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Mapping socio-environmentally vulnerable populations access and exposure to ecosystem services at the U.S.–Mexico borderlands

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A B S T R A C T

Socio-environmental vulnerable populations are often unrepresented in land-use planning yet have great potential for loss when exposed to changes in ecosystem services. Administrative boundaries, cultural differences, and language barriers increase the disassociation between land-use management and marginalized populations living in the U.S.–Mexico borderlands. This paper describes the development of a Modified Socio-Environmental Vulnerability Index (M-SEVI), using determinants from binational census and neighborhood data that describe levels of education, access to resources, migratory status, housing, and number of dependents, to provide a simplified snapshot of the region's populace that can be used in binational planning efforts. We apply this index at the SCW, located on the border between Arizona, USA and Sonora, Mexico. For comparison, the Soil and Water Assessment Tool is concurrently applied to assess the provision of erosion- and flood control services over a 9-year period. We describe how this coupling of data can form the base for an ecosystem services assessment across political boundaries that can be used by land-use planners. Results reveal potential disparities in environmental risks and burdens throughout the binational watershed in residential districts surrounding and between urban centers. The M-SEVI can be used as an important first step in addressing environmental justice for binational decision-making.

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Introduction

The most vulnerable people do not always live in the most vulnerable environments. Spatial analysis allows for the identification of where impoverished populations and marginal environments coexist. In social-ecological systems, vulnerability describes a community's resilience to change, necessary for sustainable development (Adger, 2006; Briguglio, Cordina, Farrugia, & Vella, 2009; Folke et al., 2002; Nelson, Adger, & Brown, 2007). Sustainable development is recognized as a mutual goal that provides for the inevitable population growth expected without harming resources for future generations. The United Nations identified three components necessary to be integrated for sustainable development, (i) economic development, (ii) social development, and (iii) environmental protection, as interdependent and mutually reinforcing pillars (United Nations, 1987, 1992; Brundtland, 1987). Equity and social justice are major social goals of sustainable development (Brundtland, 1987).

Prugh, Costanza, and Daly (2000) and Warner (2002) recognize that local sustainability practices are imperative but the environmental justice movement has not intersected with local sustainable initiatives to consider the social dimensions of sustainability. Environmental justice is the concept that environmental burdens and benefits should be equally distributed to all people to ensure a safe, healthy environment for all (Adger, 2004; Arnold, 1998; Been & Gupta, 1997; Camacho, 1998; Dow, Kasperson, & Bohn, 2006; Faber, 1998). Historically, spatial studies of environmental justice analyze the characteristics of the population potentially exposed to

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a hazardous land-use (Been and Gupta 1997; Maantay, 2002; United Church of Christ Commission for Racial Justice, 1987; Warner, 2002). Less-resilient or vulnerable populations may be less likely to respond to, cope with, and recover from disasters and hazards and need to be recognized as such in decision-making and land-use planning (Adger, 2006; Arnold, 1998; Butler, Corvalan, & Koren, 2005; Rodríguez et al., 2006; Tallis & Polasky, 2009). Agyeman and Evans (2003, 2004) and Warner (2002) argue that environmental justice is the social dimension and keystone of sustainable development.

Methodological difficulties, issues of data quality and access, and conceptual shortcomings within social vulnerability research limit the development of measuring social vulnerability (Cutter & Finch, 2008). However, one method that has been accepted to measure and map vulnerability is through the use of compound indices. A composite index incorporates a large number of factors that are averaged together to form a singular product, meant to be representative of an overall group. The combination of multiple factors or indicators into a compound index increases the sensitivity, reliability, and ease of communication (Donelson & Esparza, 2010a; Sholes, Biggs, Palm, & Duraiappah, 2010).

The conceptual framework for using ecosystem services to evaluate the complex interrelationships between human systems and the environment is provided by the United Nations Millennium Ecosystem Assessment (2003, 2005). The provision of ecosystem services varies when land uses change and/or land cover is altered, yet quantifying impacts on different socioeconomic systems is still a novel challenge (Tallis & Polasky, 2009). The Millennium Ecosystem Assessment states that changes in ecosystem services have disproportionate impacts on different segments of society (2005). Indigent, poorly-resourced, and otherwise disadvantaged communities may be more dependent on healthy ecosystems and/or lack the means to subsidize themselves by purchasing or importing ecosystem services (Ash et al., 2010; Butler et al., 2005; Butler & McMichael, 2006; Butler & Oluoch-Kosura, 2005). López-Hoffman, McGovern, Varady, and Flessa (2009) argue that the concept of ecosystem services could be used to promote more collaborative and equitable management of ecosystem services across international borders.

At the U.S.–Mexico border, physical barriers demarcate a division of political administration, yet international policies like the Border Industrialization Program (BIP) in 1965 and the North American Free Trade Agreement (NAFTA) in 1994 have led to the opening of this border for trade. The establishment of international *maquiladoras* (factories) and other social and economic changes associated with development has been made to accommodate trade, transforming the physical environment of the U.S.–Mexico borderlands (Esparza, Waldorf, & Chavez, 2004; Gomez, 1993; Gruben, 2001; Sassen, 2006). Related compromises in the sustainability of air- and water quality pose risks to public health, safety, and the environment for people living in *colonias* (Apitz, 2007; Carter, Peña, Varady, & Suk, 1996; Collins-Dogrul, 2006; Faber, 1998; Moda, 2007; Norman, 2010; Norman, Hirsch, & Ward, 2008, p. 63).

Colonias, the Spanish word for neighborhood, are defined by the Cranston-Gonzales Act 1992, as unincorporated communities located within 150-miles of the U.S.–Mexico border, with low incomes, that lack safe housing and/or services such as potable water, adequate sewage systems, drainage, streets, and utilities. In Arizona, *colonias* can include tribal communities, long-established mining towns, retirement communities, rural utility districts, and illegal "wildcat" subdivisions (Esparza & Donelson, 2008; Norman, 2010). In Sonora, Mexico, migrants from all over the country, and often from countries further south, relocate to the border in search of work. Mexican *colonias* can develop when family and friends join relocated workers, overcrowding individual dwellings, and/or occupying property that is not otherwise developed (Norman, Parcher, & Lam, 2004, 2010). Arnold (1998) and Henkel (2010) recognize that *colonias* are also characterized as having a disproportionate concentration of potentially hazardous land uses.

Politicians and land-use and natural resource managers cannot consider impacts to human well-being, nor preemptively shelter socio-environmentally vulnerable populations, without understanding the geography of socio-environmental vulnerability in relationship to the distribution of goods and services (Butler & Oluoch-Kosura, 2006). Socioeconomic vulnerability in the US–Mexico border region is a function globalization processes and local environmental change, as well as class, ethnicity, age, and gender (Wilder et al., 2010). People living in *colonias* do not have the resources to fund infrastructure improvements needed to minimize environmental degradation associated with development (Arnold, 1998; Fisher, 2008; Henkel, 2010; Moda, 2007; Norman, 2010; and Pepin, 1998).

Future generations living in the borderlands will be dependent on binational administrations adopting management strategies that best accommodate sustainable development. A goal of sustainable development is to eliminate risks to the most vulnerable populations by making this central to decision-making processes (Adger, 2006; Nelson et al., 2007). A more sustainable future also requires new approaches to the way decisions are made about natural resources, where the benefits and services provided by ecosystems are recognized and represented in planning and policy discussions (Hancock, 2010). The U.S. Geological Survey (USGS) has developed an Ecosystem Portfolio Model (EPM; Labiosa et al., 2009, p. 41) that presents the three pillars of sustainability (social, economic, and biophysical characteristics) together in an online decision support system to help managers visualize the impacts of management practices. The EPM offers a place-based holistic ecosystem analysis that portrays an unbiased view of regional impacts and ecosystem service tradeoffs in alternative scenarios and is being applied in the Santa Cruz Watershed at the U.S.–Mexico border of Arizona–Sonorato help decision-makers identify where ecosystem services distribution should be regulated across the US–Mexico border (Norman, Tallent-Halsell et al., 2010).

Definitional, conceptual, methodological, and data-related concerns raise questions in regards to the potential of mapping environmental equity (Maantay, 2002). This is magnified when the challenge extends across international boundaries where large economic disparities exist. The Gross Domestic Product (GDP) is the value of all goods and services produced (Briguglio & Galea, 2002). In the United States, the GDP per capita, is more than quadruple to that in Mexico – making crossborder economic comparison highly skewed. Advances made in the mapping of social indicators using compound indices can be used to identify where vulnerable populations exist in the borderlands (Anderson & Gerber, 2007; Collins et al., 2010; Lara-Valencia, Declet-Barreto, & Keys, 2008). Anderson and Gerber (2007) combine Mexican and U.S. Census variables in discussing income and poverty in *municipios* and counties. Lara-Valencia et al. (2008) developed a Socio-Environmental Vulnerability Index (SEVI) that classifies residential areas binationally at the census block level in order to investigate the health impacts of transportation facilities in Ambos Nogales.

Cutter and Finch (2008) recognize two research veins to describe vulnerability: (i) human-environmental vulnerability to global environmental processes (climate change and its impacts) and (ii) vulnerability to natural-hazards or disasters – both of which agree that exposure, sensitivity, and response require measurements of both environmental and social systems. Vulnerable populations living in *colonias* are more susceptible to harmful impacts associated with land-use and climate change (Liverman, 1990; Wilder et al., 2010). Flooding can be considered beneficial to the environment and is a natural occurrence, but can also be devastating to natural systems when impervious surface increases and vegetation is removed. Floods can interfere with drainage, damage property and infrastructure, and reduce the economic value of land. Soil erosion is the detachment of soil particles that are transported as sediment by flowing water. Sediment yield is the total amount of sediment detached, transported and deposited or discharged. Sediment is a major pollutant in waterways and a transporter of contaminants (Lane, Hernandez, & Nichols, 1997; Norman, Guertin, & Feller, 2008). Flooding and erosion are two main issues confronting people in the borderlands in the face of climate change that impact human livelihoods, health, and sometimes mortality (Norman, Hirsch et al., 2008; Norman, Huth et al., 2010, p. 63). For example, in January 2008, a 5-foot-high concrete barrier was constructed by the U.S. Border Patrol in a storm-water tunnel to block illegal immigration in Ambos Nogales – on July 12, of the same year, a severe thunderstorm caused major flooding around the structure (Wilder et al., 2010). Photographs depict five feet of standing water south of the border wall, where $8 million worth of damage was reported, including 578 homes, 45 cars, and a collapsed tunnel in Nogales, Sonora (McCombs, 2008). Regulating services, such as flood and erosion-control can help protect communities from extreme climate events such as rainstorms and droughts (Ash et al., 2010).

The objective of this paper is to demonstrate a method to map the distribution of socio-environmentally vulnerable populations across international boundaries and show how these social dimensions can be compared to regulating ecosystem services, to promote binational environmental justice. This is a challenging analysis with many methodological obstacles to overcome, including variances in resolution of the data, data quality, data comparability, modeling resolution and uncertainty – all of which constrain the analysis and generate issues of certainty and reliability in the outcomes, placing limitations on what can be achieved. Yet, this analysis is intended to present a learning process in which methodologies stand to be tried and then improved subsequently. We describe the development of a Modified Socio-Environmental Vulnerability Index (M-SEVI) for the Santa Cruz Watershed, using determinants from binational census and neighborhood data that depict levels of education, access to resources, migratory status, housing, and number of dependents. The Soil and Water Assessment Tool (SWAT), a hydrologic model, is also applied to the watershed to derive estimates of historical ecosystem services provision, of both flood and erosion-control. This combination of social (M-SEVI) and biophysical (SWAT) models, provides a tool for sustainable land-use planning that can enable more equitable management of resources.

Study area

The Santa Cruz River is a binational river in the Sonoran Desert that flows across the Arizona-Sonora portion of the U.S.–Mexico border and drains the binational Santa Cruz Watershed (Fig. 1). In this description of the study area, we will follow the river through the watershed, describing the environment, people, and potential issues associated with the nexus along the way.

The Santa Cruz River originates in the southwest corner of the Santa Cruz Watershed in a grassland and cattle-grazing region in Arizona, called the San Rafael Valley, then flows south across the international border at Lochiel into a u-turn through farmlands and ranches in Sonora, Mexico, and back into Arizona where agricultural settlements exist (Brown, 2002, p. 27). The southernmost Nogales Wash tributary begins in Sonora, Mexico and travels north through Heroica Nogales (a.k.a. Nogales), Sonora, Mexico, surrounded by the *colonias* of Solidaridad, Veracruz, Flores Magón and Margarita Maza de Juarez. The Nogales Wash runs into Nogales, Arizona and the *colonias* of Chula Vista and Pete Kitchen before it's confluence with the Santa Cruz River. Ambos Nogales ("both" Nogales) is a major urban hub of International export, that faces water issues including the provision of supply, infrastructure and waste facility maintenance, inter-basin transfers, flooding problems, and associated environmental quality issues (Morrison Institute for Public Policy 2008, 2009; Norman, Huth et al., 2010a).

Streamflow north of Nogales in the Santa Cruz River is supported mostly by wastewater (effluent) from the International Wastewater Treatment Plant at Rio Rico. The Sonoita Creek tributary to the Santa Cruz River originates in Sonoita, Arizona, northeast of Ambos Nogales, and feeds into the Patagonia and the southern Santa Rita Mountains area, which were mined intermittently from the 1600's to the mid- 1960's, for silver, lead, copper, zinc, and gold. Locally disturbed surface water is highly acidic because of the association with sulfide pyrite (Brady, Gray, Wissler, & Guertin, 2001; Norman, Gray, Guertin, Wissler, & Bliss, 2008a). However, the Sonoita Creek is one of a few remaining permanent streams in the watershed and provides for a wide array of diverse species and habitats protected by The Nature Conservancy.

The Santa Cruz River flows to the northwest with contributions from the Sonoita Creek, through the Tumacácori National Historical Park, yet surface flows are intermittent only after precipitation events in the communities of Tubac, Elephant Head, Green Valley, and Sahuarita. As the course of the river continues north, it crosses the San Xavier District of the Tohono O'odham Nation. The San Xavier District is approximately 70,000 acres, with several interrelated land and water-management issues related to leased parcels of land managed by a major copper mining firm (Brown, 2002, p. 27). East of the San Xavier and the Santa Cruz River are the communities of Vail, Old Nogales Hwy, and Littletown.

The Santa Cruz River becomes channelized for flood control purposes as its course moves through urban reaches of Tucson, Avra Valley East, and Cortaro, after which it drains to the Gila River and ultimately the Colorado River (Brown, 2002, p. 27). The population of the Tucson Metropolitan area is about 1 million people, and the city's major contributors to population and economy are the University of Arizona and Davis-Monthan Air Force Base. The Pascua Yaqui Indian Village is located inside of Tucson city limits. The Morrison Institute (2008, 2009) identifies rapid groundwater use, travel/transportation considerations, related to urbanization, water quantity, and river restoration as major issues in Tucson. Catalina and Oro Valley are located north of Tucson with urban housing, small ranches, and recreational bike paths. The tourist community of Summerhaven is located on Mount Lemmon in the Santa Catalina Mountains.

According to the 2005 Mexican and the 2000 United States' national censuses, 1,070,100 people live in the binational Santa Cruz Watershed: 194,272 are in Mexico and 875,828 in the U.S. There are 19 *colonias* in the Santa Cruz Watershed, 8 of which are south of the border (Donelson & Esparza, 2010b; Esparza & Donelson, 2008; Norman, Donelson, Pfeifer, & Lam, 2006).

Materials and methods

In order to identify where vulnerable populations coexist with declining ecosystem services in the watershed, we first developed the Modified Socio-Environmental Index (M-SEVI). People with higher levels of education, easier access to resources, nonexistent migratory status, secure housing, and limited number of dependents are shown to have stronger ties to their community, better foundations from which to draw support, and higher resilience to

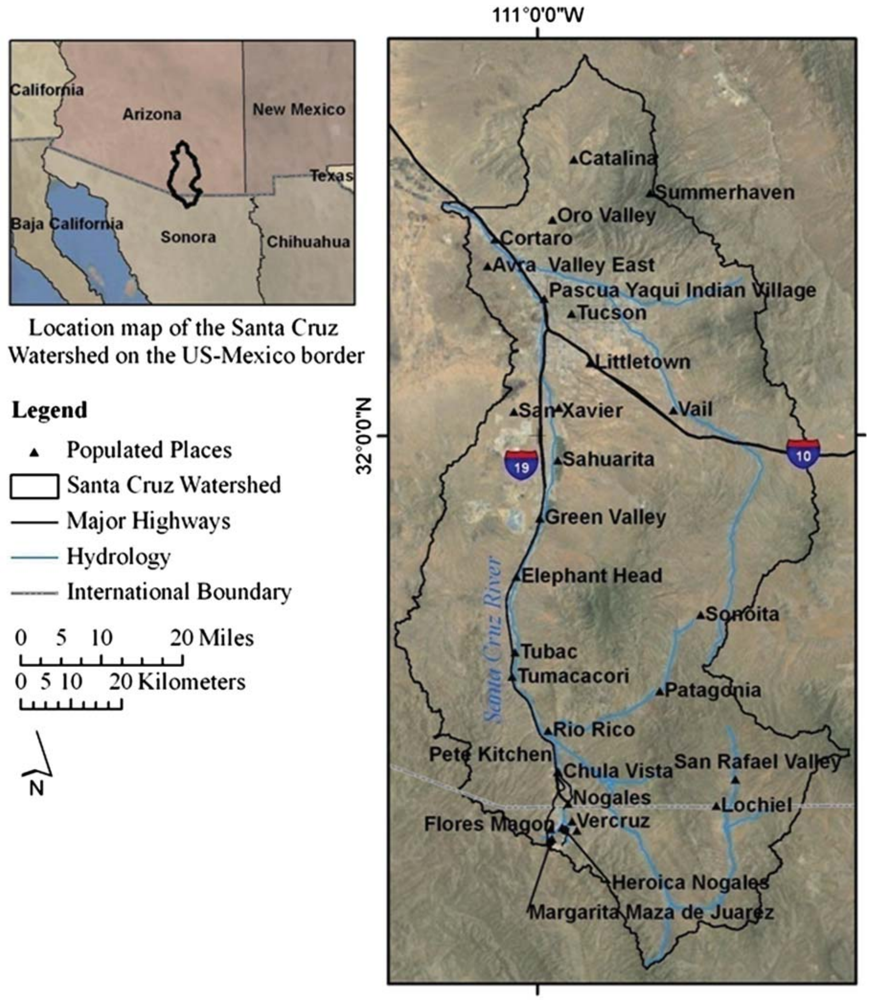

Fig. 1. Map of the Santa Cruz Watershed depicting relationship to Arizona and Sonora, Mexico with major highways, cities and towns, and hydrologic features.

change (Cutter, Boruff, & Shirley, 2003; Cutter & Finch, 2008; Donelson & Esparza, 2010a). We adapted available indicators identified by Lara-Valencia et al. (2008) and combined them with local information describing *colonias* to create the M-SEVI. We then applied the Soil and Water Assessment Tool (SWAT) model using snapshots of land cover from different time periods to create estimates of water and sediment yield. The resulting distribution of the M-SEVI is then compared to analyses of erosion- and flood-regulating services derived from the SWAT to examine environmental justice in the distribution of services.

Modified-SEVI

A compound index is applied to census data in the Santa Cruz Watershed, comprising 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 other services normally available in urban contexts; and (iii) a Household Assets dimension, which provides an indirect measure of household income by measuring the amount of wealth controlled by the families in each city. Using census data, collected and documented by U.S. (2000) and Mexico (2005), these dimensions were calculated across the U.S.–Mexico border. The Mexican census defines the census areas by the Basic Geo-Statistical Areas (AGEBs, by their Spanish acronym). The variance in institutional, governance, and social contexts of the data are representative of their origin and regular inconsistencies associated with geospatial data remain, including issues of quality, coverage, and reliability. Census data is not 100% accurate because some people do not fill out forms or may fill them out incorrectly (amongst many other potential data errors), but it is the most robust survey available in both countries and presents a general model of the social and demographic characteristics of the population (Skerry, 2000). Integration of different scales, cultural items, and statistical questions make it difficult to create completely comparable census geographies across the international border, but a set of like variables aligned across the border and a suitable spatial analysis was implemented using both countries' datasets. The Santa Cruz watershed census dataset includes information describing households and residents of 173 AGEBs in the Sonora portion of the watershed and 617 census blocks in Arizona.

The Population Characteristics dimension is made up of three variables. The 'Economic Dependency Ratio' (EDRatio) reports the number of children and elderly living in the neighborhood compared to the rest of the population. Age extremes affect the ability of a person to respond and families with large numbers of dependents often have limited finances to outsource care compromising their abilities to handle change (Cutter et al., 2003). The 'No High School Diploma Rate' (NoHSDRate) describes those with lower education, a condition that constrains the ability to understand and have access to information (John Heinz III Center for Science,

Table 1
Dimensions, measurements and formulas of Modified Socio-Environmental Vulnerability (modified from Lara-Valencia et al., 2008).

Dimension	Variable	Measurement	Formula
Population characteristics	Economic Dependency Ratio = EDRatio	Economic Dependency Ratio is the sum of residents of age 0–14 and 65+ divided by the number of residents in the small area unit (%)	(Total population 0–14 years old + Total population 65 or older)/Total Population
Population characteristics	No High School Diploma Rate = NoHSDRate	No High School Diploma Rate is the number of residents of age 25+ with no high school diploma divided by all the residents of age 25+ in the small area unit (%)	Population 25 years and older high school graduate/Population of 25 years or older
Population characteristics	New Resident Rate = NewResidRate	New Resident Rate is the number of residents of age 5+ that moved from a different municipality after 1995 divided by all the residents of age 5+ (%)	Number of residents of age 5+ that moved from a different municipality after 1995/Population of five years or older
Urban aharacteristics	Incomplete Plumbing Rate = IncPlumbRate	Incomplete Plumbing Rate is the number of occupied housing units with incomplete plumbing divided by all the occupied housing in the small area unit (%)	Owner occupied, incomplete plumbing facilities/Total Households
Household assets	One Bedroom Rate = OneBedRate	One Bedroom Rate in the number of housing units with only 1 bedroom divided by all housing units in the small area unit (%)	Owner occupied – 1 rooms/Total Households
Household assets	Occupancy Rate = OccRate	Occupancy Rate is the aggregate number of households in the small area unity divided by the total number of residents (household size)	Total Population/Total Households

Economics, and the Environment 1999). Further, those with higher education have access to higher earnings, which leads to increased socioeconomic status, political power, and prestige – creating the ability to absorb losses and enhance resilience using insurance, social safety nets, and entitlement programs (Cutter et al., 2003). And, the third of the population variables is the 'New Resident Rate' (NewResidRate), which represents peoples who are new to their neighborhood. New migrants may not speak the language and not be familiar with how to obtain information, which increases vulnerability (John Heinz III Center for Science, Economics, and the Environment 1999; Donelson & Esparza, 2010a).

The Urban Characteristics dimension has only one variable in the M-SEVI, the 'Incomplete Plumbing Rate' (IncPlumbRate). According to the Census, complete plumbing facilities means that a housing unit has hot and cold piped water, a flush toilet, and a bathtub or shower – those homes who do not have these three things somewhere in their house are considered those with "incomplete plumbing facilities". In the U.S., Arizona has the second highest rate of incomplete plumbing (7.8 percent) after Alaska (U.S. Environmental Protection Agency 2011). The Household Assets dimension is represented by two variables in the M-SEVI: the 'One Bedroom Rate' (OneBedRate) and the 'Occupancy Rate' (OccRate). These variables represent the value and quality of living conditions, an indicator of the state of economic health of a community. Table 1 describes how each dimension of the M-SEVI is quantified using binational census data in a GIS.

These dimensions mimic the variables developed by Lara-Valencia et al. (2008) or are slightly altered to accommodate available data, as follows:

- the "EDRatio" variable was adjusted to calculate population of youths 14 and under vs. 11 (based on data available) and under;
- binational information describing telephone service, renter occupancy automobile ownership, and complete kitchens are not available and therefore left out of this index; and
- the "OccRate" variable was altered to represent number of people per household vs. number of people per room.

The six variables are calculated across the census boundaries in Santa Cruz Watershed (Fig. 2).

The census data are used to identify several communities that, compared to surrounding areas, are disproportionately either young or elderly, low-income, and whose residents are more likely than residents of surrounding areas to lack a high school education. Because Hispanics are undercounted in the census at a rate approximately seven times higher than that of non-Hispanic whites (Skerry, 2000), and to better depict lifestyles in the borderlands, we developed a *colonias* variable to be factored in. Migrant workers usually engage in agriculture and low skilled service jobs (housekeeping, childcare, and gardening) that put them at a disadvantage when disposable income decreases and these jobs are less marketable (Cutter et al., 2003; John Heinz III Center for Science, Economics, and the Environment 1999).

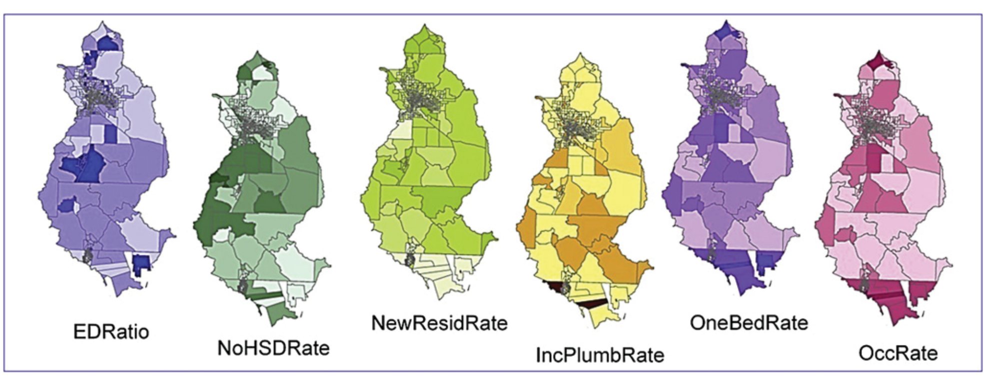

Fig. 2. Spatial distribution of each variable in the Santa Cruz Watershed (stretched from 0 to 1 in a geometrical interval classification—darker colors represent higher rates), where Economic Dependency Ratio = EDRatio, No High School Diploma Rate = NoHSDRate, New Resident Rate = NewResidRate, Incomplete Plumbing Rate = IncPlumbRate, One Bedroom Rate = OneBedRate, and Occupancy Rate = OccRate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The United States federal government does not define spatial units called *colonias* in the same way that it defines census tracts or counties. However, the U.S. Department of Housing and Urban Development (HUD) funded a project in 2000 that enabled the mapping and monitoring of *colonias* along the U.S.–Mexico Border (Norman et al., 2004, 2006). The project was implemented by the USGS working in cooperation with the Mexican Instituto Nacional de Estadística Geografía e Informática (INEGI). The project required the identification of *colonia* boundaries in a geospatial information system (GIS) format in sister cities along the Arizona–Sonora border, including Ambos Nogales (Norman et al., 2004). Community members identified the locations of waterlines, sewer lines, and inadequate housing – using these, *colonia* boundaries were identified and traced onto hard-copy maps and automated into digital format (Norman et al., 2006). Esparza and Donelson (2008) and Donelson and Esparza (2010b) depict the locations of federally-recognized *colonias* in the U.S.-portion of the Santa Cruz Watershed. The *colonias* boundaries were overlain onto the merged census boundaries and where overlap occurred, census boundaries are given a value of 1 vs. 0 (for areas that are not *colonias*) to comprise a 'Colonia Rate' (Fig. 3).

We weighted the variables used to calculate the M-SEVI equally – first summing the variables and then dividing by 7 – to generate an index range between 0 and 1, depicting low-high socio-environmental vulnerability (Eq.1).

Equation 1. Modified Socio-Environmental Vulnerability Index Formula

$$\begin{aligned}&\text{Modified Socio-Environmental Vulnerability Index (M-SEVI)}\\&= (\text{EDRatio} + \text{NoHSDRate} + \text{NewResidRate} + \text{IncPlumbRate}\\&\quad + \text{OneBedRate} + \text{OccRate} + \text{ColoniaRate})/7\end{aligned}$$

Soil and water assessment tool

The Soil and Water Assessment Tool (SWAT) is a process-based, semi-distributed watershed model developed to predict impacts of

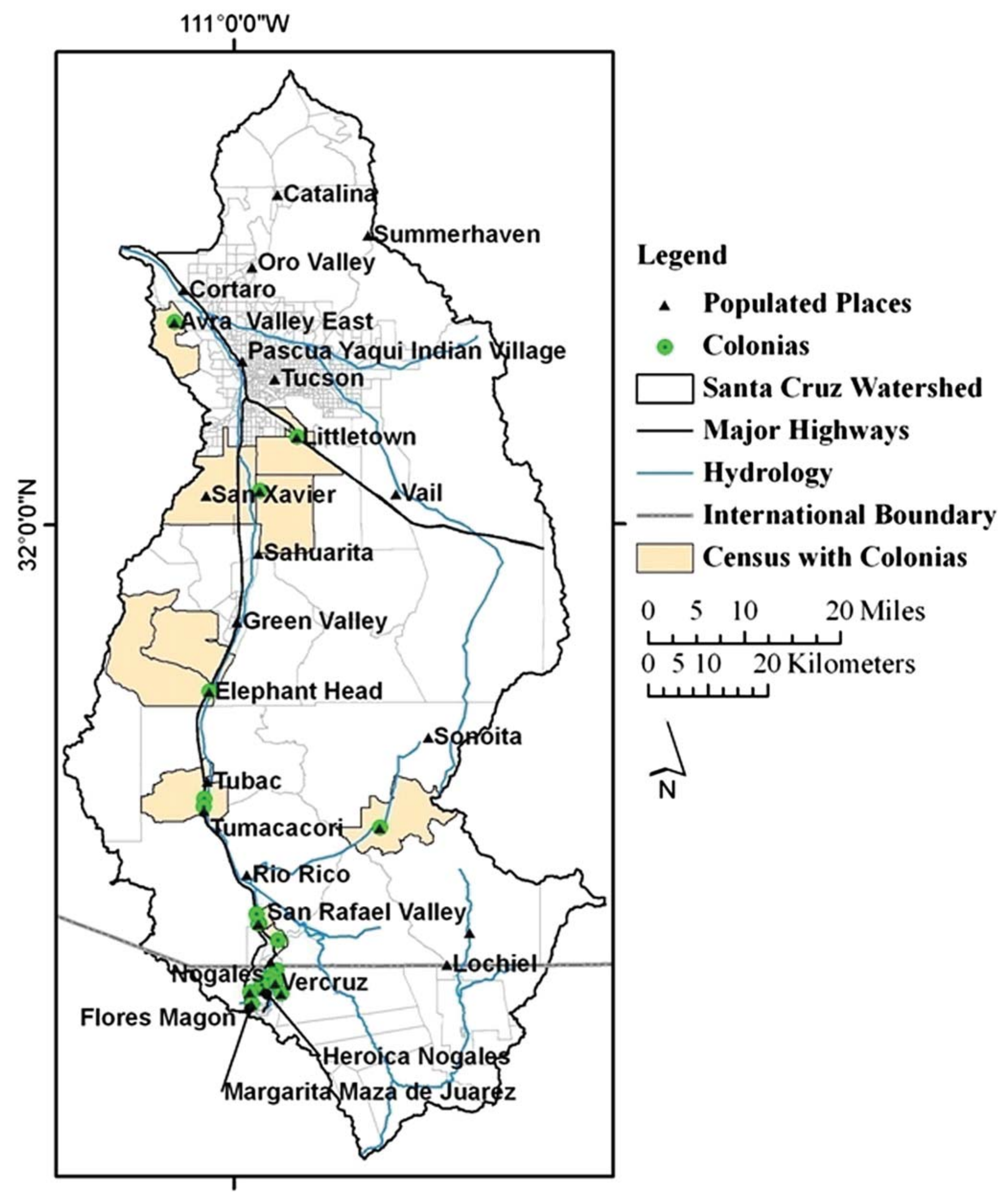

Fig. 3. *Colonias* locations (modified from Donelson & Esparza, 2010b; Esparza & Donelson, 2008; Norman et al., 2006) overlain on merged census boundaries of the Santa Cruz Watershed.

management practices on water and sediment with varying land-use/land cover (Arnold, Srinivasan, Muttiah, & Williams, 1998). The SWAT model has been applied to assess erosion- and flood potential under different development scenarios in many locations internationally and has been used in the field of ecosystem services to assess and quantify tradeoffs with water quality (Lautenbach, Gruber, Dorman, Strauch, & Seppelt, 2010), economic values (Immerzeel, Stoorvogel, & Antle, 2008), and agricultural provisioning (Swallow et al., 2009). The SWAT model is being adapted for the first time herein to offer a biophysical representation of ecosystem services that can be compared with social characteristics across the U.S.–Mexico border. We calibrated and validated SWAT at monthly-time step for four USGS gages using 22 weather stations in hydrological response units (Nie, Yuan, Tallent-Halsell et al., 2010; Nie, Yuan, Norman, Tallent-Halsell, & Callegary, 2010). SWAT was used to simulate long-term hydrological processes for two land-use scenarios, 1992 and 2001, derived from the U.S.–Mexico Border Environmental Health Initiative (BEHI) project (USGS, 2011), to determine the impacts of land-use change over a 9-year period.

Results

Socio-environmental vulnerability

The results of the M-SEVI and the distribution and range of socio-environmental vulnerability of neighborhoods in the Santa Cruz Watershed is presented in Fig. 4. The M-SEVI was classified for this map by geometric interval by minimizing the square sum of element per class to produce a result that is visually appealing and cartographically comprehensive. The index was divided into 5 categories to portray levels of vulnerability associated with the Santa Cruz Watershed, where no neighborhood scored higher than 0.4. Neighborhoods scoring in the top two of five categories of the classification (0.22–0.40) of the M-SEVI were deemed highly socio-environmentally vulnerable neighborhoods, compared to the rest of the watershed; this includes Avra Valley East, Green Valley, San Xavier, Tubac, Tumacacori, Littletown, Old Nogales Hwy, Chula Vista, Elephant Head, Pete Kitchen and Patagonia, Arizona, as well as Flores Magon, Margarita Maza de Juarez, Solidaridad, and Vercruz, Sonora. Twelve of these fifteen localities are recognized

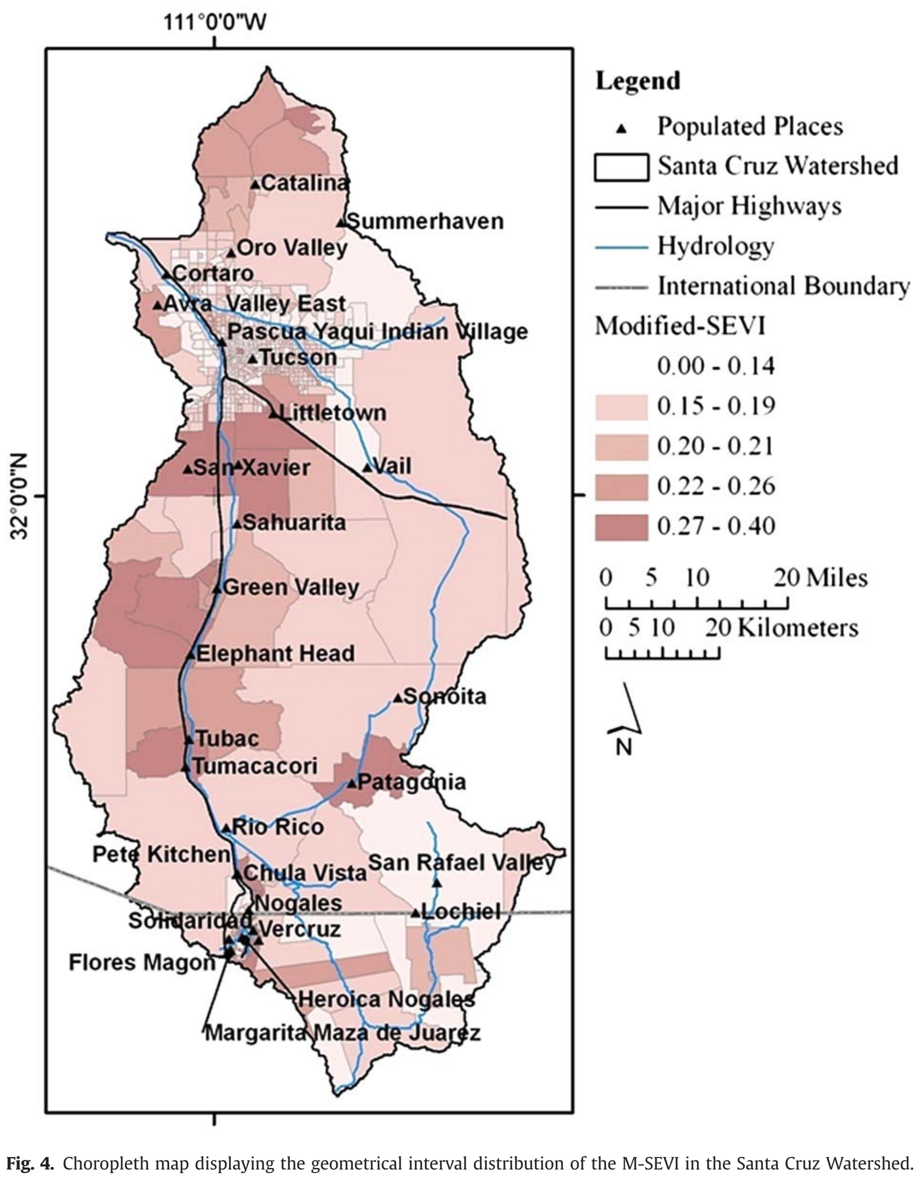

Fig. 4. Choropleth map displaying the geometrical interval distribution of the M-SEVI in the Santa Cruz Watershed.

colonias with inadequate housing and/or access to sewer or waterlines. The occupancy rate is higher, and a large proportion of the households in the area are composed mostly of persons at productive age, with no college education. This combination of attributes seems to indicate that the area is in a transitional stage with newly formed households replacing old-time resident families. Families who are predisposed to transitional change are more vulnerable to environmental changes since they are not yet rooted in communities.

A cluster of moderately socio-environmentally vulnerable (a combination of the two middle classes; 0.15–0.21) residential areas are located at Oro Valley, Catalina, Cortaro, Sahuarita, Sonoita, and Rio Rico, Arizona. In contrast with the high socio-environmental vulnerability neighborhoods described above, neighborhoods in this area report slightly higher dependency ratios, which might be indicative of a larger number of more mature households. Less educated households are also in this group and the percentage of houses with only one bedroom or lacking basic services, like plumbing, is lower.

The residential areas of Vail, Lochiel, Tucson, Pascua Yaqui Indian Village, Summerhaven, San Rafael Valley, and Nogales, Arizona and Heroica Nogales, Sonora report very low socio-environmental vulnerability (the lowest class; 0–0.14). Additionally, the outskirts of the watershed, in more rural zones portray a lower socio-environmental vulnerability. There are scatterings of neighborhoods located at the mid-section of the Tucson metropolitan area and that present a short time of residence and high occupancy, though housing and urban conditions are slightly above average. Fig. 4 is a choropleth map that portrays the population as distributed homogenously throughout the census units.

Using a combination of the two highest categories portrayed (0.22–0.26 and 0.27–0.4) to identify more vulnerability, neighborhood areas greater than 0.22 were extracted from M-SEVI map (Fig. 4) to create a new layer depicting "highly socio-environmentally vulnerable populations" and overlaid on the population density map (Fig. 5). The dasymetric mapping tool was applied to develop the population density map, using the merged census and land cover data of the watershed from 2009 (Villarreal, Norman, Wallace, & van Riper, 2011, p. 26). Dasymetric mapping provides a surface representation of population density (population/grid cell; Sleeter, 2008, p. 2). Population density was mapped with intervals selected to cartographically portray the

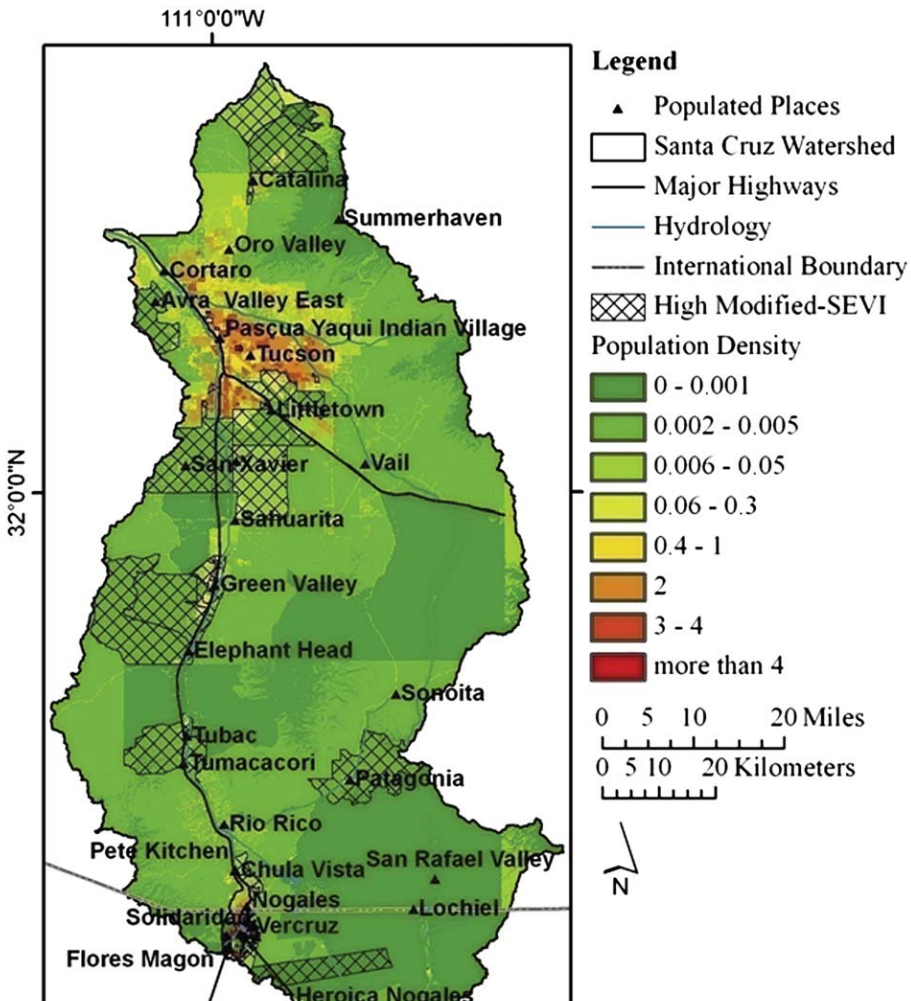

Fig. 5. Population map displaying persons per 30-m. pixel overlain by neighborhood areas identified as having a high socio-environmental vulnerability.

extent and density of population across the watershed. In the Santa Cruz Watershed, areas north of Catalina, south of Tucson, and parts of Green Valley, Nogales, Arizona, and south of Nogales, Sonora, are clearly identified as being more densely-populated, as well as, socio-environmentally vulnerable communities (Fig. 5).

Ecosystem services assessment

Ecosystem service value is determined by the location of ecological processes that create the provision of services (supply) and the location of people who derive benefits from the services (demand; Tallis & Polasky, 2009). The coupling of the biophysical (SWAT) and social (M-SEVI) aspects of the watershed allows us to identify densely-populated and socio-environmentally vulnerable communities subjected to a decline in water and erosion regulating ecosystem services through time. The SWAT model cannot provide reliable quantitative estimates of runoff and erosion without careful calibration, and both SWAT and M-SEVI are subject to the assumptions described herein and limitations of data input. While results are provided numerically, this study was designed to evaluate relative change and should only be used to provide qualitative estimates of runoff and erosion for comparison-sake. Further, we are not trying to assess causality between the M-SEVI and ecosystem services, but are simply comparing them.

Land-use input from 1992 and from 2001 in the upper Santa Cruz Watershed is the only difference in two iterations of the SWAT model, everything else was kept constant. The major land-use change recognized is the 45% increase in urbanization over ten years. Surface runoff mimicked this urban expansion and the increase in runoff volume (water yield) and velocity impacts associated erosion processes and associated sediment yield. In Fig. 6, difference maps showing the spatial distribution of the difference between the 1992 and 2001 SWAT-simulated annual averaged sediment yield (t/ha; left) and annual averaged water yield (mm; right) are overlain with highly socio-environmentally vulnerable (>0.22) neighborhood areas identified using the M-SEVI. Both the results for sediment yield and water yield are portrayed using quantile intervals, for which data are classified into five categories with an equal number of units in each category for the most accurate and informative visual portrayal of the information.

The results for each populated place in the Santa Cruz Watershed, of both models, the social (M-SEVI) and biophysical (SWAT), are listed in Table 2.

In order to convey relative change of the provision of ecosystem services in the watershed in relation to vulnerable populations, we normalized the M-SEVI data to MIN = −1 and MAX = 1; note that this process identified values greater than 0.22 (our two previous categories identified as highly vulnerable)

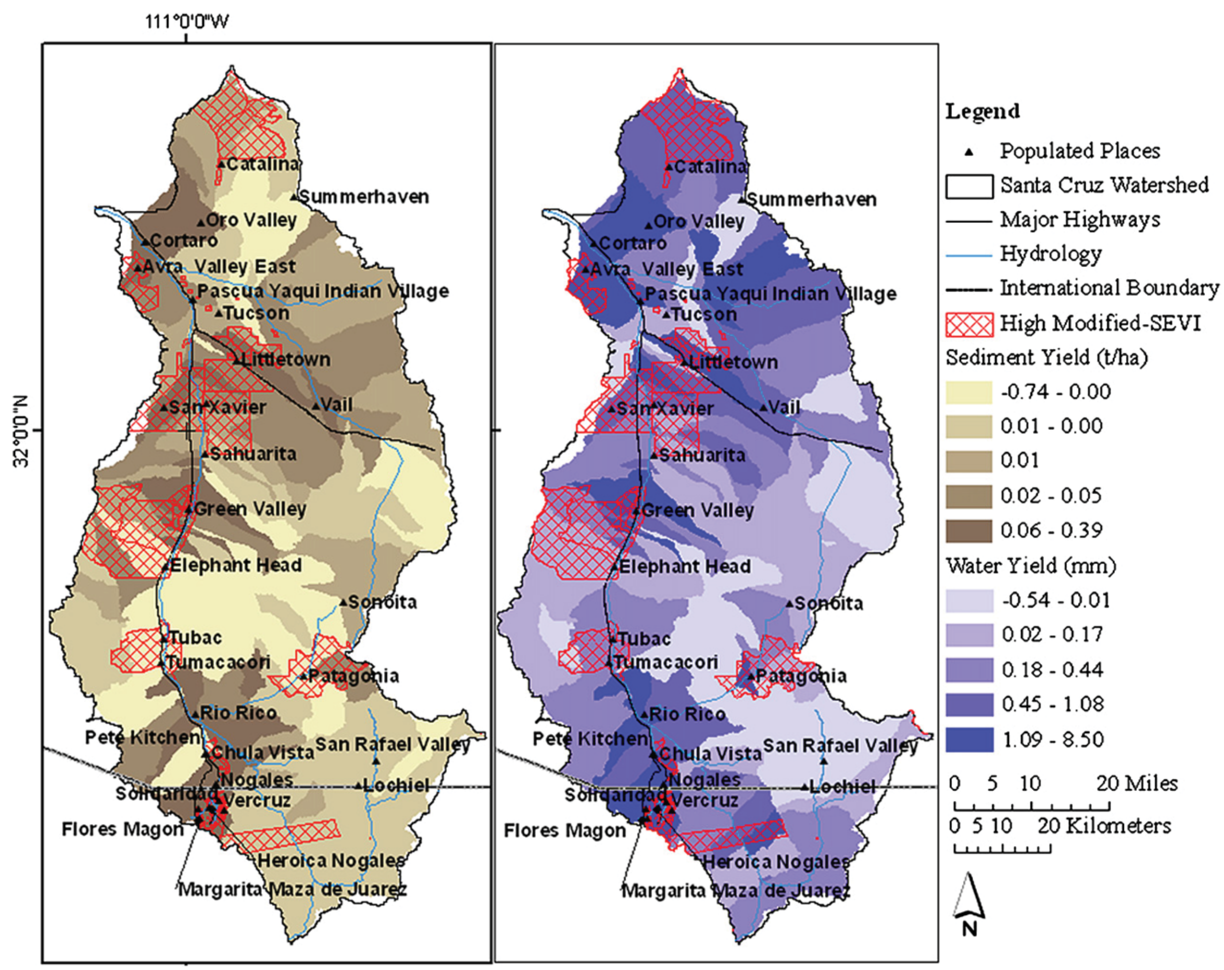

Fig. 6. Difference maps displaying the simulated difference that land-use change has on Sediment Yield (left) and Water Yield (right) in the Santa Cruz Watershed—these are calculated by subtracting SWAT results derived using classified land cover data in 1992 from 2001 and are overlain by neighborhood areas identified as highly socio-environmentally vulnerable by the M-SEVI.

Table 2
Comparison of the M-SEVI values and associated relative socio-environmentally vulnerability, change in the 1992 and 2001 SWAT-simulated annual averaged sediment yield (t/ha) and associated relative change in erosion prevention services, and change in annual averaged water yield (mm) and associated relative change in flood control services in localities of the Santa Cruz watershed.

Locality	M-SEVI	Change in sediment yield (t/ha)	Change in water yield (mm)
Avra Valley East, Arizona	0.25	0.22	2.52
Catalina, Arizona	0.17	0.01	0.73
Chula Vista, Arizona	0.30	−0.74	0.88
Cortaro, Arizona	0.18	0.11	4.50
Elephant Head, Arizona	0.38	−0.02	0.14
Flores Magon, Sonora	0.39	0.39	1.60
Green Valley, Arizona	0.26	0.06	1.19
Heroica Nogales, Sonora	0.11	0.39	1.60
Littletown, Arizona	0.30	0.06	1.10
Lochiel, Arizona	0.13	0.00	0.01
Margarita Maza de Juarez, Sonora	0.39	0.39	1.60
Nogales, Arizona	0.14	0.39	1.60
Old Nogales Hwy, Arizona	0.32	0.04	0.46
Oro Valley, Arizona	0.17	0.21	3.14
Pascua Yaqui Indian Village, Arizona	0.14	0.05	1.20
Patagonia, Arizona	0.33	−0.01	0.25
Pete Kitchen, Arizona	0.30	−0.10	0.56
Rio Rico, Arizona	0.16	0.05	1.43
Sahuarita, Arizona	0.20	0.00	0.10
San Rafael Valley, Arizona	0.13	0.00	−0.02
San Xavier, Arizona	0.31	0.06	0.72
Solidaridad, Sonora	0.37	0.39	1.60
Sonoita, Arizona	0.18	0.00	0.10
Summerhaven, Arizona	0.13	−0.04	−0.54
Tubac, Arizona	0.31	−0.22	0.29
Tucson, Arizona	0.11	0.00	0.01
Tumacacori, Arizona	0.31	−0.71	0.36
Vail, Arizona	0.13	0.08	0.62
Vercruz, Sonora	0.36	0.39	1.60

as greater than 0 (Fig. 7). To demonstrate the relationship between vulnerability and ecosystem services, the M-SEVI of populated places are displayed in order from low vulnerability to a high vulnerability on the chart in Fig. 7, with the provision of both flood and erosion-control regulating services. Environmental justice neighborhoods to be considered are those that have high socio-environmental vulnerability and a history of decreased regulating ecosystem services (flood and/or erosion-control). In Arizona, Avra Valley East has shown a decrease in erosion prevention services. Other social-environmentally vulnerable neighborhoods in the Arizona-portion of the watershed include Chula Vista, Tubac, and Tumacacori, which demonstrate a decrease in flood control services and Green Valley, Littletown, Pete Kitchen, San Xavier, Old Nogales Hwy, Patagonia, and Elephant Head, which show a decrease in both erosion prevention and flood control services over time. In Sonora, Mexico, the socio-environmentally vulnerable communities of Vercruz, Solidaridad, Flores Magon, and Margarita Maza de Juarez demonstrate a decrease in both erosion prevention and flood control services.

It is noted that because of rapid urbanization in the Santa Cruz Watershed, the land cover is changing to become more impervious and associated water and sediment yield are expected processes. In the areas of Oro Valley, Cortaro, Chula Vista, Tumacacori, and Avra Valley East, however, the SWAT model estimates a decrease in both of these. This could be because they are newer establishments in the United States, for which planning protocol requires permits enforcing more comprehensive flood and erosion-control practices. Newer developments south of the border (Margarita Maza de Juarez, Flores Magon, etc.), on the other hand, are most susceptible to flooding and erosion because no such imperative exists.

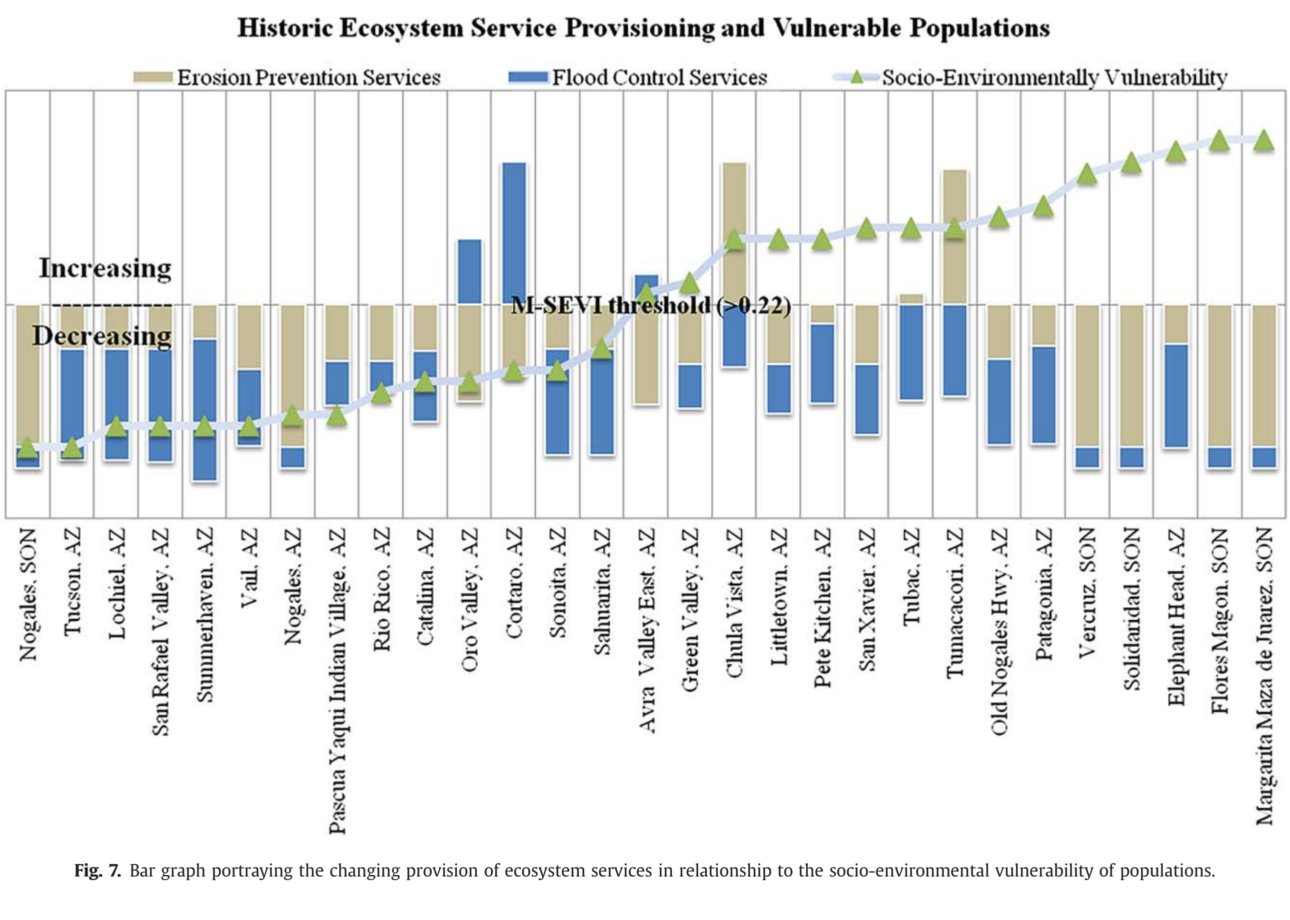

Fig. 7. Bar graph portraying the changing provision of ecosystem services in relationship to the socio-environmental vulnerability of populations.

Discussion

Costs of ecosystem service degradation are being consistently and disproportionately felt by the poor, which exacerbates social inequalities and conflict (Millennium Ecosystem Assessment, 2005). Free trade policies have allowed large investments between the U.S. and Mexico that are mutually beneficial; however, to promote sustainability in the region, binational land-use planners and others need tools to consider the impacts of development in terms of social displacement and environmental degradation. A more flexible approach to incorporate local variability of temporal and spatial changes in socio-environmental vulnerability within federal policy is necessary, especially along International boundaries.

In the United States, environmental justice is part of every federal agency's mission (Executive Order 12898) but the concept of vulnerability is complex and often argued about within the research community, which makes the establishment of viable metrics for measuring vulnerability problematic (Cutter & Finch, 2008). More conclusive spatial correlations need to be produced, with higher resolution and more up-to-date data, but this research offers a starting point to integrate ecosystem services and environmental justice considerations into sustainable development plans. The addition of the M-SEVI data layer for an ecosystem services assessment provides binational decision-makers with a mechanism to identify which socio-environmentally vulnerable populations have a history of access or exposure to ecosystem services and integrate environmental justice into future sustainable land-use planning. Resulting hot spots of vulnerability are critical for binational managers to consider in making decisions concerning land-use planning or policy change.

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References

Adger, W. N. (2004). The right to keep cold. *Environment and Planning A, 36*(10), 1711–1715. doi:10.1068/a37108.

Adger, W. (2006). Vulnerability. *Global Environmental Change, 16*(3), 268–281. doi:10.1016/j.gloenvcha.2006.02.006.

Agyeman, J., & Evans, B. (2004). "Just sustainability": the emerging discourse of environmental justice in Britain? *The Geographical Journal, 170*(2), 155–164. doi:10.1111/j.0016-7398.2004.00117.x.

Agyeman, J., & Evans, T. (2003). Toward just sustainability in urban communities: building equity rights with sustainable solutions. *Annals of the American Academy of Political and Social Science, 590*, 35–53.

Anderson, J. B., & Gerber, J. (2007). *Fifty years of change on the U.S.-Mexico border: Growth, development, and quality of life*. University of Texas Press.

Apitz, S. E. (2007). Conceptual frameworks to balance ecosystem and security goals. In I. Linkov, R. J. Wenning, & G. A. Kiker (Eds.), *Managing critical infrastructure risks: Decision tools and applications for port security* (pp. 147–173). Springer.

Arnold, C. A. (1998). Planning milagros: environmental justice and land use regulation. *Denver University Law Review, 76*, 1.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: model development. *JAWRA Journal of the American Water Resources Association, 34*(1), 73–89. doi:10.1111/j.1752-1688.1998.tb05961.x.

Ash, N., Bennett, K., Reid, W., Irwin, F., Ranganathan, J., Scholes, R., et al. (2010). Assessing ecosystems, ecosystem services, and human well-being. In N. Ash, H. Blanco, C. Brown, K. Garcia, T. Tomich, B. Vira, et al. (Eds.), *Ecosystems and human well-being: A manual for assessment practitioners* (1st ed.). Island Press.

Been, V., & Gupta, F. (1997). Coming to the nuisance or going to the barrios – a longitudinal analysis of environmental justice claims. *Ecology Law Quarterly, 24*, 1.

Briguglio, L., Cordina, G., Farrugia, N., & Vella, S. (2009). Economic vulnerability and resilience: concepts and measurements. *Oxford Development Studies, 37*(3), 229–247.

Briguglio, L., & Galea, W. (2002). *Updating and augmenting the economic vulnerability index*. Occasional Paper by the Islands and Small States Institute of the University of Malta. https://secure.um.edu.mt/__data/assets/pdf_file/0012/44130/eviar_briguglio_galea_ver4.pdf Version 4. Retrieved from.

Brady, L. M., Gray, F., Wissler, C. A., & Guertin, D. P. (2001). *Spatial variability of sediment erosion processes using GIS analysis within watersheds in a historically mined region, Patagonia Mountains, Arizona*. U.S. Geological Survey Open File Report 01–267. http://geopubs.wr.usgs.gov/open-file/of01-267/ Retrieved June 21, 2011.

Brown, C. (2002). *Binational watershed councils as instruments for conflict resolution in the Upper Santa Cruz River Basin*. Udall Center Publications. http://udall.jsdix.com/publications/sites/default/files/143_en.pdf Retrieved from.

Brundtland, G. H. (1987). World commission on environment and development. *Our Common Future*, 8–9.

Butler, C. D., Corvalan, C. F., & Koren, H. S. (2005). Human health, well-being, and global ecological scenarios. *Ecosystems, 8*(2), 153–162. doi:10.1007/s10021-004-0076-0.

Butler, C. D., & McMichael, A. J. (2006). Environmental health. In B. S. Levy, & V. W. Sidel (Eds.), *Social injustice and public health* (pp. 318–336). USA: Oxford University Press.

Butler, C., & Oluoch-Kosura, W. (2005). Human well-being across scenarios. In Millennium Ecosystem Assessment. (Ed.), *Ecosystems and human well-being* (1st ed.).. *Scenarios: Findings of the scenarios working group, Vol. 2* Island Press.

Butler, C. D., & Oluoch-Kosura, W. (2006). Linking future ecosystem services and future human well-being. *Ecology and Society, 11*(1), 30. http://www.ecologyandsociety.org/vol11/iss1/art30/ Retrieved June 21, 2011.

Camacho, D. E. C. (1998). *Environmental injustices, political struggles: Race, class, and the environment*. Duke University Press.

Carter, D. E., Peña, C., Varady, R., & Suk, W. A. (1996). Environmental health and hazardous waste issues related to the U.S.-Mexico border. *Environmental Health Perspectives, 104*(6), 590–594.

Collins, K., Guhathakurta, S., Sadalla, E., Pijawka, D., Peña, S., & Ley, J. (2010). *A longitudinal assessment of quality of life in the US-Mexico border region*. http://scerpfiles.org/cont_mgt/doc_files/EIR_06_2-3.pdf Project Number: EIR-06–2/3. Retrieved from.

Collins-Dogrul, J. (2006). Managing US-Mexico "border health": an organizational field approach. *Social Science & Medicine, 63*(12), 3199–3211. doi:10.1016/j.socscimed.2006.07.031.

Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003). Social vulnerability to environmental hazards*. *Social Science Quarterly, 84*(2), 242–261.

Cutter, S. L., & Finch, C. (2008). Temporal and spatial changes in social vulnerability to natural hazards. *Proceedings of the National Academy of Sciences, 105*(7), 2301–2306. doi:10.1073/pnas.0710375105.

Donelson, A., & Esparza, A. X. (2010a). Undocumented immigrants and quality of life in New Mexico and Arizona colonias. *Journal of Borderlands Studies, 22*(1), 39–52.

Donelson, A., & Esparza, A. X. (2010b). *The colonias reader: Economy, housing, and public health in U.S.-Mexico border colonias*. Tucson: University of Arizona Press.

Dow, K., Kasperson, R. E., & Bohn, M. (2006). Exploring the social justice implications of adaptation and vulnerability. In W. N. Adger, J. Paavola, S. Huq, & M. J. Mace (Eds.), *Fairness in adaptation to climate change*. The MIT Press.

Esparza, A. X., & Donelson, A. J. (2008). *Colonias in Arizona and New Mexico: Border poverty and community development solutions*. University of Arizona Press.

Esparza, A., Waldorf, B., & Chavez, J. (2004). Localized effects of globalization: the case of Ciudad Juárez, Chihuahua, Mexico. *Urban Geography, 25*(2), 120–138. doi:10.2747/0272-3638.25.2.120.

Faber, D. J. (1998). *The struggle for ecological democracy: Environmental justice movements in the United States*. Guilford Press.

Fisher, K. (2008). *The colonia and the landfill: Colonias development council V*. Rhino Environmental Services, Inc.. http://repository.unm.edu/handle/1928/6838 Retrieved June 21, 2011.

Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C. S., & Walker, B. (2002). Resilience and sustainable development: building adaptive capacity in a world of transformations. *AMBIO, 31*(5), 437–440.

Gomez, S. (1993). Environmental risks related to the maquiladora industry and the likely environmental impact of NAFTA. *La Raza Law Journal, 6*, 174.

Gruben, W. C. (2001). Was NAFTA behind Mexico's high maquiladora growth? *Economic and Financial Review*21. http://dallasfed.org/research/efr/2001/efr0103b.pdf Third QuarterRetrieved from.

Hancock, J. (2010). The case for an ecosystem service approach to decision-making: an overview. *Bioscience Horizons*, . doi:10.1093/biohorizons/hzq013.

Henkel, D. S., Jr. (2010). Upholding environmental justice in the colonias: a New Mexico approach. *Journal of Borderlands Studies, 24*(1), 62–75.

Immerzeel, W. W., Stoorvogel, J., & Antle, J. (2008). Can payments for ecosystem services secure the water tower of Tibet? *Agricultural Systems, 96*(1–3), 52–63. doi:10.1016/j.agsy.2007.05.005.

John Heinz III Center for Science, Economics, and the Environment, H. (1999). *The hidden costs of coastal hazards: Implications for risk assessment and mitigation* (1st ed.). Island Press.

Labiosa, W. B., Bernknopf, R., Hearn, P., Hogan, D., Strong, D., Pearlstine, L., et al. (2009). *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 http://pubs.usgs.gov/sir/2009/5181/ Retrieved June 21, 2011.

Lane, L. J., Hernandez, M., & Nichols, M. (1997). Processes controlling sediment yield from watersheds as functions of spatial scale. *Environmental Modelling & Software, 12*(4), 355–369. doi:10.1016/S1364-8152(97)00027-3.

Lara-Valencia, F., Declet-Barreto, J., & Keys, E. (2008). Spatial equity and transportation hazard along cross-border trade corridors: the case of ambos nogales. *Journal of Borderlands Studies, 23*(2), 1–18.

Lautenbach, S., Gruber, B., Dorman, C. F., Strauch, M., & Seppelt, R. (2010). Quantifying ecosystem service trade-offs. In *Modelling for environment's sake, fifth biennial meeting*. Ottawa, Canada: International Congress on Environmental Modelling and Software.

Liverman, D. M. (1990). Vulnerability to global change. Report on an International Workshop. In R. Kasperson (Ed.), *Understanding global environmental change: The contributions of risk analysis and management* (pp. 8–23) Worcester MA: Clark University, Earth Transformed Program. http://www.environment.arizona.edu/files/env/profiles/liverman/liverman-1990-kasperson-et-al.pdf Retrieved June 22, 2011.

López-Hoffman, L., McGovern, E. D., Varady, R. G., & Flessa, K. W. (2009). *Conservation of shared environments: Learning from the United states and Mexico*. University of Arizona Press.

Maantay, J. (2002). Mapping environmental injustices: pitfalls and potential of geographic information systems in assessing environmental health and equity. *Environmental Health Perspectives, 110*(Suppl. 2), 161–171.

McCombs, B. (2008). Mexico ties flooding in Nogales to U.S. Border Patrol-built wall. *Arizona Daily Star*, July 23. http://azstarnet.com/news/local/border/article_a11265b0-17c3-5bed-b50a-72e5d17e1369.html#ixzz1d9O3wLR8 Retrieved November 7, 2011.

Millennium Ecosystem Assessment. (2003). *Ecosystems and human well-being: A framework for assessment* (1st ed.). Island Press.

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Current state and trends: Findings of the condition and trends working group* (1st ed.). Island Press.

Moda, M. A. (2007). *A critical review of current EJ research: Where do we go from here*. Master thesis; Clark University: Worcester, MA, USA. Retrieved from https://www.clarku.edu/departments/idce/docs/Moda_2007.pdf.

Morrison Institute. (2008). *Megapolitan: Arizona's sun corridor*. http://morrisoninstitute.asu.edu/publications-reports/Mega_AzSunCorr/view Retrieved June 21, 2011.

Morrison Institute. (2009). *Megapolitan: Arizona's sun corridor*. http://morrisoninstitute.asu.edu/morrison-update/megapolitan-arizonas-sun-corridor Retrieved June 21, 2011.

Nelson, D. R., Adger, W. N., & Brown, K. (2007). Adaptation to environmental change: contributions of a resilience framework. *Annual Review of Environment and Resources, 32*(1), 395–419. doi:10.1146/annurev.energy.32.051807.090348.

Nie, W., Yuan, Y., Tallent-Halsell, N., Norman, L. M., Jackson, M., & Erickson, C. (2010). Assessing surface water availability in the Upper Santa Cruz watershed. In *65th international soil and water conservation society (SWCS) annual conference*. St. Louis: Missouri, July 18–21, 2010.

Nie, W., Yuan, Y., Norman, L. M., Tallent-Halsell, N., & Callegary, J. (2010). *Assessing climate change impacts on surface water availability in the Upper Santa Cruz Watershed*. Tucson, Ariz: Arizona Hydrological Society. Sept 1–4.

Norman, L. M. (2010). Urbanization and environmental health in Arizona colonias. In A. Donelson, & A. X. Esparza (Eds.), *The colonias reader: Economy, housing, and public health in U.S.-Mexico border colonias*. Tucson: University of Arizona Press.

Norman, L. M., Donelson, A., Pfeifer, E., & Lam, A. H. (2006). *Colonia development and land use change in Ambos Nogales, United states-Mexican border*. U.S. Geological Survey Open File Report: 2006-1112. http://pubs.usgs.gov/of/2006/1112/ Retrieved June 21, 2011.

Norman, L. M., Gray, F., Guertin, D. P., Wissler, C., & Bliss, J. D. (2008). Tracking acid mine-drainage in Southeast Arizona using GIS and sediment delivery models. *Environmental Monitoring and Assessment, 145*(1–3), 145–157. doi:10.1007/s10661-007-0024-5.

Norman, L., Guertin, D., & Feller, M. (2008). A coupled model approach to reduce nonpoint-source pollution resulting from predicted urban growth: a case study in the Ambos Nogales watershed. *Urban Geography, 29*(5), 496–516. doi:10.2747/0272-3638.29.5.496.

Norman, L. M., Hirsch, D. D., & Ward, A. W. (2008). *Proceedings of a USGS workshop on facing tomorrow's challenges along the U.S.-Mexico border; monitoring, modeling, and forecasting change within the Arizona-Sonora transboundary watersheds*. U.S. Geological Survey Circular 1322. http://pubs.usgs.gov/circ/1322/ Retrieved June 21, 2011.

Norman, L. M., Huth, H., Levick, L., Shea Burns, I., Phillip Guertin, D., Lara-Valencia, F., et al. (2010). Flood hazard awareness and hydrologic modelling at Ambos Nogales, United States–Mexico border. *Journal of Flood Risk Management, 3*(2), 151–165. doi:10.1111/j.1753-318X.2010.01066.x.

Norman, L. M., Parcher, J. W., & Lam, A. H. (2004). *Monitoring colonias along the U.S.-Mexico border*. U.S. Geological Survey Fact Sheet. USGS FS 2004-3070 – Colonias. http://egsc.usgs.gov/isb/pubs/factsheets/fs307004.html Retrieved June 21, 2011.

Norman, L. M., Tallent-Halsell, N., Labiosa, W., Weber, M., McCoy, A., Hirschboeck, K., et al. (2010). Developing an ecosystem services online decision support tool to assess the impacts of climate change and urban growth in the Santa Cruz watershed; where we live, work, and play. *Sustainability, 2*(7), 2044–2069. doi:10.3390/su2072044.

Pepin, M. (1998). *Texas colonias: An environmental justice case study* (November 5, 1998). http://itc.ollusa.edu/faculty/pepim/philosophy/cur/colonias.htm Retrieved December 2, 2003.

Rodríguez, J. P., Beard, T. D., Jr., Bennett, E. M., Cumming, G. S., Cork, S., Agard, J., et al. (2006). Trade-offs across space, time, and ecosystem services. *Ecology and Society, 11*(1), 28. http://www.ecologyandsociety.org/vol11/iss1/art28/ Retrieved June 21, 2011.

Prugh, T., Costanza, R., & Daly, H. E. (2000). *The local politics of global sustainability*. Island Press.

Sassen, S. (2006). *Cities in a world economy* (3rd ed.). Pine Forge Press.

Sholes, R., Biggs, R., Palm, C., & Duraiappah, A. (2010). Assessing state and trends in ecosystem services and human well-being. In N. Ash, H. Blanco, C. Brown, K. Garcia, T. Tomich, B. Vira, et al. (Eds.), *Ecosystems and human well-being: A manual for assessment practitioners* (1st ed.). Island Press, chap. 4.

Skerry, P. (2000). *Counting on the census?: Race, group identity, and the evasion of politics*. Brookings Institution Press.

Sleeter, R. (2008). *A new method for mapping population distribution*. U.S. Geological Survey Fact Sheet 2008-3010. http://pubs.usgs.gov/fs/2008/3010/ Retrieved June 21, 2011.

Swallow, B. M., Sang, J. K., Nyabenge, M., Bundotich, D. K., Duraiappah, A. K., & Yatich, T. B. (2009). Tradeoffs, synergies and traps among ecosystem services in the Lake Victoria basin of East Africa. *Environmental Science & Policy, 12*(4), 504–519. doi:10.1016/j.envsci.2008.11.003.

Tallis, H., & Polasky, S. (2009). Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. *Annals of the New York Academy of Sciences, 1162*(1), 265–283. doi:10.1111/j.1749-6632.2009.04152.x.

United Church of Christ Commission for Racial Justice. (1987). *Toxic wastes and race in the United States: A national report on the racial and socio-economic characteristics of communities with hazardous waste sites*. Public Data Access.

United Nations. (1987). *Report of the world commission on environment and development: Our common future – A/42/427 Annex – UN Documents: Gathering a body of global agreements*. http://www.un-documents.net/wced-ocf.htm.

United Nations. (1992). *Agenda 21, the Rio declaration on environment and development, the statement of forest principles, the United Nations framework convention on climate change and the United Nations convention on biological diversity*. Rio de Janeiro, Brazil: United Nations Conference on Environment and Development (UNCED); The Earth Summit. http://www.un.org/geninfo/bp/enviro.html.

United States Environmental Protection Agency. (2011). *U.S census data on small community housing and wastewater disposal and plumbing practices | septic | US EPA*. http://water.epa.gov/infrastructure/wastewater/septic/census_index.cfm Retrieved January 20, 2012.

United States Geological Survey. (2011). *U.S.-Mexico border environmental health initiative home page*. http://borderhealth.cr.usgs.gov/projectindex.html Retrieved January 20, 2012.

Villarreal, M. L., Norman, L. M., Wallace, C. S. A., & van Riper, C., III. (2011). *A multitemporal (1979–2009) land-use/land-cover dataset of the binational Santa Cruz watershed*. U.S. Geological Survey Open-File Report 2011-1131 and database. http://pubs.usgs.gov/of/2011/1131/ Retrieved June 21, 2011.

Warner, K. (2002). Linking local sustainability initiatives with environmental justice. *Local Environment, 7*(1), 35–47. doi:10.1080/13549830220115402.

Wilder, M., Scott, C. A., Pablos, N. P., Varady, R. G., Garfin, G. M., & McEvoy, J. (2010). Adapting across boundaries: climate change, social learning, and resilience in the U.S.–Mexico border region. *Annals of the Association of American Geographers, 100*(4), 917–928. doi:10.1080/00045608.2010.500235.