrics that reflect biodiversity (Sparks et al., 2011; UNEP-WCMC, 2011; BIP, 2011). However, the services that biodiversity reflects are multi-faceted, such that multiple metrics are needed to provide a comprehensive assessment. We used an approach of combining habitat models (species distribution models) based on input from stakeholders to identify biodiversity metrics of concern. We then clustered the spatial depictions of the habitat models into metrics, and mapped and quantified these metrics for portions of two watersheds and a 5-state region. This approach, including the stakeholder evaluation, can be employed anywhere and at varying scales where datasets such as GAP are available.

We evaluated 20 metrics and focused on four metrics that reflect broad aspects of biodiversity (i.e., all vertebrate species richness, T&E species richness, harvestable species richness, and ecosystem diversity). Total species richness is a fundamental metric of biodiversity that is commonly used to characterize conservation areas of interest (Scott, 1987; Egoh et al., 2009). T&E species and harvestable species are regulated by public law. Species richness for these two groups reflect stakeholder interest and are both directly tied to economic benefit (e.g., hunting industry) and expenditure (e.g., T&E recovery). Ecosystem diversity reflects a mix of environmental and conservation influences such as topography, land use, and fragmentation.

The use of a variety of metrics to represent biological diversity provides users the opportunity to focus on aspects of biodiversity of greatest interest. The relative importance given the biological diversity of an area may differ widely depending on the metric used. Notably, the spatial patterns for the four metrics illustrated by maps in the present study differ considerably. For example, the patterns for T&E and harvestable species richness are generally similar whereas both contrast considerably from the pattern for total species richness. Moreover, the patterns for total species richness and ecosystem diversity show little association, which may partly reflect the different scales for the two metrics (i.e., 30-m pixel for species richness and 1-km window for ecosystem diversity). Among the full suite of 20 metrics, similarities among metric values revealed redundancies. For example, richness for the SGCN taxon groups is similar to values for the parent taxon groups (e.g., SGCN birds vs. all birds). This finding may have accrued because SGCN species comprise about half of the total species. At this stage of development of our approach, however, we have retained all metrics to offer stakeholders a variety of metrics to consider.

The representation of biodiversity metrics at 30-m resolution allows for comparison of many areas within a region and at many scales. The present study compared portions of two watersheds within the southwestern US, but much smaller areas could also be evaluated. Moreover, metrics can be evaluated based on mean values for an area as exemplified by the present study, or by statistics representing particular values, such as high diversity values. For example, waterfowl species richness is high in localized wetland areas, whereas mean waterfowl species richness over a large area is extremely low because of the small extent of wetland habitat in the arid Southwest. In such cases, comparisons of areas may be more meaningful by restricting the analysis to small areas or to certain land cover types.

As these biodiversity metrics are developed and represented as contemporary spatially explicit data, they will serve as a baseline to anticipate future changes to biodiversity and the associated ecosystem services. Changing climate and human population and distribution presents the potential to alter land cover and therefore the habitat that supports biodiversity. For example, the US Environmental Protection Agency developed the Integrated Climate and Land Use Scenarios (ICLUS; USEPA, 2009), which are consistent with the broad-scale Intergovernmental Panel on Climate Change (IPCC, 2001) emission storylines. The scenarios incorporate economic development and population growth's impact on land-use change, specifically housing density and impervious surfaces, based on the 2000 US Census (Bierwagen et al., 2010; USEPA, 2010). Five spatially explicit scenarios are projected in ten year increments from 2000 to 2100 and can be incorporated to model potential changes to climate. Analyzing these future case scenarios in conjunction with the biodiversity metrics will confer the ability to predict areas that will experience the greatest change to biodiversity, as was done in the South Platte River Basin in Colorado, US (Samson et al., 2011).

Ecosystem services are valued by humans in diverse ways and have subjective significance depending on culture and perspectives based on assumed roles, e.g., user groups, resource managers, and regulatory decision-makers. The stakeholder outreach conducted in the present study, i.e., workshop and presentations, yielded a better understanding of the needs and relevance of existing metrics and the identification of additional relevant metrics. Although some of the richness metrics may be useful to some users for characterizing a single area or theme of interest, other users may consider the metrics to be of great utility in addressing biodiversity conservation. Ecosystem services represented by biodiversity may not be provided by the entire ecosystem and the 'service' may only be provided by select sets or groups of species, especially those that provide specific ecosystem functionality or economic incentive (Ridder, 2008).

Multiple national and international (e.g., IPBES, TEEB, GEO BON, DIVERSITAS) outlets are appropriate for the maps and datasets described herein. Our work is a component of the National Atlas for Sustainability that relates directly to ecosystem services and is currently under development by the US Environmental Protection Agency and its partner agencies. The National Atlas for Sustainability will allow users to view and analyze these data spatially and within a framework that simultaneously allows the analysis of multiple categories of ecosystem services, highlighting opportunities for improving the provision of ecosystem services and benefits from the environment. By incorporating sustainability measures related to ecosystems and by linking to other decision support tools, the national atlas will provide an increasingly functional tool to inform decision-making from the national to local scale.

5. Conclusions

The purpose of this initial project was to develop a methodology to map biodiversity and ecosystem service metrics that could be used for comparative assessments in a variety of geographies at multiple spatial scales. The broader focus of our effort, however, was to design a flexible approach for mapping such metrics that could be applied to produce a national-scale product, e.g., a national atlas, which could be used for interpretive assessment, scenario analysis, and decision-making. Our approach uses species distribution models and digital land cover data, and clusters them into functional groups (metrics) identified through stakeholder input and scientific expertise. Input from policy-makers, practitioners, and other stakeholders is key in identifying and prioritizing a diverse set of metrics that reflect different ecosystem functionalities and stakeholder concerns. The approach is convenient by using commonly available spatial datasets (e.g., species distribution models and digital land cover), and flexible by allowing exploration and addition of other metrics as they become identified. This approach also can be integrated with scenario analyses, such as analyses using ICLUS scenarios, to explore future trends in biodiversity that illustrate the implications of policy alternatives, a process that has been envisioned by the Millennium Assessment, IPBES, and a number of other international organizations.

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Figure Legends

Figure 1. Map of the three study areas: Southwest US study area (white), San Pedro study area, Arizona, and Rio Grande study area, New Mexico (black polygons).

Figure 2. Maps for selected biodiversity metrics throughout the Southwest study area: (A) species richness (number of species per pixel) for all terrestrial vertebrates (i.e., amphibians, birds, mammals, reptiles), (B) species richness for federally listed threatened and endangered vertebrates (T&E), (C) harvestable species richness, and (D) ecosystem diversity (number of land cover classes in 1-km square centered on each 30-m pixel). Left polygon outline (black) indicates San Pedro study area, Arizona; right polygon outline (black) indicates Rio Grande study area, New Mexico.

Figure 3. Pixel frequency distribution for selected biodiversity metrics throughout the Southwest study area: (A) species richness (number of species per pixel) for all terrestrial vertebrates, (B) species richness for federally threatened and endangered vertebrates, (C) harvestable species richness, and (D) ecosystem diversity (number of land cover classes in 1-km square centered on 30-m pixel).

Figure 4. Biodiversity metric values for the three study areas for (A) all terrestrial vertebrate species, all amphibians, all birds, all mammals, and all reptiles, and (B) federally listed threatened and endangered species (T&E), harvestable species, the five groups comprising harvestable species (i.e., big game, furbearers, small game, upland game, and waterfowl), and ecosystem diversity. The top of each bar indicates mean number of species per pixel for the species metrics and mean number of land cover classes per 1-km window for ecosystem diversity. Vertical bars indicate standard deviation. Data are from Table 2.

Figure 5. Radar graph for 20 normalized biodiversity metrics for the Southwest, San Pedro, and Rio Grande study areas. Values are computed as mean pixel value for area/maximum pixel value for Southwest study area. SGCN refers to state-designated Species of Greatest Conservation Need.

TABLES

Table 1. Description of 20 biodiversity metrics reflecting ecosystem services or resources of conservation concern.

Metric	Description
Vertebrate Species Richness	Number of terrestrial vertebrate species (i.e., amphibians, birds, mammals, reptiles) as measured by predicted habitat present within a pixel (Boykin et al. 2007).
Amphibian Richness	Number of amphibian species as measured by predicted habitat present within a pixel.
Bird Richness	Number of bird species as measured by predicted habitat present within a pixel.
Mammal Richness	Number of mammal species as measured by predicted habitat present within a pixel.
Reptile Richness	Number of reptile species as measured by predicted habitat present within a pixel.
Bat Richness	Number of bat species as measured by predicted habitat present within a pixel.
All Species of Greatest Conservation Need Richness	Number of terrestrial vertebrate species identified as Species of Greatest Conservation Need by a southwestern US state as measured by predicted habitat present within a pixel (AGFD 2005a, AGFD 2005b, CDOW 2005, NDOW 2005, UDWR 2005, NMDGF 2006).
Amphibian SGCN Richness	Number of amphibian species identified as Species of Greatest Conservation Need by a southwestern US state as measured by predicted habitat present within a pixel.
Bird SGCN Richness	Number of bird species identified as Species of Greatest Conservation Need by a southwestern US state as measured by predicted habitat present within a pixel.
Mammal SGCN Richness	Number of mammal species identified as Species of Greatest Conservation Need by a southwestern US state as measured by predicted habitat present within a pixel.
Reptile SGCN Richness	Number of reptile species identified as Species of Greatest Conservation Need by a southwestern US state as measured by predicted habitat present within a pixel.
Bat SGCN Richness	Number of bat species identified as Species of Greatest Conservation Need by a southwestern US state as measured by predicted habitat present within a pixel.
Threatened and Endangered Species Richness	Number of Federally listed Threatened and Endangered Species as measured by predicted habitat present within a pixel (USFWS 2011)
Harvestable Species	Number of harvestable terrestrial vertebrate species (defined by each states hunting regulations) as measured by predicted habitat present within a pixel
Furbearers	Number of furbearer species as measured by predicted habitat present within a pixel.
Big Game	Number of big game species as measured by predicted habitat present within a pixel.
Small Game	Number of small game species as measured by predicted habitat present within a pixel.
Upland Game	Number of upland game species as measured by predicted habitat present within a pixel.
Waterfowl	Number of waterfowl species as measured by predicted habitat present within a

Metric	**Description**
	pixel.
Ecosystem Diversity	Number of land cover types within a 1-km neighborhood by pixel.

Table 2. Descriptive statistics for 20 biodiversity metrics in the three study areas. For the 19 metrics representing species groups, Total Number of Species/Classes in SW refers to the total number of species in the Southwest study area for the designated species group. Other statistics refer to number of species in each 30-m pixel. For the Rio Grande study area there was a total of 436 species, and for the San Pedro study area there were 452 species. For ecosystem diversity, Total Number of Species/Classes in SW refers to the total number of land cover classes in the Southwest study area. Descriptive statistics refer to number of land cover classes in each 1-km moving window.

Biodiversity Metric (Richness)	**Rio Grande ($9,723\ km^2$)**			**San Pedro ($8,317\ km^2$)**			**Southwest ($1,389,000\ km^2$)**			**Total Number Species/ Classes in SW**
	Max	**Mean**	**SD**	**Max**	**Mean**	**SD**	**Max**	**Mean**	**SD**	
Vertebrate Species Richness										
All	258	141.32	37.33	260	162.72	31.73	271	110.46	37.20	817
Amphibians	7	2.14	0.92	7	1.55	0.87	11	1.41	1.03	37
Birds	154	65.22	22.01	174	76.45	19.73	180	54.94	22.98	435
Mammals	71	50.03	14.00	75	56.71	11.18	78	40.97	12.48	215
Reptiles	49	23.93	11.39	41	28.00	7.69	54	13.14	10.58	130
Bats	18	13.16	2.18	23	17.74	3.66	24	11.23	4.22	30
SGCN Species Richness										
All	111	61.78	17.12	117	73.73	14.17	131	51.33	16.48	396
Amphibians	7	1.70	0.87	8	1.86	1.15	10	1.46	0.89	26
Birds	58	22.71	7.57	67	29.76	6.84	73	21.20	8.22	189
Mammals	38	23.07	5.80	39	25.86	5.25	44	20.71	6.37	104
Reptiles	29	14.31	6.82	27	16.25	5.04	32	7.96	6.95	77
Bats	15	10.44	1.42	18	13.70	2.70	19	3.49	9.01	24
T & E Species Richness	10	4.19	1.56	7	3.89	1.26	11	3.81	1.55	21
Harvestable Species Richness										
All	35	15.60	5.20	36	17.79	3.62	48	14.54	5.23	93
Big Game	8	3.91	1.72	9	5.02	1.77	10	4.17	2.07	15
Furbearers	13	7.34	2.31	10	6.50	1.42	15	6.10	2.12	21
Small Game	20	5.03	2.32	20	6.91	1.95	22	4.07	2.52	36
Upland Game	11	5.26	2.16	11	7.16	1.94	14	4.66	2.22	31
Waterfowl	24	0.33	1.41	23	0.09	0.65	25	0.47	1.89	25

Ecosystem Diversity	13	4.55	1.86	13	5.68	1.73	20	4.45	2.32	125

570 **FIGURES**

571

572 **Figure 1.**

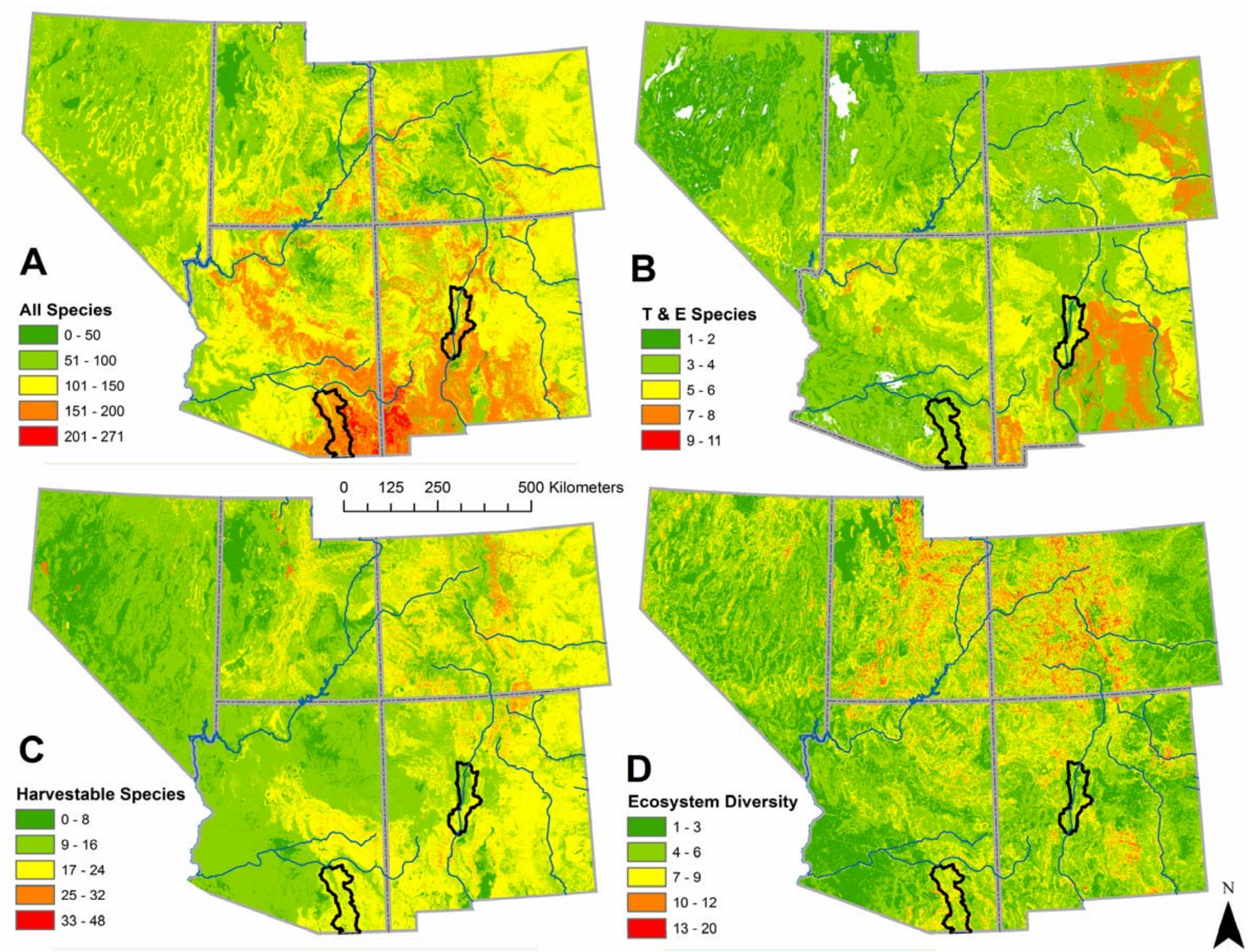

A
All Species
0 - 50
51 - 100
101 - 150
151 - 200
201 - 271
B
T & E Species
1 - 2
3 - 4
5 - 6
7 - 8
9 - 11
0 125 250 500 Kilometers
C
Harvestable Species
0 - 8
9 - 16
17 - 24
25 - 32
33 - 48
D
Ecosystem Diversity
1 - 3
4 - 6
7 - 9
10 - 12
13 - 20
N

Figure 2.

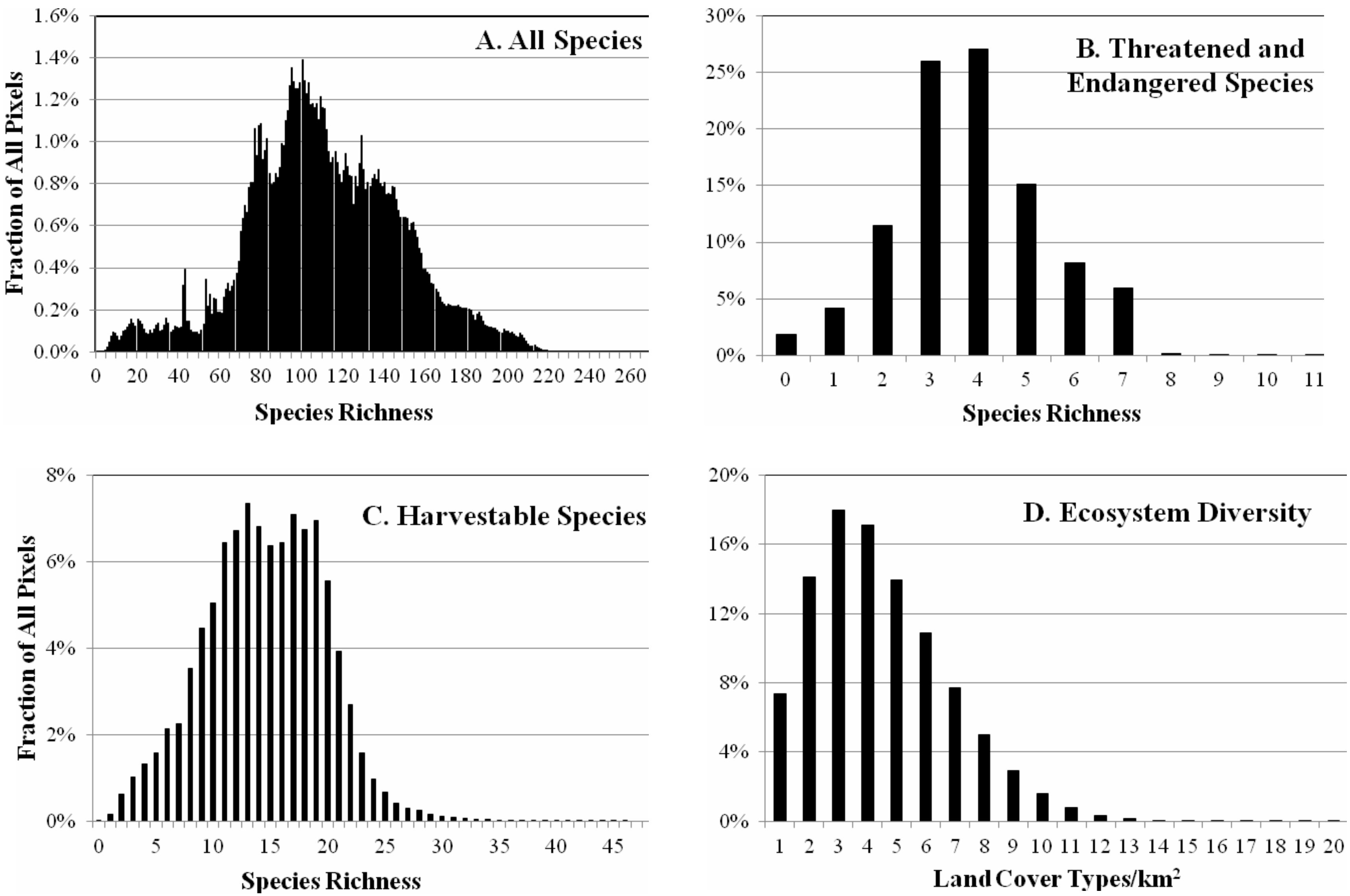
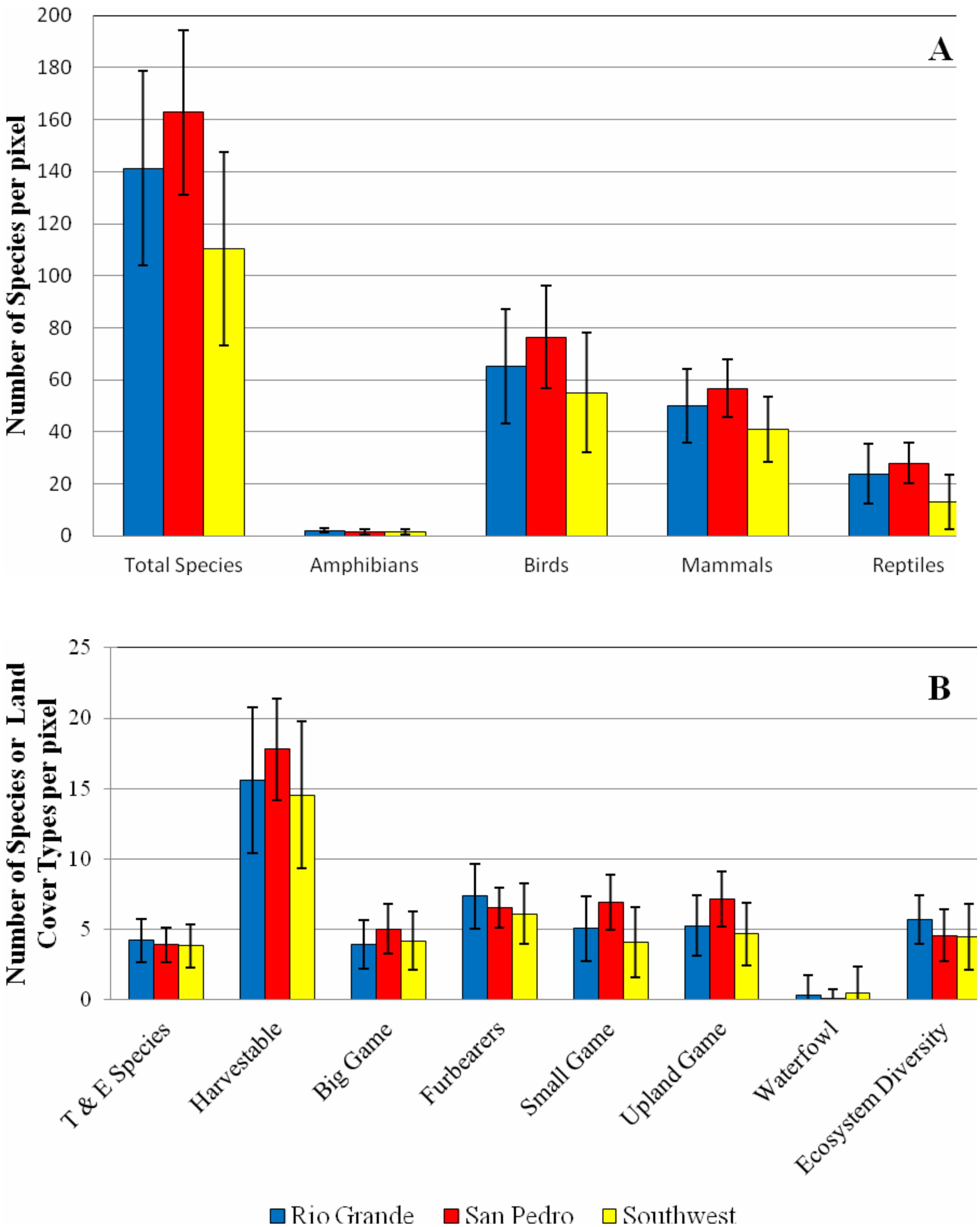

A. All Species
Fraction of All Pixels
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
0 20 40 60 80 100 120 140 160 180 200 220 240 260
Species Richness
B. Threatened and Endangered Species
30%
25%
20%
15%
10%
5%
0%
0 1 2 3 4 5 6 7 8 9 10 11
Species Richness
C. Harvestable Species
Fraction of All Pixels
8%
6%
4%
2%
0%
0 5 10 15 20 25 30 35 40 45
Species Richness
D. Ecosystem Diversity
20%
16%
12%
8%
4%
0%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Land Cover Types/km²

Figure 3.



576 Figure 4.

577

578

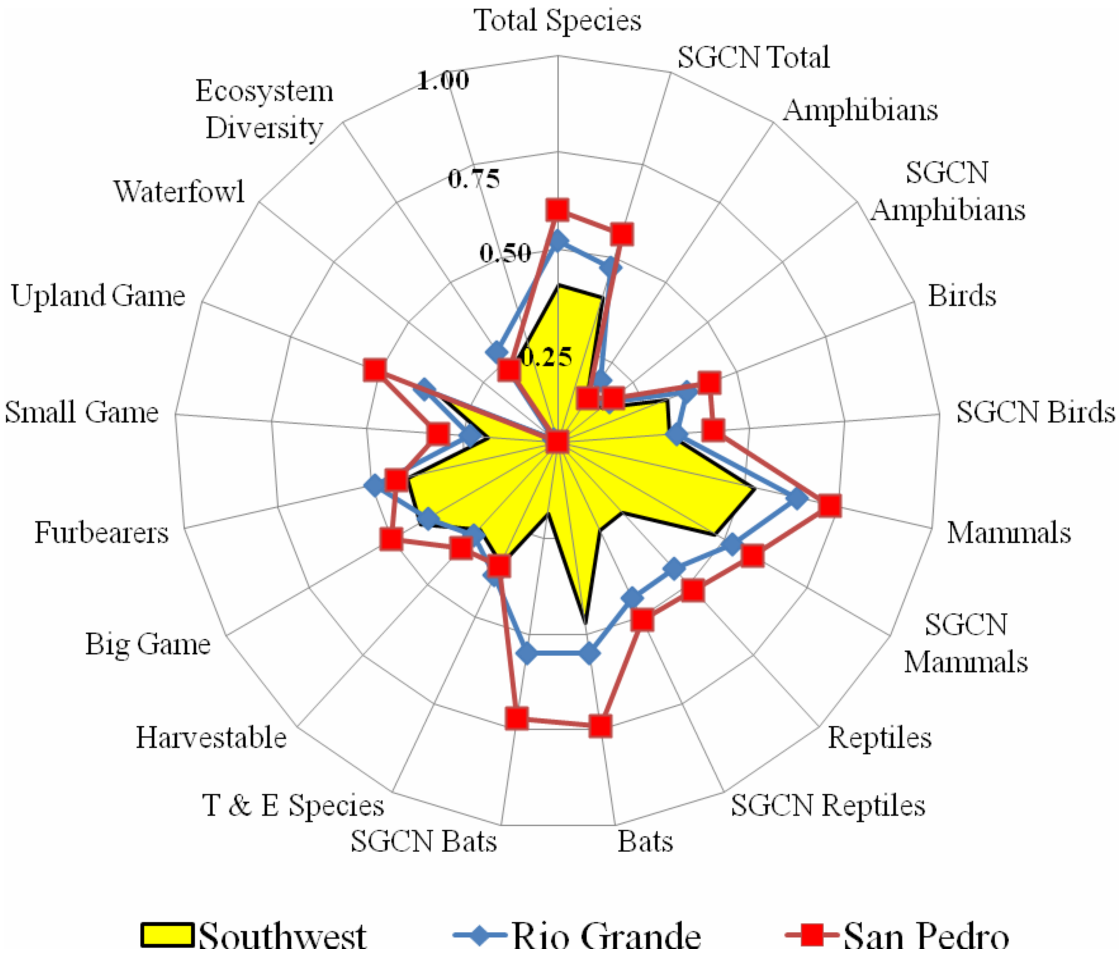

Total Species
SGCN Total
Amphibians
SGCN Amphibians
Birds
SGCN Birds
Mammals
SGCN Mammals
Reptiles
SGCN Reptiles
Bats
SGCN Bats
T & E Species
Harvestable
Big Game
Furbearers
Small Game
Upland Game
Waterfowl
Ecosystem Diversity
1.00
0.75
0.50
0.25
Southwest
Rio Grande
San Pedro

Figure 5.