International Congress on Environmental Modelling and Software

6th International Congress on Environmental Modelling and Software - Leipzig, Germany - July 2012

Jul 1st, 12:00 AM

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International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

Assessing the vulnerability of human and biological communities to changing ecosystem services using a GIS-based multi-criteria decision support tool

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Abstract: In this paper we describe an application of a GIS-based multi-criteria decision support web tool that models and evaluates relative changes in ecosystem services to policy and land management decisions. The Santa Cruz Watershed Ecosystem Portfolio (SCWEPM) was designed to provide credible forecasts of responses to ecosystem drivers and stressors and to illustrate the role of land use decisions on spatial and temporal distributions of ecosystem services within a binational (U.S. and Mexico) watershed. We present two SCWEPM sub-models that when analyzed together address bidirectional relationships between social and ecological vulnerability and ecosystem services. The first model employs the Modified Socio-Environmental Vulnerability Index (M-SEVI), which assesses community vulnerability using information from U.S. and Mexico censuses on education, access to resources, migratory status, housing situation, and number of dependents. The second, relating land cover change to biodiversity (provisioning services), models changes in the distribution of terrestrial vertebrate habitat based on multitemporal vegetation and land cover maps, wildlife habitat relationships, and changes in land use/land cover patterns. When assessed concurrently, the models exposed some unexpected relationships between vulnerable communities and ecosystem services provisioning. For instance, the most species-rich habitat type in the watershed, Desert Riparian Forest, increased over time in areas occupied by the most vulnerable populations and declined in areas with less vulnerable populations. This type of information can be used to identify ecological conservation and restoration targets that enhance the livelihoods of people in vulnerable communities and promote biodiversity and ecosystem health.

Keywords: decision support; ecosystem services; species richness; biodiversity; environmental vulnerability

1 INTRODUCTION

1.1 Background

The concept of ecosystem services has in recent years gained traction among economists, scientists, land managers, and policy-makers as a means to quantify and demonstrate the value of the societal benefits provided by ecosystems and their physical and biological processes. These benefits are not, however, distributed evenly over space and time, and in some cases the goods and services provided by ecosystems may be disproportionately enjoyed by affluent segments of society while the burdens of environmental degradation and biodiversity loss fall upon economically vulnerable communities [Sathirathai and Barbier 2001, Srinivasan et al. 2008]. In addition, social and economic forces, ranging from local to global, may drive land use decisions that influence the spatial pattern and rate of ecosystem service degradation and/or restoration. Analyzing the provision and use of ecosystem services relative to social and economic indicators can provide, for instance, land managers, policy- and decision-makers with information to guide natural hazards prevention (due to flooding or erosion) or identify locations for conservation and restoration. Socially and environmentally vulnerable communities may ultimately be more receptive to incentive-based policy tools than more affluent and urbanized communities. For instance, PES (Payment for Ecosystem Services) programs, where landowners are compensated or subsidized for producing or maintaining environmental services [Bohlen et al. 2009], may prove to be particularly suited to rural ranching communities, communally owned lands in Mexico, or within Native American reservations.

Socio-economic vulnerability in the U.S.-Mexico border region, which stems in part from rapid economic growth, globalization and environmental change, is often associated with natural resource degradation, industrialization and pollution [Liverman et al. 1999]. However, socially and environmentally vulnerable communities in the border region are not concentrated strictly around industrialized areas of the border, but are distributed throughout the urban to rural spectrum. Several vulnerable rural communities in the study area are located within landscapes that provide a number of important ecosystem services and may be targeted for conservation or restoration. These vulnerable communities may be more inclined to utilize and consume natural services (i.e. through hunting and poaching, fuel-wood collection, over-grazing, or high-intensity agricultural practices) when economic conditions are unstable. Urban and suburban areas, on the other hand, experience declines in natural services (i.e. through excessive ground water use by golf communities, habitat conversion for housing developments) when economic conditions are good.

The USGS has developed an Ecosystem Portfolio Model [EPM; Labiosa et al. 2009] that can be used to present and analyze social, economic, and biophysical data together in an online decision support system, helping managers visualize the often complex impacts of management and land use practices. The EPM offers a place-based, holistic ecosystem analysis tool that allows users to develop and display ecosystem service trade-offs in alternative scenarios. The EPM is being applied in the Santa Cruz Watershed at the U.S.-Mexico border of Arizona-Sonora to help decision-makers identify where ecosystem services distribution should be regulated across the U.S.-Mexico border. With this research we used SCWEPM sub-models to quantify access to natural capital by populations in the SCW with varying levels of vulnerability. In doing so we aim to understand how available ecosystem services are distributed relative to vulnerable communities, how that distribution has changed over time, and how land use may change future distributions.

1.2 Study Area

The binational Santa Cruz Watershed (SCW) is located in Arizona, U.S. and Sonora, Mexico (Figure 1). The watershed is geographically situated at the boundary of the Sonoran Desert and Apache Highlands ecoregions of North America, and is as a result an area of exceptional plant and animal biodiversity [Felger and Wilson 1994; Spector 2002]. The watershed contains two major urban areas, the Tucson metropolitan area and Ambos Nogales (Nogales Arizona and Nogales Sonora) (Figure 1). According to the 2005 Mexican and the 2000 United States' national censuses, the binational Santa Cruz is home to over 1 million people: 194,272 in Mexico and 875,828 in the U.S. There are 19 *colonias* (rural settlements with weak social and physical infrastructure located within 240 km of the U.S./Mexico border) in the Santa Cruz Watershed, 8 of which are south of the border [Norman et al. 2006].

1.3 Ecosystem Portfolio Model

The Ecosystem Portfolio Model (EPM) is a Geographic Information System-based multi-criteria decision support web tool that evaluates proposed changes in ecosystem services with performance criteria related to three dimensions of value: 1) modeled ecological criteria related to ecosystem services, expressed as “ecological value” 2) modeled economic criteria related to land use and water management outcomes, and 3) community quality-of-life and/or human well-being indicators related to land use, water management, and ecosystem services [Labiosa et al. 2009]. Each of these dimensions is implemented as a sub-model of the EPM that generates “value maps” based on a set of user-elicited preferences, and reflects changes in attributes and value. The modeled attribute changes can include changes in habitat potential and landscape fragmentation, distances to human perceived amenities, community “character”, flooding evacuation risks, water quality buffer potential, ecological restoration potential, and other relevant performance criteria. The EPM web interface allows the user to explore the individual value maps for each unique criterion or, after applying user-chosen multi-criteria weights, as an aggregated value map. The EPM also allows users to evaluate and compare potential land use patterns in a variety of ways. Users can compare maps of ecological value, predicted land price, and community quality-of-life indicators for sets of land use/cover patterns to characterize regional-scale trade-offs between ecological, economic, and social values.

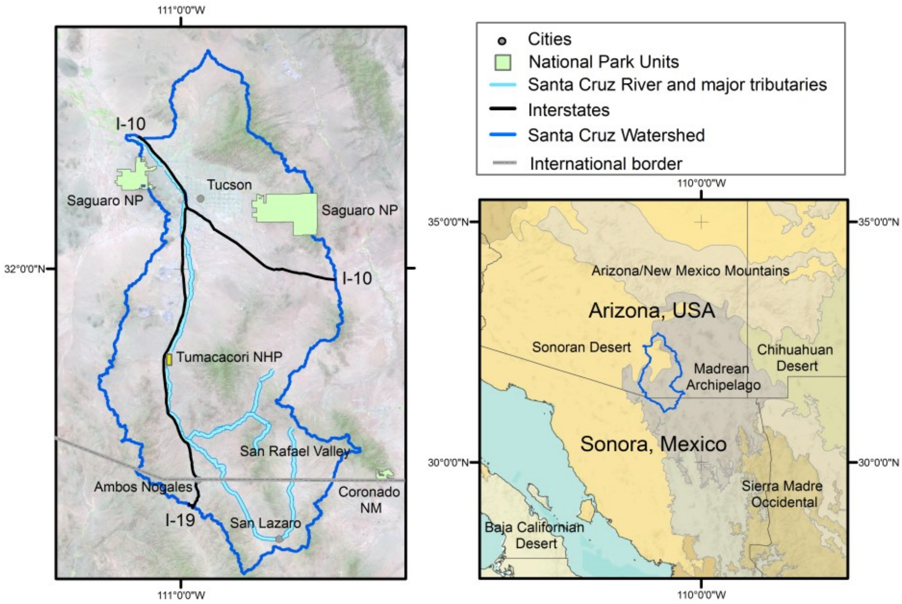

Figure 1. Location of study area, ecoregions, transportation corridors and National Parks units that provided biological inventory data for this study.

1.4 Previous Modelling

1.4.1 M-SEVI

As part of the SCWEPM’s Human Well-Being (HWB) sub-model, we developed a Modified Socio-Environmental Vulnerability Index (M-SEVI) using binational census and neighborhood data for the watershed measured by objective determinants like education, access to resources, migratory status, housing situation, and number of dependents [Norman et al. 2012]. M-SEVI is a compound index calculated using census data from the United States and Mexico. The index is comprised of three dimensions: (i) a Population Characteristics dimension, which describes social and demographic attributes of the residents; (ii) an Urban Characteristics dimension, which measures the extent to which families have access to basic infrastructure; and (iii) a Household Assets dimension, which provides an indirect measure of household income through use of the amount of wealth controlled by the families in each city. When applied to mapped census units, the distribution of vulnerable populations can be mapped and visualized across international boundaries and compared to mapped ecosystem services to better understand environmental equity in the SCW (Figure 2). To aid visualization and analysis, M-SEVI values were classified into 5 categories using a geometrical interval distribution.

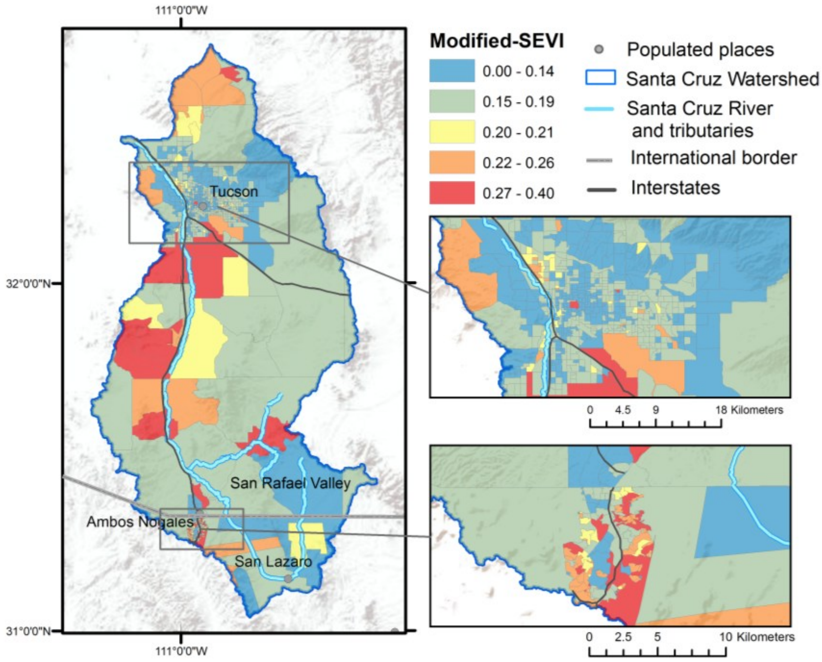

Figure 2. Map displaying a geometrical interval distribution of M-SEVI values in the Santa Cruz Watershed.

1.4.2. Ecosystem services: Biodiversity and habitat provisioning

Species richness values for habitat types were identified using the Southwest Regional Gap Analysis (SWReGAP) Wildlife Habitat Relations (WHR) models [Boykin et al. 2007] in combination with a binational vegetation map [Wallace et al. 2011]. Using the WHR models we identified the total number of potential terrestrial vertebrates present in the watershed given their vegetation habitat requirements, and assigned a species richness value to the mapped vegetation classes (Figure 3). Overall species richness values identified using WHR models were independently validated using data from local National Park Service biological inventories [Villarreal et al. *in review*].

The total number of potential terrestrial vertebrates identified using SWReGAP WHR models across all vegetation and land cover types was 451, with Desert Riparian Woodland and Shrubland and Desert Riparian Forest supporting the greatest number of both total species (267) and avian species (171). Apacherian-Chihuahuan Piedmont Semi-Desert Grasslands had lower total species richness (215), but the highest mammal species richness (75) of all the types.

Two future land-use/cover change scenarios [Norman et al., *in press*] were developed using cellular automata-based SLEUTH model for a 1) “Current Trends” scenario, that represented continued growth without management intervention and, 2) “Megalopolis” scenario, that represented a transnational growth corridor with open-space conservation attributes. Both scenarios were projected to the year 2050. Urban class rasters were extracted from these scenarios and merged with species richness maps [Villarreal et al. *in review*].

2 METHODS

In addition to current and projected scenarios of species richness described above, we developed historical species richness models by cross-walking vegetation and land use classes from three decades of land cover data [1979-2009; Villarreal et al.

2011] to SWReGAP ecological system classes. Species richness values identified using WHR models were then applied to the multitemporal land cover data. Temporal changes of species richness values generated for these models were assessed by census unit and compared to M-SEVI values.

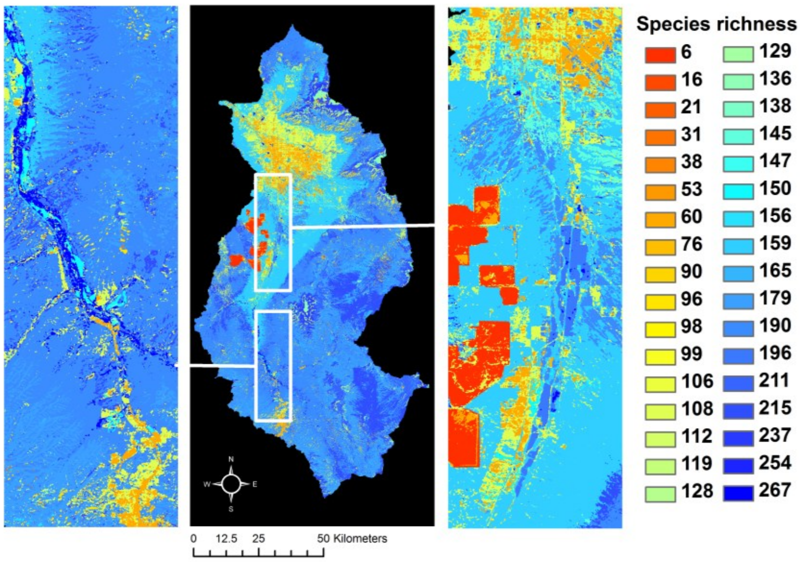

Figure 3. Species richness map of the Santa Cruz Watershed (center) including enlargements of the Santa Cruz River riparian corridor at the US/Mexico border (left) and Tucson metropolitan area (right).

2.1 Data analysis

We analyzed the relationship between biodiversity/habitat provisioning and social environmental vulnerability by focusing on species-rich habitat types that primarily occur on private lands (as opposed to a species-rich type like Rocky Mountain Ponderosa Pine Woodland that occurs almost exclusively on land owned and protected by federal land management agencies). Two biodiverse habitat types that are often targeted for conservation and restoration activities are desert grasslands and riparian forests and woodlands. Coupling of biological (species richness) and social (M-SEVI) models allows us to identify densely-populated and socio-environmentally vulnerable communities subjected to changes in habitat provisioning through time. We examine three aspects of M-SEVI/biodiversity relationships: 1) whether habitat provisioning services are distributed equally throughout the watershed, 2) where historical changes to habitat and biodiversity occurred, and 3) where future changes are projected to occur. For this analysis the M-SEVI geometrical intervals were further grouped into 3 categories: Low M-SEVI (0-0.19), Moderate M-SEVI (0.20-0.21) and High M-SEVI (0.22-0.40).

3 RESULTS

3.1 Historical changes

Although not statistically significant, the relationship between change in riparian vegetation cover (1979-2009) and M-SEVI indicate that most riparian vegetation loss over the 30 year period occurred within census blocks with low or moderate M-SEVI values (Figure 4). Three of the four census units with the greatest increase in riparian vegetation were part of the high M-SEVI class with index values of 0.20 or higher. Grasslands and M-SEVI displayed contrasting results with most of the major grassland increases occurring in areas with low and moderate M-SEVI values (Figure 4). Grassland losses occurred nearly equally within low, moderate and high M-SEVI units.

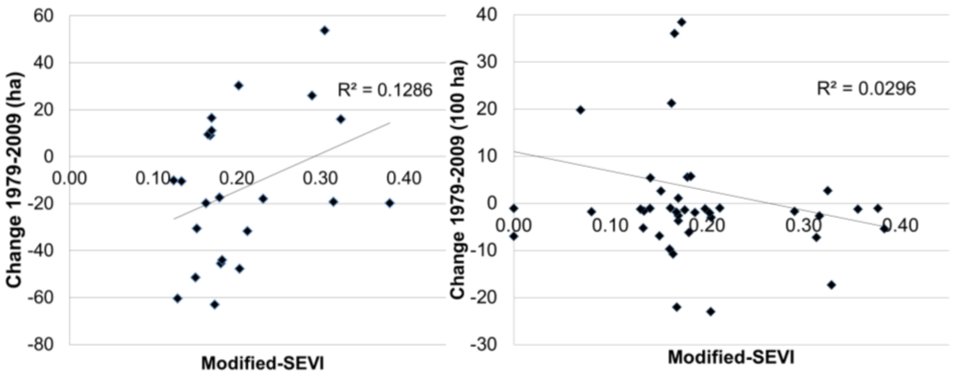

Figure 4. Relationship between the Modified-SEVI and riparian vegetation change (left) and grassland vegetation change (right).

3.2 Future scenarios

Unlike the historical trends, both future scenarios (which were not developed using socio-economic data or projected climate data) suggest that by 2050 riparian habitat will decrease across all census units (Figure 5). Census units currently exhibiting low M-SEVI values had the most access to Desert Riparian Woodland and Shrubland and Desert Riparian Mesquite Bosque, two vegetation types with high biodiversity, however the largest declines are projected to occur within these low M-SEVI units (Figure 5). Like the historical trends, high M-SEVI units currently have the most access to species rich Desert Riparian Forest, and while the area of this type is projected to decrease by 2050, high M-SEVI units will continue to have the greatest access to services provided by riparian forest habitat. While the species richness values (267) are the same for Desert Riparian Woodland and Shrubland and Desert Riparian Forest, the forest represents the maturation of the type and is of greater interest for conservation and preservation.

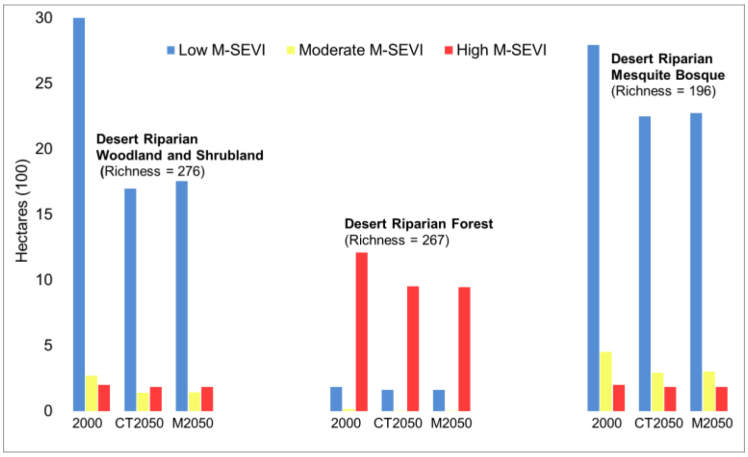

Figure 5. Current and projected distributions of species-rich riparian habitat relative to M-SEVI classes. 2000 = current, CT2050 = Current Trends scenario, and M2050 = Megalopolis scenario.

A majority of Apacherian-Chihuahuan Piedmont Semi-Desert Grassland area falls within low M-SEVI census units (Figure 6). This habitat type is projected to decrease considerably by 2050, particularly under the Current Trends scenario where urban development continues to convert and fragment grasslands in rural area of the watershed. Moderate and high M-SEVI units currently have little direct access to ecosystem services provided by the grasslands, and this access will be further reduced under both future scenarios (Figure 6).

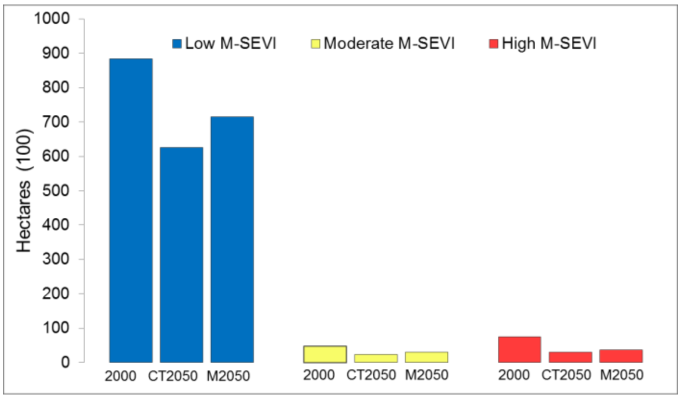

Figure 6. Current and projected distributions of Apacherian-Chihuahuan Piedmont Semi-Desert Grasslands (215 species) relative to M-SEVI classes. 2000 = current, CT2050 = Current Trends scenario, and M2050 = Megalopolis scenario.

4 DISCUSSION

Within the Santa Cruz Watershed, species-rich riparian vegetation increased over time within socially and environmentally vulnerable census units, and declined in less vulnerable units. These findings indicate that vulnerable communities have more direct access to ecosystem services provided by riparian habitat and associated biodiversity, including the local distribution of ecotourism dollars spent on birding-related activities, flood control services and agricultural runoff filtration. Most of the declines in riparian habitat occurred in areas with moderate M-SEVI values, likely associated with direct habitat conversion and groundwater use related to urban development and leisure-related activities (i.e. groundwater use for golf courses, urban and industrial uses). Future scenarios project a considerable loss of Desert Riparian Woodland and Shrubland as urban areas continue to grow, but differences in the amount of riparian habitat lost due to Current Trends or Megalopolis were generally negligible. Desert Riparian Forest, a conservation keystone in arid lands, is distributed primarily within areas of high M-SEVI values, and future scenarios suggest these locations will not experience such a radical decline over time as do the Desert Riparian Woodland and Shrubland communities distributed within low M-SEVI units. Changes to grassland habitats depict contrasting results, with most of the increases in grassland areas occurring within moderate M-SEVI units. These units are likely comprised of large portions of public lands and restored or conserved ranch lands with low levels of urbanization and low population. Projected future scenarios depict a considerable decline in Apacherian-Chihuahuan Piedmont Semi-Desert Grassland habitat by 2050; reduction of ecosystem services provided by this habitat type will be experienced primarily by communities with low M-SEVI values. Future declines of grassland ecosystem services (e.g. forage for livestock, biodiversity, habitat connectivity, erosion control) may have feedbacks that increase economic and ecological vulnerability in rural areas.

Analysis of coupled social and biological data provided new insights into the distribution of ecosystem services within the SCW. That a majority of the area of biodiverse Desert Riparian Forest falls within areas that are home to socially and environmentally vulnerable populations suggests that opportunities exist to preserve the ecosystem services of the SCW and enhance livelihoods of people living in these areas through restoration, PES programs and/or ecotourism. While historical trends indicate that riparian areas are increasing within high M-SEVI units, these areas should be carefully monitored as they may be at risk of degradation in the future if the natural goods and services are targeted for consumption (fuel wood cutting, water diversion) by increasingly resource-impoverished populations. The information presented in this paper makes the case for joint enhancement of community and ecosystem stability through the conservation, maintenance and restoration of biodiverse ecosystems.

ACKNOWLEDGMENTS

The authors thank the U.S. Geological Survey's Mendenhall Research Fellowship Program, Geographic Analysis and Monitoring (GAM) Program, and U.S.-Mexico Border Environmental Health Initiative (BEHI) for supporting this research.

REFERENCES

Bohlen, P. J., Lynch, S., Shabman, L., Clark, M., Shukla, S., and H. Swain, Paying for environmental services from agricultural lands: an example from the northern Everglades, *Frontiers in Ecology and the Environment*, *7*(1), 46-55, 2009.

Boykin, K.G., B.C. Thompson, R.A. Deitner, D. Schrupp, D., and others, Predicted animal habitat distributions and species richness. In: Prior- Magee J.S., K.G. Boykin, D.F. Bradford, W.G. Kepner, J.H. Lowry, D.L. Schrupp, K.A. Thomas, and B.C. Thompson (Eds.), Southwest Regional Gap Analysis Final Report. U.S. Geological Survey, Gap Analysis Program, Moscow, ID, pp. 39–78, 2007.

Felger R.S., and M.F. Wilson, Northern Sierra Madre Occidental and its Apachian outliers: a neglected center of biodiversity. *Pages* 36–59 *in* DeBano F.L., P.F. Ffolliott, A. Ortega–Rubio, G.J. Gottfried and R.H. Hamre, *Eds.* Biodiversity and management of the Madrean Archipelago: the sky islands of southwestern United States and northwestern Mexico. U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station, Tucson, Arizona, 1994.

Labiosa, W. B., R. Bernknopf, P. Hearn, D. Hogan, D. Strong, and others, The South Florida ecosystem portfolio model: A map-based multicriteria ecological, economic, and community land-use planning tool, U.S. Geological Survey Scientific Investigations Report 2009-5181, 2009.

Liverman, D. M., R. G. Varady, O. Chávez, and R. Sánchez, Environmental issues along the United States-Mexico border: Drivers of change and responses of citizens and institutions, *Annu. Rev. Energy. Environ.*, *24*(1), 607–643, 1999.

Norman, L.M., A. Donelson, E. Pfeifer, and A.H. Lam, Colonia development and land use change in Ambos Nogales, United States-Mexican Border. U.S. Geological Survey Open File Report: 2006-1112, 2006.

Norman, L.M., M.L., Villarreal, F. Lara-Valencia, S. Wilson, and others, Mapping socio-environmentally vulnerable populations access and exposure to ecosystem services at the U.S.-Mexico borderlands, Applied Geography, 34, 413-424, 2012.

Norman, L.M., Feller, M., and M.L. Villarreal, Developing Plausible Scenarios for Ecosystem Services Assessment—Santa Cruz Watershed, Arizona and Sonora, *Landscape and Urban Planning*, *In press.*

Sathirathai, S., and E. Barbier, Valuing mangrove conservation in southern Thailand, *Contemporary Economic Policy*, *19*(2), 109–122, 2001.

Spector S., Biogeographic crossroads as priority areas for biodiversity conservation, *Conservation Biology*, 16, 1480–1487, 2002.

Srinivasan, U.T., S.P. Carey, E. Hallstein, P.A.T. Higgins, and others, The debt of nations and the distribution of ecological impacts from human activities, *Proceedings of the National Academy of Sciences*, *105*(5), 1768 –1773, 2008.

Villarreal, M.L., L.M. Norman, K.G. Boykin, and C.S.A. Wallace, Biodiversity losses and conservation tradeoffs: assessing future growth scenarios for a North American transnational trade corridor. *In review*.

Villarreal, M.L., L. M. Norman, C. S. A. Wallace, and C. van Riper III, A Multi-temporal (1979-2009) Land Use/Land Cover Data Set of the Bi-National Upper Santa Cruz Watershed. U.S. Geological Survey Open-File Report 2011-1131, 26 p., 2011.

Wallace, C.S.A., M.L. Villarreal, and L.M. Norman, Development of a high-resolution binational vegetation map of the Santa Cruz River riparian corridor and surrounding watershed, southern Arizona and northern Sonora, Mexico: U.S. Geological Survey Open-File Report 2011-1143, 22 p., 2011.