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Spatially explicit land-use and land-cover scenarios for the Great Plains of the United States

Terry L. Sohl[a,*], Benjamin M. Sleeter[b], Kristi L. Sayler[a], Michelle A. Bouchard[c], Ryan R. Reker[c], Stacie L. Bennett[d], Rachel R. Sleeter[b], Ronald L. Kanengieter[d], Zhiliang Zhu[e]

[a] U.S. Geological Survey, Earth Resources Observation and Science (EROS) Center, 47914 252nd Street, Sioux Falls, SD 57198, USA
[b] U.S. Geological Survey, Western Geographic Science Center, 345 Middlefield Road MS 531, Menlo Park, CA, 94025 USA
[c] ARTS, Contractor to Earth Resources Observation and Science (EROS) Center, 47914 252nd Street, Sioux Falls, SD, 57198, USA
[d] SGT, Inc., Contractor to Earth Resources Observation and Science (EROS) Center, 47914 252nd Street, Sioux Falls, SD 57198, USA
[e] U.S. Geological Survey, 12201 Sunrise Valley Drive, Reston, VA20192, USA

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ABSTRACT

The Great Plains of the United States has undergone extensive land-use and land-cover change in the past 150 years, with much of the once vast native grasslands and wetlands converted to agricultural crops, and much of the unbroken prairie now heavily grazed. Future land-use change in the region could have dramatic impacts on ecological resources and processes. A scenario-based modeling framework is needed to support the analysis of potential land-use change in an uncertain future, and to mitigate potentially negative future impacts on ecosystem processes. We developed a scenario-based modeling framework to analyze potential future land-use change in the Great Plains. A unique scenario construction process, using an integrated modeling framework, historical data, workshops, and expert knowledge, was used to develop quantitative demand for future land-use change for four IPCC scenarios at the ecoregion level. The FORE-SCE model ingested the scenario information and produced spatially explicit land-use maps for the region at relatively fine spatial and thematic resolutions. Spatial modeling of the four scenarios provided spatial patterns of land-use change consistent with underlying assumptions and processes associated with each scenario. Economically oriented scenarios were characterized by significant loss of natural land covers and expansion of agricultural and urban land uses. Environmentally oriented scenarios experienced modest declines in natural land covers to slight increases. Model results were assessed for quantity and allocation disagreement between each scenario pair. In conjunction with the U.S. Geological Survey's Biological Carbon Sequestration project, the scenario-based modeling framework used for the Great Plains is now being applied to the entire United States.

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1. Introduction

The grasslands of the Great Plains are considered one of the most endangered ecosystems in North America (Samson et al., 2004; Cully et al., 2003), and have undergone the greatest reduction in size of any North American ecosystem (Samson and Knopf, 1994). The conversion of Great Plains grasslands to agricultural land began around 1850, with a peak extent in cultivated land around 1940, and slight declines in agricultural extent since (Waisanen and Bliss, 2002). During that time, between 60% and 70% of land in the eastern Great Plains has been directly cultivated, while nearly 30% in the western Great Plains has been plowed (Hartman et al., 2011). Only 1% of the original tallgrass prairie remains in the region (Cully et al., 2003). Even in remaining prairie grasslands, there have been large declines in native species and declines in species diversity as planted monocultures of crested wheatgrass (*Agropyron cristatum*) have replaced native prairie in many locations, while exotic grasses such as smooth brome (*Bromus inermis*) and Kentucky bluegrass (*Poa ptratensis*) now comprise a large portion of prairie biomass in many prairies where the ground has never been broken (Lesica and DeLuca, 1996; Christian and Wilson, 1999; Cully et al., 2003).

Changes in land use and land cover (LULC) in the Great Plains have had dramatic impacts on ecological resources and processes in the region. Water availability is the most important factor driving land use in the Great Plains, with nearly 76 billion liters of water pumped from the High Plains aquifer every day for irrigation and for drinking water (U.S. Global Change Climate Program 2009). Moore and Rojstaczer (2001) note that the dramatic increase in irrigated agriculture in the Great Plains since 1950 represents

* Corresponding author. Tel.: +1 605 594 6537; fax: +1 605 594 6529.
E-mail address: sohl@usgs.gov (T.L. Sohl).

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the largest human-induced hydrologic change in North America, while Mahmood and Hubbard (2002) note large impacts on near-surface hydrologic processes (soil moisture, evapotranspiration) due to conversion of Great Plains grasslands to crops. Land-use change, especially loss of prairie land and wetlands, has had a profound negative impact on native plants and animals (Samson and Knopf, 1994; Higgins et al., 2002). Widespread livestock grazing has resulted in a loss of biodiversity, altered nutrient cycling, and potentially harmful changes in the physical characteristics of terrestrial and aquatic habitats (Fleischner, 1994). Land use also strongly affects carbon and greenhouse gas fluxes in the region, as Great Plains grasslands can be either a carbon source or sink, depending upon land use and management (Fuhlendorf et al., 2002). Land cover has large effects on climate to due changes in albedo, surface roughness, leaf area, and transpiration, and numerous studies have linked land-use change in the region with both local and remote impacts on weather and climate (Pielke et al., 1997; Chase et al., 1999; Mahmood et al., 2006). Stohlgren et al. (1998) suggests that the local and regional effects of land-use change might overshadow even global climate change associated with increased CO_2 and other greenhouse gases.

The Great Plains could continue to experience dramatic changes in land use over the next several decades. The region currently relies heavily on government support through the form of agricultural subsidies, with agricultural income only positive in some years because of government payments (Rosenberg and Smith, 2009). Future shifts in political structure or government payments could have a tremendous impact on profitability, and resultantly, land use, in the Great Plains. Demand for traditional biofuels (corn-based ethanol, soy-based biodiesel) has already strongly impacted the region. Demand for both traditional and newly developed cellulosic biofuels could dramatically increase in the region, with the 2007 Energy Independence and Security Act of 2007 already mandating the U.S. produce 136 billion liters of ethanol annually by 2022, 21 billion of which must come from "advanced" biofuels such as cellulosic ethanol (Rosenberg and Smith, 2009). In addition to biofuels demand, global population growth will likely drive an increased need for agricultural food products produced in the region. Climate change also is likely to impact the region, as temperatures are projected to continue increase through 2100, precipitation is projected to increase in the northern plains and decrease in the south, and extreme events such as flooding, drought, and heat waves are expected to increase (U.S. Global Change Research Program 2009).

Given the impact of LULC change on ecosystems in the Great Plains, and given the uncertainty of future driving forces of LULC change, a scenario-based modeling framework is needed to support the analysis of potential LULC change, and to mitigate potentially negative future impacts on ecosystem processes. Specifically, LULC projections are needed that (1) are scenario-based, providing multiple potential future LULC pathways, (2) have relatively high thematic detail, representing the complete scope of natural and anthropogenic land covers, (3) are transparent and straightforward to implement. The U.S. Geological Survey's Biological Carbon Sequestration Project has developed a methodology to quantify carbon sequestration and greenhouse gas fluxes for ecosystems of the United States (Zhu et al., 2010), work which includes the scenario-based LULC modeling framework that is the focus of this paper. We are producing LULC projections for the entire United States based on four scenarios. The Great Plains is the first major region to have been completed. What follows is a summary of the creation of spatially explicit, scenario-based LULC projections for the Great Plains of the United States from 2006 through 2100.

2. Background

2.1. Relevant LULC modeling approaches

We will not provide a complete summary of existing LULC modeling methods, as a number of papers provide an excellent summary of general modeling issues and existing modeling frameworks (Veldkamp and Lambin, 2001; Verburg et al., 2004; Heistermann et al., 2006). Here we provide a summary of existing modeling frameworks relevant to the regional, scenario-based work presented in this paper, including specific modeling applications in the Great Plains. Economic optimization approaches likely represent the most widely used methodology to date for examining agricultural practices and land use in the Great Plains. The Forest and Agricultural Sector Optimization Model (FASOM) has a long history of practice, and has been used to examine the forest and agricultural sectors for the conterminous United States, including the Great Plains (Adams et al., 1996; Alig et al., 2002). While model output is thematically detailed, provides projections for several dozen agricultural variables, and has been used for scenario analyses, FASOM is not spatially explicit, as it provides regional estimates for modeled variables to the state level, at best. An econometric model developed and used by Lubowski et al. (2006) and Plantinga et al. (2007) is less detailed thematically, providing projections for six basic land categories, but generates projections down to the county level. This model has been applied nationally, but issues are noted with accuracy at the regional level, including the Great Plains (Plantinga et al., 2007), and the model only models private land use. General issues with econometric models include an inability to represent behavior not based on optimal economic returns (hence the difficulty with public lands), underestimation of the role of institutions, and poor representation of biophysical factors (Veldkamp et al., 2001).

Several different types of models have provided spatially explicit projections for the Great Plains, but only represented one or a few types of LULC change. Vegetation dynamics models focus on transitions in natural vegetation classes, often as a response to climate change. Bachelet et al. (2001, 2003), for example, modeled potential vegetation distribution for the entire U.S. in response to expected climate change, but anthropogenic land-use change was not considered, and the spatial resolution was coarse (0.5° grid cells). The integrated climate and land-use scenarios (ICLUS) model was used to produce national-level projections for housing-density and impervious surface under multiple scenarios, but only urban change was modeled. White et al. (2009) also projected developed land area for the U.S., but only to the state level.

One of the only approaches to spatially map the complete suite of LULC types for all of the Great Plains was the Integrated Model to Assess the Global Environment (IMAGE) (Strengers et al., 2004). IMAGE uses population and macro-economic assumptions to drive a scenario-based, global, integrated modeling framework. A land-use model interacts with models on climate and macro-economics to produce land-use projections at a 0.5° resolution. While the model does provide estimates for most major LULC types, including agricultural land and natural vegetation classes, it does not address urban development, the spatial resolution is quite coarse, and, as a global model, regional accuracy for the Great Plains is questionable.

Other commonly used LULC modeling approaches include agent-based models that attempt to replicate the decision-making process of relevant land-use "agents" (land owners, political entities, conservation groups, government agencies, and other entities that make land-use decisions). However, most agent-based models are focused on local applications, and are generally impractical when applied to the regional extent of the Great Plains. Geostatistical/empirical modeling frameworks such as CLUE model series (Veldkamp and Fresco, 1996; Verburg et al., 1999; Verburg and