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# Developing spatially explicit footprints of plausible land-use scenarios in the Santa Cruz Watershed, Arizona and Sonora

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## HIGHLIGHTS

► The SLEUTH model is applied to a binational dryland watershed to develop future scenarios.
► Three scenarios simulate changing spatial patterns to help guide planning for the future.
► Limit growth beyond cross-border commerce areas, protects forests and wildlife habitat.
► Trade-offs between urban area, the economy, and environmental impacts can be realized.

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## ABSTRACT

The SLEUTH urban growth model is applied to a binational dryland watershed to envision and evaluate plausible future scenarios of land use change into the year 2050. Our objective was to create a suite of geospatial footprints portraying potential land use change that can be used to aid binational decision-makers in assessing the impacts relative to sustainability of natural resources and potential socio-ecological consequences of proposed land-use management. Three alternatives are designed to simulate different conditions: (i) a Current Trends Scenario of unmanaged exponential growth, (ii) a Conservation Scenario with managed growth to protect the environment, and (iii) a Megalopolis Scenario in which growth is accentuated around a defined international trade corridor. The model was calibrated with historical data extracted from a time series of satellite images. Model materials, methodology, and results are presented. Our Current Trends Scenario predicts the footprint of urban growth to approximately triple from 2009 to 2050, which is corroborated by local population estimates. The Conservation Scenario results in protecting 46% more of the Evergreen class (more than 150,000 acres) than the Current Trends Scenario and approximately 95,000 acres of Barren Land, Crops, Deciduous Forest (Mesquite Bosque), Grassland/Herbaceous, Urban/Recreational Grasses, and Wetlands classes combined. The Megalopolis Scenario results also depict the preservation of some of these land-use classes compared to the Current Trends Scenario, most notably in the environmentally important headwaters region. Connectivity and areal extent of land cover types that provide wildlife habitat were preserved under the alternative scenarios when compared to Current Trends.

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## 1. Introduction

Cellular automata (CA) models can create projections of land-use change useful for proactive decision-making in linked human-environment systems (Hegselmann, 1998; Li & Reynolds, 1997; Li & Yeh, 2000; Phipps, 1989; White & Engelen, 2000). Compared to other geographical models, CA-based models can capture non-linear, spatial and stochastic processes of urban growth in simple but realistic ways (Al-kheder, Wang, & Shan, 2008; Liu, 2008; Santé, García, Miranda, & Crecente, 2010; Stevens, Dragicevic, & Rothley, 2007). A distinguishing feature of CA models is the potential to define transition rules, which represent the various spatial and non-spatial factors that might impact urban development (Al-kheder et al., 2008; Almeida, Gleriani, Castejon, & Soares-Filho, 2008; Liu, 2008; Santé et al., 2010).

The SLEUTH model, named as an acronym for its input data layer requirements—slope, land use, exclusion, urban extent, transportation and hillshade data—is a fuzzy constrained CA model that can predict potential future urban growth and land-use change

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in a spatially explicit fashion (Clarke & Gaydos, 1998; Clarke, Hoppen, & Gaydos, 1997; Dietzel & Clarke, 2006; Jantz, Goetz, & Shelley, 2004; Jantz, Goetz, Donato, & Claggett, 2010; Silva & Clarke, 2002). The SLEUTH model was developed, verified, and validated by Clarke et al. (1997) and Clarke and Gaydos (1998). The SLEUTH model processes a raster grid of cells representing the land surface that changes state as the model iterates, and is regulated by neighborhood rule conditions. Each cell is represented with an automaton—an entity that independently executes its own state-transition rules—while recognizing the states and attributes of nearby cells (Jantz et al., 2010). It has been applied in many locations, including the Washington-Baltimore area by Jantz et al. (2004) and at Ambos Nogales by Norman, Feller, & Phillip Guertin (2009), and there are multiple variants currently in use that attempt to improve upon the early model (Jantz et al., 2010). The SLEUTH-3r-.rev.1.1includes an urban model and a land-cover change transition model, which is applied in this study (Jantz et al., 2010). Land-use/land-cover change in human-influenced landscapes is complex and adaptive and cannot be predicted with confidence over decadal time scales, yet CA and other agent-based models offer the potential for exploring some possibilities through scenarios. SLEUTH is very sensitive to initial model conditions but is an appropriate model for regional land cover modeling in a watershed analysis.

We describe the application of SLEUTH in the binational Santa Cruz Watershed, which is located on the US-Mexico border of Arizona and Sonora (Fig. 1), to develop alternative future scenarios of land-use change. Kepner et al. (2009) found that the most significant hydrologic changes in alternative future scenario analysis in a semi-arid watershed are associated with urbanization and the associated replacement of vegetation with impervious surfaces. In addition to this, we consider challenges for the future that may include the loss of wildlife habitat, increased demands for natural resources, and economic incentives of international trade in our scenario development. This research tests the ability of SLEUTH to generate scenarios under differing assumptions about land-use change drivers and increases the understanding of how land use/land cover expands in space and over time. Results provide spatially explicit footprints of plausible future scenarios that are useful to investigate social-ecological linkages and sustainable development options for this transboundary watershed.

## 2. Background

The Santa Cruz Watershed is partially located in the Sonoran Desert, one of the largest and hottest deserts in North America. The climate is ideal for many animals and plants that have developed adaptations to the bimodal rainfall patterns and high temperatures—but people too are attracted to the sunny days and warm dry air—and the fragile desert ecosystems are extremely sensitive to impacts of human habitation and associated land use.

Throughout the last 4 or 5 hundred years, human population has increased exponentially (Carr-Saunders, 1936). According to Anderson (2003), the population in the US-Mexico border region has grown more rapidly than in either country as a whole. *Colonias* (the Spanish word for neighborhood) are defined in the United States as predominantly Hispanic, poor, unplanned settlements that lack sewer, clean water, and/or safe and sanitary housing that are located within 150-miles of the international boundary. Norman et al. (2006) identified many new *colonias* in the Santa Cruz Watershed around Ambos Nogales (Nogales, Sonora, Mexico, and Nogales, Arizona; Fig. 1), but many more exist today. Aside from Ambos Nogales, where population estimates vary around 370,000, humans in the Santa Cruz Watershed are mostly found in Tucson, Arizona (Fig. 1), where population estimates are 530,000 (US Environmental Protection Agency, 2012). According to Vest (2010), the population of the larger Tucson Metropolitan Area (Pima County) is predicted to triple by 2040.

It is well-documented that growing populations have impacts on all aspects of the natural world (Daily et al., 1998; Ehrlich, 1968). Nie et al. (2010) demonstrate a relationship between the urban growth between 1992 and 2001, in which the increase in developed area of 45.3%, impacted local hydrology in the Santa Cruz Watershed by decreasing average evapotranspiration (ET) by 0.29% and increasing surface runoff by 6.7% and water yield by 5.1%. The conversion of land for development also impacts agricultural, recreational, and cultural aspects of the land, and tests the resilience of social-ecological systems. Resilience is the capacity of a system to withstand disturbance while maintaining the same functions (Adger, Hughes, Folke Carl Carpenter Stephen, & Rockström, 2005; Walker, Holling, Carpenter, Kinzig, & Resilience, 2004). The dryland ecosystem of the Santa Cruz Watershed faces many biophysical and social challenges to maintain long-term socio-ecological resilience and is becoming more vulnerable through time (Morehouse et al., 2008). Poverty, environmental degradation, and resource overconsumption are all tied to the urban development and associated population growth that is not sustainable at current rates (Bartlett, 1998; Meadows et al., 1972).

Sustainable development promotes using resources sparingly to satisfy the requirements of society, while preserving the environment for future generations (World Commission on Environment & Development, 1987). The United Nations World Summit Outcome Document (2005) describes sustainable development using three "pillars" of (i) economic development, (ii) social development, and (iii) environmental protection. It has been suggested that using an ecosystem services approach supports planning for sustainable development by highlighting the links between environmental management and economic and societal goals (Ash et al., 2010; Costanza et al., 1997; Daily, 1997). Linking social and ecological systems in management and planning helps communities prepare for and cope with disasters (Berkes et al., 2000; Adger et al., 2005).

Dryland ecosystems were identified in the Millennium Ecosystem Assessment (MEA; 2005) as particularly vulnerable to change based on the combination of growing populations, variability of environmental conditions, poor human well-being and societal vulnerability. Morehouse et al. (2008) recognized a need for more transboundary science–society interactions in the Santa Cruz Watershed. Norman et al. (2012) compared the distribution of regulating ecosystem services with the geography of socio-environmental vulnerability in the Santa Cruz Watershed, revealing potential disparities in environmental risks and burdens in residential districts surrounding and between urban centers. However, accurately quantifying the impacts of future urban growth on ecosystem services is difficult because of the lack of information associating alternate landscapes to ecosystem services (Oguz, Klein, & Srinivasan, 2007).

The United States Geological Survey (USGS) has developed the Ecosystem Portfolio Model (EPM), to portray sustainability's three "pillars" as sub-models in an online decision support system and visualize tradeoffs of ecosystem services (Labiosa et al., 2009). This model is being applied at the Santa Cruz Watershed to investigate the costs and benefits of binational land-use and water management practices (SCWEPM; Norman et al., 2010). Inputs to the SCWEPM include biophysical and socio-economic models, as well as climate and land-use change scenarios. In this paper, we present the development of three alternative futures, based on current trends, and the popular management goals of environmental protection and economic promotion. Spatially explicit raster scenarios of the alternative futures are generated using the SLEUTH model—materials and methods are described herein. Results are