Ecological Indicators xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

A national approach for mapping and quantifying habitat-based biodiversity metrics across multiple spatial scales

Kenneth G. Boykin[a,*], William G. Kepner[b], David F. Bradford[b], Rachel K. Guy[a], Darin A. Kopp[a], Allison K. Leimer[a], Elizabeth A. Samson[a], N. Forrest East[a], Anne C. Neale[b], Kevin J. Gergely[c]

[a] New Mexico Cooperative Fish and Wildlife Research Unit, Department of Fish, Wildlife, and Conservation Ecology, New Mexico State University, 2980 S. Espina St., 124 Knox Hall, PO Box 30003, MSC 4909, Las Cruces, NM 88003, USA
[b] U.S. Environmental Protection Agency, Office of Research and Development, 944 E. Harmon Ave., Las Vegas, NV 89119, USA
[c] U.S. Geological Survey, USGS Gap Analysis Program, Core Science Systems, Core Science Analytics and Synthesis, 970 Lusk Avenue, Boise, ID 83706, USA

ARTICLE INFO

Keywords:
Biodiversity
Ecosystem services
Habitat maps
Terrestrial vertebrates
San Pedro River
Rio Grande River
Western United States

ABSTRACT

Ecosystem services, i.e., services provided to humans from ecological 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 aspects 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 harvestable species), whereas others may 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 present an approach that (1) identifies mappable biodiversity metrics that are related to ecosystem services or other stakeholder concerns, (2) maps these metrics throughout a large multi-state region, and (3) compares the metric values obtained for selected watersheds within the regional context. The broader focus is to design a flexible approach for mapping metrics to produce a national-scale product. We map 20 biodiversity metrics reflecting ecosystem services or other aspects of biodiversity for all vertebrate species except fish. 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 also a metric 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.

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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) 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

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.

* Corresponding author. Tel.: +1 575 646 6303; fax: +1 575 646 1281.
E-mail address: kboykin@nmsu.edu (K.G. Boykin).

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http://dx.doi.org/10.1016/j.ecolind.2012.11.005

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 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. Thus, while managing for biodiversity is not a substitute for identifying key ecosystem service providers, managing for biodiversity may be a workable way to achieve an acceptable balance among the sometimes competing demands for various ecosystem services (Duffy, 2009).

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 subregional 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, such as DIVERSITAS (Larigauderie et al., 2012), The Economics of Ecosystems and Biodiversity (TEEB, 2010), and Group on Earth Observatory Biodiversity Observation Network (GEO BON, 2010a,b) have engaged in similar calls for action.

Within the US, a national atlas (Atlas) of datasets that pertain to ecosystem services is currently under development by US Environmental Protection Agency, US 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; and cultural, recreational, and esthetic amenities. The Atlas will also include metrics of biodiversity. Some biodiversity metrics clearly reflect ecosystem services (e.g., abundance and diversity of harvestable species, species richness for watchable wildlife). Other metrics, however, may reflect indirect and difficult to quantify relationships to services (e.g., relevance of species diversity to ecosystem resilience, cultural value of native species), that nevertheless have substantial stakeholder interest (e.g., abundance and diversity of threatened and endangered species; total species richness). The Atlas 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, and the geographic distribution of biodiversity metrics, as well as drivers of change. This paper addresses the biodiversity 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 conterminous 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 and biodiversity because they are readily available, can be assembled in broad functional groups that represent ecosystem services or biodiversity metrics of concern, and they can be used 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 are related to ecosystem services (e.g., harvestable species representing recreation and subsistence value) or other stakeholder concerns; (2) to map terrestrial biodiversity metrics throughout the conterminous United States beginning with selected regions such as the southwest; and (3) to compare metric values obtained for selected areas of interest at various spatial scales, i.e., watersheds, regions, and the entire conterminous US. Herein, we illustrate progress to date by comparing values for 20 biodiversity metrics for three areas: the southwestern US (5 states) and two areas within this region.

2. Materials 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; USFWS, 1978; 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

Fig. 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).

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." Examples of ecological systems include Southern Rocky Mountain Ponderosa Pine Woodland, Chihuahuan Mixed Desert and Thorn Scrub, Sonora-Mojave Creosotebush-White Bursage Desert Scrub, Rocky Mountain Mesic Montane Mixed Conifer Forest and Woodland, and agriculture (Lowry et al., 2007a). The area includes large 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 (9723 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; Krueper et al., 2003). 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 (8317 km^2 or 0.6% of the Southwest study area). The Rio Grande River flows 1350 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.

We used species richness for selected species groups, and ecosystem diversity (primarily reflected by vegetation diversity), as metrics to represent ecosystem services or other biodiversity aspects of concern. Species richness and vegetation diversity have been used in prior ecosystem services studies (Egoh et al., 2009). For example, metrics reflecting harvestable species and high bird species richness represent economic, recreational, and esthetic value.

To develop the species richness metrics, we used all the deductive habitat models for terrestrial vertebrates (i.e., amphibians, birds, mammals, reptiles; Boykin et al., 2007) from SWReGAP. These data (http://fws-nmcfwru.nmsu.edu/swregap/) are Imagine (ERDAS, Atlanta, GA, 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). These models were reviewed by species experts (Boykin et al., 2007). Deductive model processes were shown to have ≥60% concordance with known habitat features on the ground (Boykin et al., 2010). We then determined species richness for selected groups of taxa by combining the binary SWReGAP habitat datasets for the individual species included in the group and identified the number of species with predicted suitable habitat for each pixel using ArcGIS 10.1 (ESRI, Redlands, CA, US). To calculate ecosystem diversity, we analyzed the digital SWReGAP land cover map (Lowry et al., 2007a,b) using a moving window to identify the number of land cover types within a 1-km^2 centered on each pixel. Accuracy assessment of SWReGAP land cover predictions identified an average of 61% accuracy for the 85 land cover classes covering 91% of the area (Lowry et al., 2007b).

The groups of taxa used for species richness metrics were identified through a stakeholder workshop to identify biodiversity metrics of concern, and through presentations at scientific meetings. Stakeholders comprised individuals from federal and state agencies and nongovernmental organization who may ultimately benefit from the information generated within the project in regard to improved environmental decision making. Stakeholders were considered a key element to the metric selection process and they provided great input and influence over the project's objectives and outcomes. We selected 20 species richness metrics including the total SWReGAP model set, and the individual taxa of amphibians,

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,b; CDOW, 2005; NDOW, 2006; 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. Examples include beaver, badger, and marten.
Big game	Number of big game species as measured by predicted habitat present within a pixel. Examples include Elk, mule deer, and pronghorn.
Small game	Number of small game species as measured by predicted habitat present within a pixel. Examples include sandhill crane, scaled quail and dusky grouse.
Upland game	Number of upland game species as measured by predicted habitat present within a pixel. Examples include desert cottontail, red squirrel, wild turkey.
Waterfowl	Number of waterfowl species as measured by predicted habitat present within a pixel. Examples include mallards, Canada geese, and trumpeter swan.
Ecosystem diversity	Number of land cover types within a 1-km neighborhoodby pixel.

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 (USFWS, 2011). 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 (AGFD, 2005a,b; CDOW, 2005; NDOW, 2006; NMDGF, 2006; UDWR, 2005). The metrics represented all SGCN combined and the individual SGCN taxa of amphibians, birds, mammals, reptiles, and bats. Workshop participants also identified metrics for further 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. In the interest in brevity, we feature results from four of the 20 metrics, i.e. 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. 2A). 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. 2B and C), and ecosystem diversity is generally greatest in the north central part of the region (Fig. 2D). 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. 2B and 3B). Similarly, corresponding values for ecosystem diversity for the highest and lowest map categories are approximately 0.3% and 39.4%, respectively (Figs. 2D and 3D). 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 (Table 2 and Fig. 2A).

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,

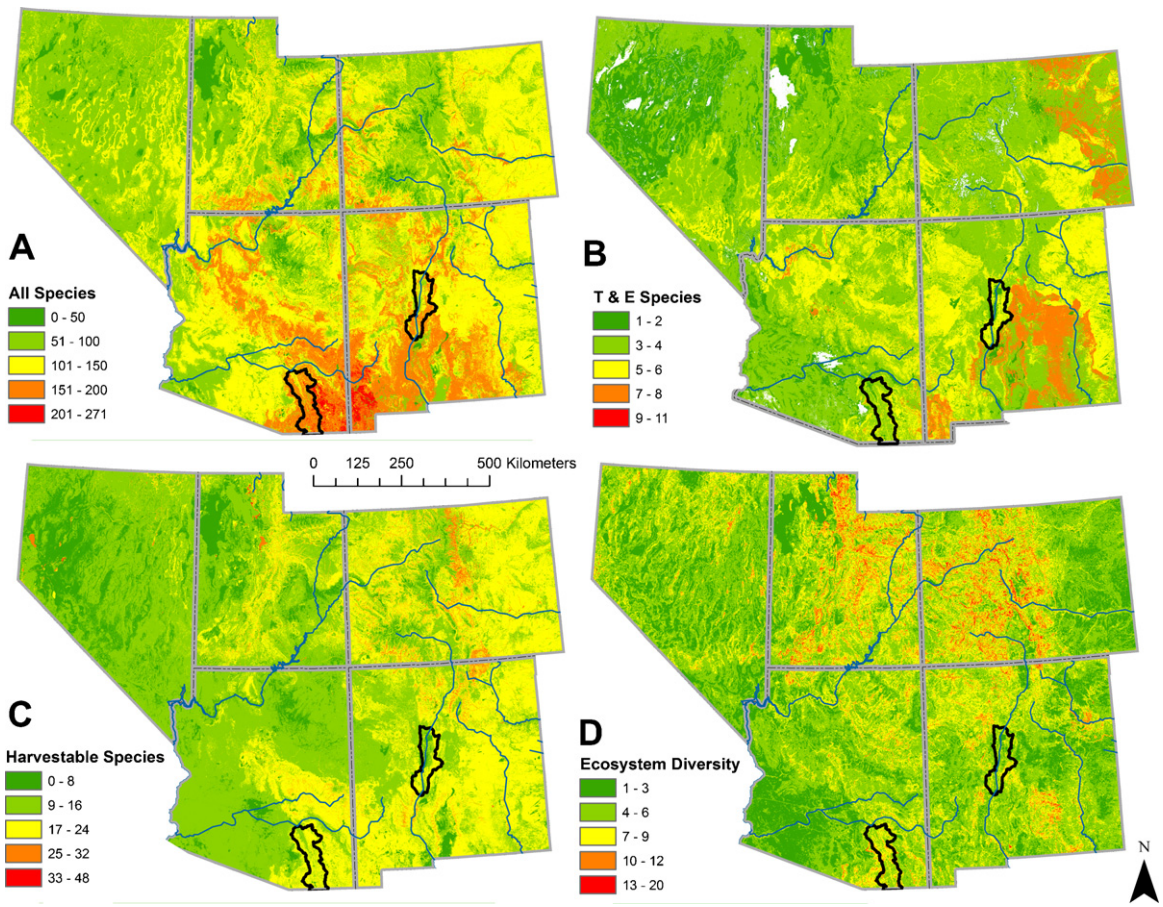

Fig. 2. Maps for selected biodiversity metrics throughout the Southwest study area: (A) species richness (number of species per pixel) for all terrestrial vertebrates (i.e., amphibians, birds, mammals, reptiles), (B) species richness for federally listed threatened and endangered vertebrates (T&E), (C) harvestable species richness, and (D) ecosystem diversity (number of land cover classes in 1-km^2 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.

Table 2
Descriptive statistics for 20 biodiversity metrics in the three study areas. Number of species in each area is indicated by "*n*". 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 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, $n = 436$ (9723 km^2)			San Pedro, $n = 452$ (8317 km^2)			Southwest, $n = 817$ (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

Please cite this article in press as: Boykin, K.G., et al., A national approach for mapping and quantifying habitat-based biodiversity metrics across multiple spatial scales. Ecol. Indicat. (2012), http://dx.doi.org/10.1016/j.ecolind.2012.11.005

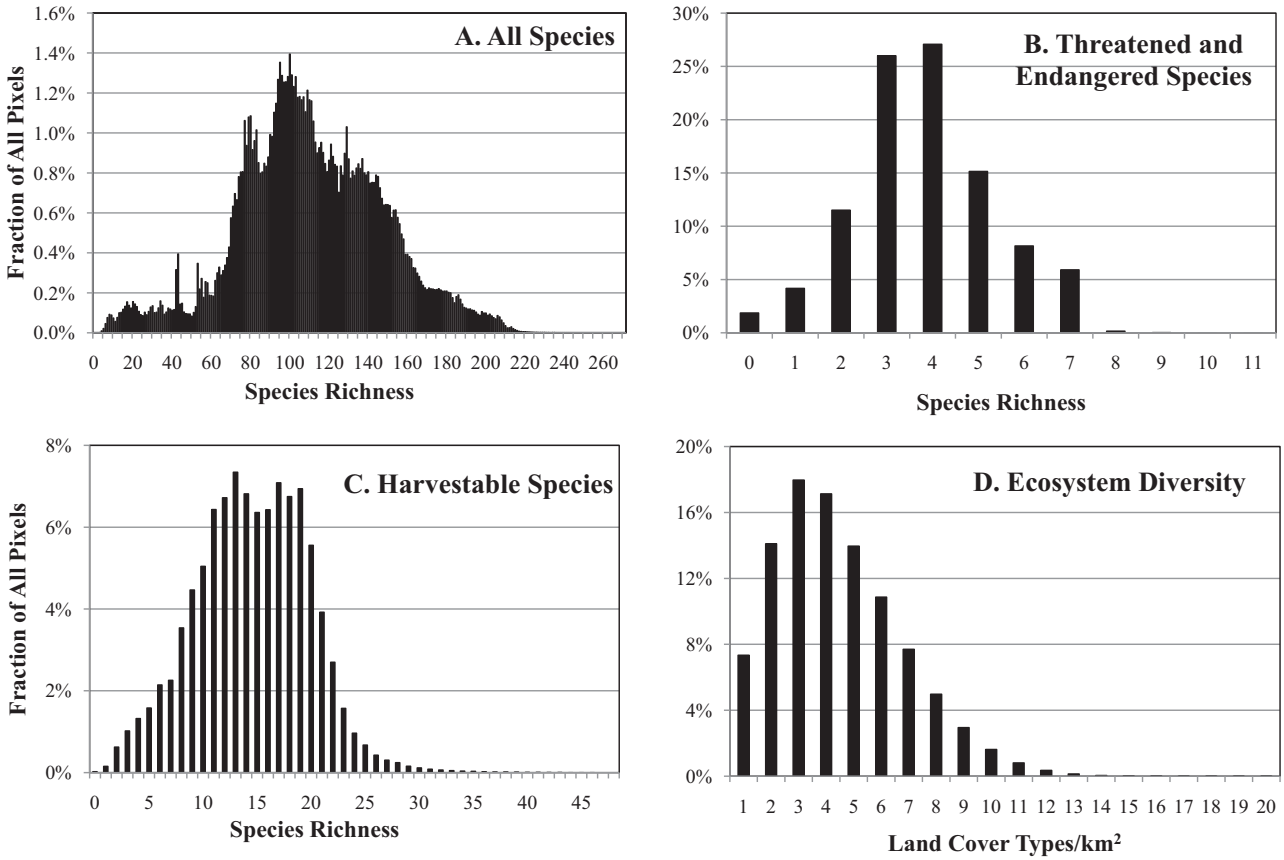

Fig. 3. Pixel frequency distribution for selected biodiversity metrics throughout the Southwest study area:(A) species richness (number of species per pixel) for all terrestrial vertebrates, (B) species richness for federally threatened and endangered vertebrates, (C) harvestable species richness, and (D) ecosystem diversity (number of land cover classes in 1-km^2 centered on 30-m pixel).

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 and Fig. 4). Birds dominate species richness values, whereas few amphibian species are represented (Table 2 and Fig. 4A). 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 and Fig. 4B). 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 and Fig. 4).

Although comparison of diversity metrics among the three study areas can be made using descriptive statistics (i.e., Table 2 and Fig. 4), such comparisons are facilitated by normalizing metric values to the maximum pixel value (Fig. 5). For example, nearly all of the normalized diversity metrics average greater for the two watershed study areas in comparison to the southwestern region as a whole. Thus, this normalization approach provides a quantitative way to visualize the observation that the San Pedro and Rio Grande study areas have high biodiversity and ecological importance (Simpson, 1964; USFWS, 1978; Finch and Tainter, 1995). Also, most diversity metrics for the San Pedro study area average greater than for the Rio Grande study area. Among the four featured 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 and waterfowl.

4. Discussion

Currently, there is keen interest in developing common processes and methodologies to monitor the status and trends of ecosystem services and biodiversity, especially scalable metrics (Sparks et al., 2011; UNEP-WCMC, 2011; BIP, 2011). However, ecosystem services and biodiversity 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) into groups of taxa based on input from stakeholders to identify biodiversity (primarily species richness) metrics of concern. We then 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 deductive habitat models and contemporary digital land cover datasets 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 et al., 1987; Egoh et al., 2009). T&E species and harvestable species are regulated by public law and provide recreational and cultural services. 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).

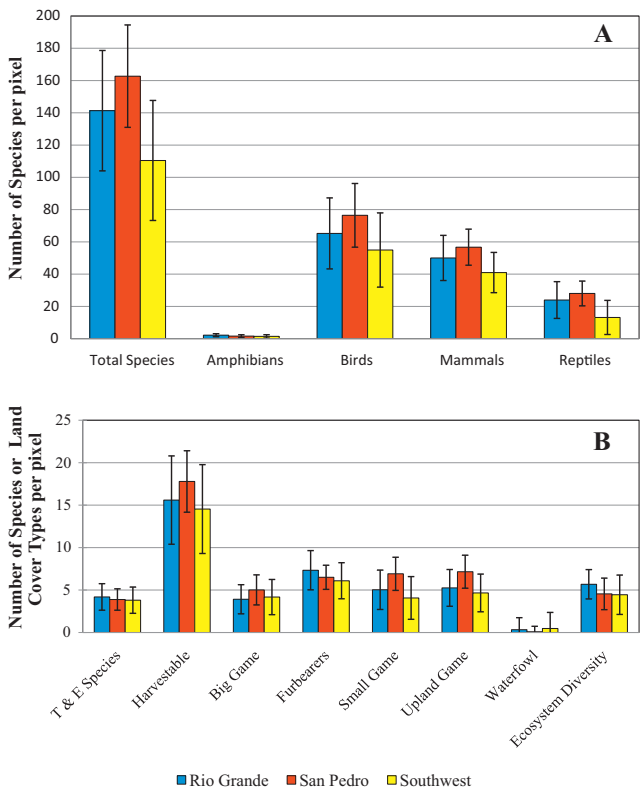

Fig. 4. Biodiversity metric values for the three study areas for (A) all terrestrial vertebrate species, all amphibians, all birds, all mammals, and all reptiles, and (B) federally listed threatened and endangered species (T&E), harvestable species, the five groups comprising harvestable species (i.e., 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.

The state of Arizona for example, has established a recreation strategy to "identify, assess, develop, and promote watchable wildlife recreational opportunities" in addition to promoting sustainable harvests via hunting. Recreational opportunities beyond harvest include birding, hiking, wildlife viewing and photography and in 2001 they amounted to almost $26 million USD for Cochise County, the location of the upper San Pedro River (Southwick Associates, 2003). Ecosystem diversity reflects a mix of environmental and conservation influences such as topography, land use, and fragmentation.

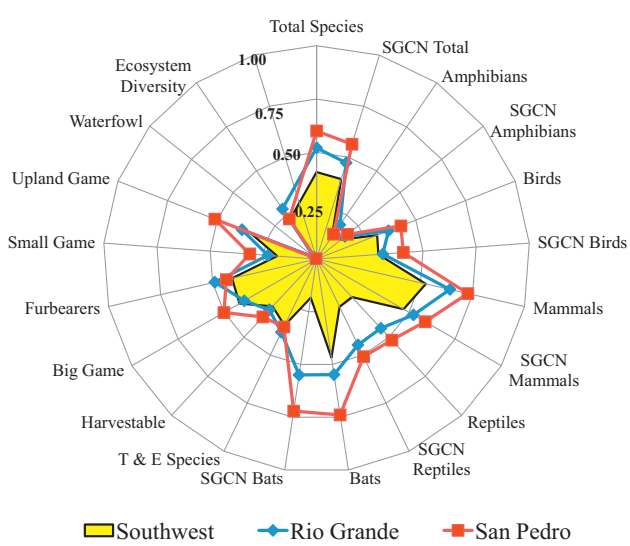

Fig. 5. Radar graph for 20 normalized biodiversity metrics for the Southwest, San Pedro, and Rio Grande study areas. Values are computed as mean pixel value for area/maximum pixel value for Southwest study area. SGCN refers to state-designated Species of Greatest Conservation Need.

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. By providing our stakeholder involvement in this process, we include a validation step ensuring "credibility, quality, and practical relevance of knowledge" (Turnhout et al., 2012). As the project evolves to other regions and ultimately to a national level product, we anticipate identifying a smaller set of metrics of greatest concern, thus eliminating some of the redundancies we are now reporting. For example, key species richness metrics may include total species to reflect overall diversity, amphibians and waterfowl to reflect aquatic systems, birds and mammals to reflect terrestrial systems and watchable wildlife, threatened and endangered species to reflect species of regulatory concern, and harvestable species to reflect primarily hunting interests.

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. For example, specific areas proposed for development could be compared, such as alternative routes for roads, pipelines, transmission lines, or other facilities or activities. 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 10-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 and biodiversity 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 (Turnhout et al., 2012). The stakeholder outreach conducted in the present study, i.e., workshop and presentations at scientific conferences, yielded a better understanding of the needs and relevance of existing metrics and the identification of additional relevant metrics. Although some of the 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. Moreover, ecosystem services represented by biodiversity metrics 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 one component of the national atlas of ecosystem services that is currently under development by the US Environmental Protection Agency and its partner agencies. The Atlas 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 and biodiversity, highlighting opportunities for improving the provision of ecosystem services and benefits from the environment. 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 or taxonomic 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.

Acknowledgements

We would like to acknowledge those individuals that worked on previous research efforts to create and compile the datasets used in the present study including personnel associated with the Southwest Regional Gap Analysis Project and the state Comprehensive Wildlife Conservation Strategies and Wildlife Action Plans. This research was funded in part by the US Environmental Protection Agency (EPA) through its Office of Research and Development and the US Geological Survey (USGS) Gap Analysis Program. The article has been approved for publication by the EPA and USGS. Additional financial assistance was provided by the USGS New Mexico Cooperative Fish and Wildlife Research Unit and the New Mexico State University, Agricultural Experiment Station.

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