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

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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

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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

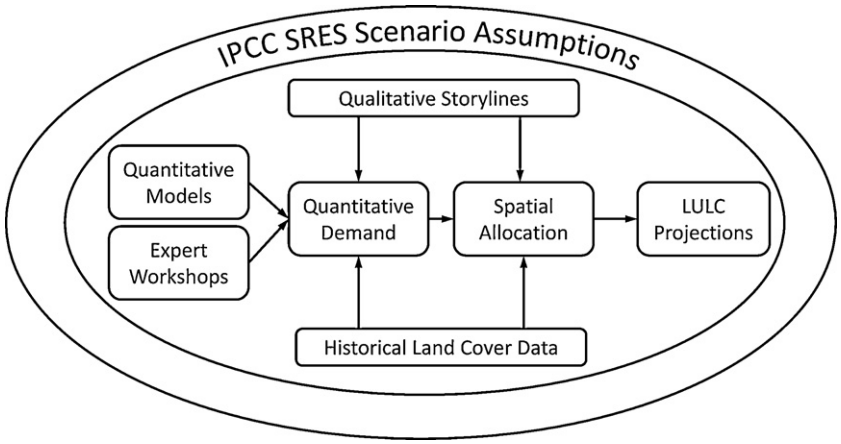

Fig. 1. Conceptual diagram of the LULC modeling framework. The modeling framework included linked demand and spatial allocation components, all within the framework of IPCC SRES scenario assumptions. Downscaled qualitative storylines consistent with IPCC SRES scenario assumptions were developed for the Great Plains. Quantitative demand for each scenario was constructed in a workshop setting using qualitative storylines, quantitative SRES model runs from IMAGE 2.2., historical land-cover data from the USGS Land Cover Trends project, and expert knowledge. Scenario-based quantity demand and model parameterization consistent with the qualitative storylines and historical land-cover data served as input to the spatial allocation component which produced spatially explicit LULC maps consistent with each scenario.

Overmars, 2009), FORE-SCE (Sohl et al., 2007; Sohl and Sayler, 2008), and GEOMOD (Hall et al., 1995; Pontius et al., 2001) are based on empirical quantification of relationships between land-use and its relative driving forces. This class of models offers the most potential for producing spatially explicit, scenario-based, thematically detailed LULC projections for a large region such as the Great Plains, as shown by similar applications in China (Verburg et al., 1999), the southeastern United States (Sohl and Sayler, 2008), and Europe (Verburg and Overmars, 2009).

When used in an integrated, modular LULC framework, approaches such as these offer the potential to incorporate not only geostatistical modeling, which excels at placing change on the landscape, but also many of the other modeling approaches listed above. Models such as CLUE, FORE-SCE, and GEOMOD use a modular approach to attempt to address issues of scale, with "demand" for quantity of LULC change at an aggregate level often modeled separately from a "spatial allocation" component that spatially maps LULC change. Such an approach offers the advantages of potentially linking "top-down" economic modeling with "bottom-up" spatial modeling, being compatible with scenario-frameworks, and producing spatially explicit LULC projections at a suitable spatial, temporal, and thematic resolution for our work in the Great Plains. For example, in an integrated model assessment of LULC change in Europe, the EURURALIS project linked IMAGE with the global economic model GTAP to produce scenario-based LULC demand for individual countries in Europe, with a spatially explicit representations of those scenarios modeled using the CLUE-s model (Westhoek et al., 2006; Verburg et al., 2008).

The general paradigm used by EURURALIS is very attractive for this application. However, we had concerns about model complexity and uncertainties in complex, integrated modeling approaches such as the EURURALIS framework. As part of EURURALIS, Westhoek et al. (2006) found that policy makers wanted to know specific cause-and-effect relationships in the scenarios, yet it was difficult to pinpoint those relationships due to the complexity of the modeling framework. Clark et al. (2001) notes that when modeling uncertainties are not properly communicated, confidence in the use of those models is lost, while Waddell (2011) states many modeling efforts leave it to the user to simply believe in model outputs when model validation and uncertainties are impossible to provide. To alleviate these concerns, we developed an integrated scenario construction and spatial modeling framework that resulted in a "story-and-simulation" approach advocated by Alcamo (2001, 2008), with storylines providing qualitative descriptions of relevant future events, and a quantitative model providing spatial results consistent with the qualitative storyline. With the described framework, we were able to produce spatially explicit, scenario-based LULC projections for the entire Great Plains at relatively fine thematic and spatial resolutions. The following describes the scenario-construction process and spatial modeling results for four scenarios in the Great Plains.

3. Materials and methods

One of the highest priorities for LULC models is to address multi-scale characteristics of land-use change (Verburg et al., 2004; Sohl et al., 2010; Ewert et al., 2011). We are using a modular modeling framework to allow for integration of both "top-down" (macro-scale) and "bottom-up" (local scale) drivers of change (Fig. 1). The framework uses a qualitative storyline and quantitative scenario-development procedure to produce demand for future quantities of modeled LULC classes at annual intervals. A separate modeling framework, FORE-SCE, ingests scenario-driven demand and produces spatially explicit LULC maps.

While many other LULC modeling applications examine LULC change using a spatial framework based on political boundaries, we are examining LULC change using an ecoregion framework, as ecoregion boundaries have proven to be very useful for organizing, analyzing, and reporting information about land-use change (Gallant et al., 2004). The U.S. Environmental Protection Agency (EPA) ecoregions (US EPA, 1999) form the spatial framework for this application. In the hierarchical EPA ecoregion framework, we are defining the Great Plains to consist of Level II ecoregions 9.2 (Temperate Prairies), 9.3, (West-Central Semiarid Prairies), and 9.4 (South-Central Semiarid Prairies), covering approximately 2,170,000 km^2 (Fig. 2). Modelling of LULC change is initiated in 1992 to facilitate model "spin-up" (obtaining a modeling equilibrium) and calibration for the biogeochemical models used on the Biological Carbon Sequestration Project. Modeling the 1992–2005 historical period also potentially enables validation of LULC model results, as discussed below. Scenarios of future LULC change are constructed and modeled for the period of 2006–2100.

3.1. Scenarios

Scenario analysis is used to explore a wide range of future potential conditions in land use and land cover resulting from the interaction of multiple driving force variables, including

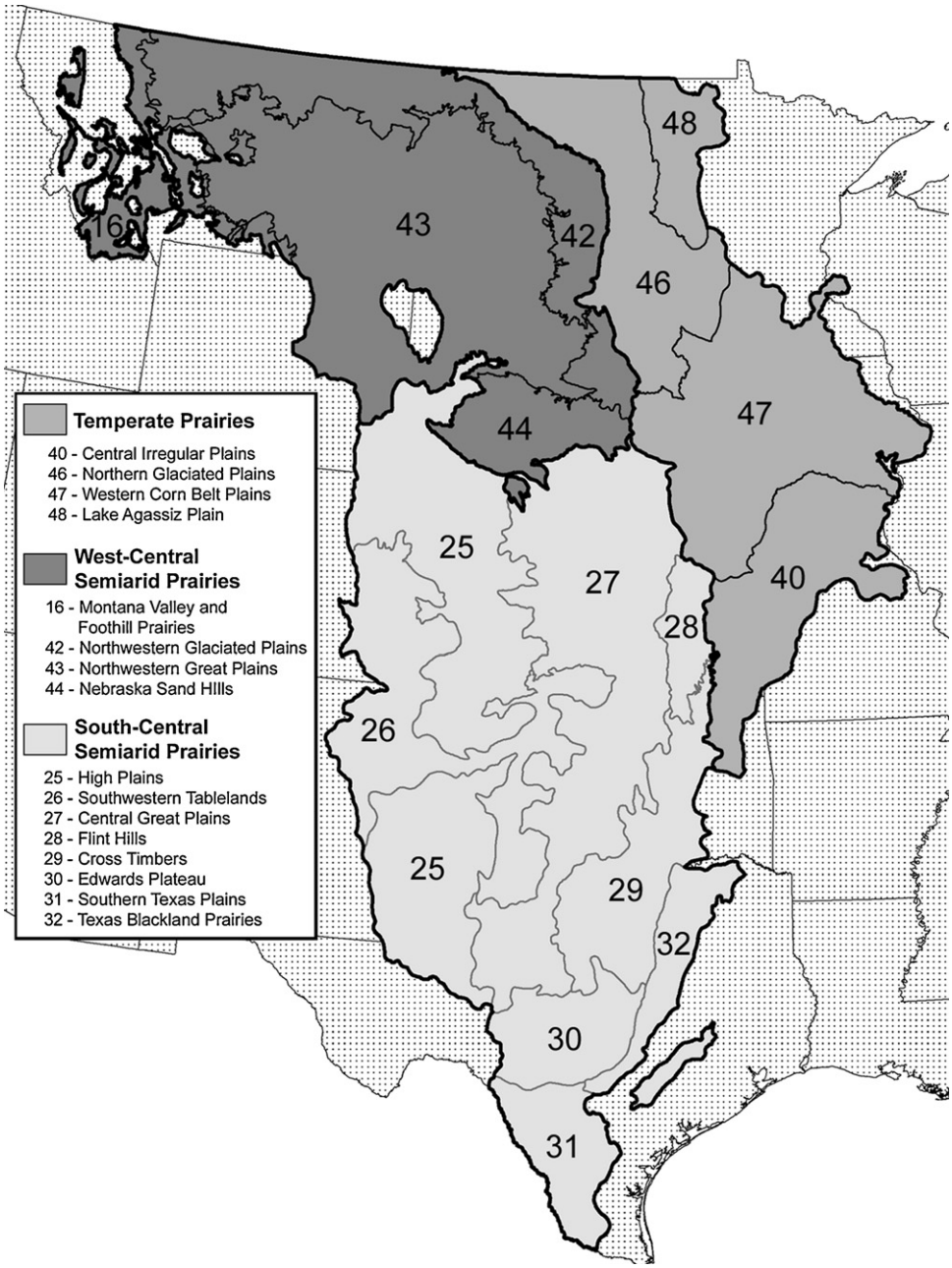

Fig. 2. Great Plains Study Area. The study area includes three EPA Level II ecoregions, composed of 16 hierarchically nested Level III ecoregions (US EPA, 1999). While overall LandCarbon project greenhouse gas analysis will be performed at the resolution of Level II ecoregions, the land-cover modeling work presented here parameterizes scenarios and the FORE-SCE model for each Level III ecoregion.

population, economic growth, technological innovation, global and regional market forces, societal attitudes, and climate change. The scenarios are roughly based on four storylines from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000). The scenarios cover all four of the SRES scenario families and span a wide range of alternative future conditions. The scenarios are organized along two axes and each is given an alpha-numeric name. The alpha designation, either "A" or "B", denotes an economic (A) or environmental emphasis (B), and the numeric designation, either "1" or "2", denotes a global (1) or regional (2) orientation. The A1 scenario family was further broken down into three scenario groups to explore alternative futures in energy production. This resulted in the A1B (balanced resources), A1FI (fossil fuel intensive), and A1T (technological advancement in renewables) scenarios. We used the A1B, A2, B1, and B2 storylines as the basis for the four scenarios developed for this work.

Each scenario is characterized by specific assumptions regarding population dynamics, economic growth, and other socioeconomic variables. However, the SRES scenarios are global in nature and provide no specific characterization of potential land-use trajectories, particularly for regional applications such as this. A scenario downscaling process was required to develop regional scenarios for the Great Plains that were consistent with SRES storylines, and that provided quantitative regional proportions of land use. The EURURALIS project used an integrated, quantitative modeling framework to develop downscaled demand for regional LULC quantities based on SRES scenarios (Westhoek et al., 2006; Verburg et al., 2008). To mitigate potential stakeholder concerns about model complexity and uncertainties, we developed our own unique, multi-component

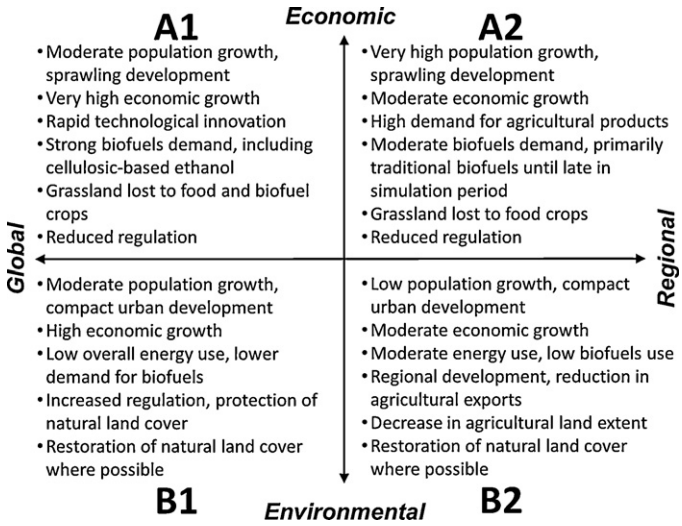

Fig. 3. Scenario storylines. IPCC SRES scenarios are oriented along two axes, one focused on global vs. regional development, and one focused on economic growth vs. environmental protection. Major assumptions and storyline narratives are shown for each of the four scenarios used in this work.

scenario construction process that relied on historical LULC data, integrated modeling results from IMAGE 2.2 (Strengers et al., 2004), expert knowledge and a workshop setting, and a spreadsheet downscaling model. The complete downscaling process used for this research is documented in Sleeter et al. (in press). A short review of the methodology that was used to develop downscaled SRES scenarios for the Great Plains follows.

The first step in the downscaling process was to develop regionally specific narrative storylines. Qualitative descriptions of future developments, or narratives, were an important element of SRES scenarios and have become an important part of many global scenario frameworks (Nakicenovic and Swart, 2000; Alcamo, 2008). The use of narratives provides increased explanatory power to quantitative scenarios, often resulting in a higher degree of acceptance and use (Raskin, 2005; Gaffin et al., 2004). We analyzed the narrative storylines developed for SRES along with relevant literature related to downscaling and developed narrative storylines for the Great Plains region of the United States, using regional land-use experts in a workshop environment. A schematic of the IPCC SRES scenario framework and the primary characteristics of the qualitative storylines are found in Fig. 3.

In addition to storylines consistent with SRES, we also require quantitative proportions of future LULC change at the regional level to be used as input to the FORE-SCE spatial model. The quantitative scenarios were initially based on national-level model simulations for the United States from IMAGE 2.2 (Strengers et al., 2004). IMAGE was used to provide initial demand for projected future LULC quantities at the national resolution for four primary land uses: developed, mining, agriculture, and forest harvest. However, as a global model, validity of the raw IMAGE 2.2 output was questionable for the U.S., with proportions of land-use change that often far outstripped any historical change. In addition, we had concerns about relying solely on IMAGE 2.2 data where validity and uncertainty of results were impossible to assess due to model complexity. We determined IMAGE data could not be used "as-is", and therefore modified the IMAGE projections to levels more consistent with historical measurements, using land-use experts in a workshop setting. We used projections of population and coal use as proxies for development and mining, respectively, and similarly developed national trends in an expert workshop. A land-use accounting model was developed to convert initial land-use demand at a national resolution into a full range of LULC transitions

Table 1
Modeled land-cover and land-use classes. Land use and land cover is projected for each class below, a slight modification of the 1992 NLCD classification scheme.

(1)	Open water
(2)	Urban/developed
(3)	Mechanically disturbed
(4)	Mining
(5)	Naturally barren
(6)	Deciduous forest
(7)	Evergreen forest
(8)	Mixed forest
(9)	Shrubland
(10)	Grassland
(11)	Cultivated crop
(12)	Hay/pasture
(13)	Woody wetland
(14)	Herbaceous wetland

between nine broad LULC categories (Sleeter et al., in press). Specific transitions were based primarily on land-use histories from the USGS Land Cover Trends project (Loveland et al., 2002), but were also modified within an expert workshop to ensure consistency with storyline characteristics.

National-level LULC transitions were then downscaled using the hierarchical ecoregion framework shown in Fig. 2. Using land-use histories from the USGS Land Cover Trends project to partition national level change, LULC transitions were first allocated to four major regions of the U.S., followed by distribution to Level II and III ecoregions. From Level II to III, the classification scheme was expanded to include 14 classes for spatial modeling (Table 1), with thematic downscaling primarily based on regional LULC composition from the National Land Cover Database (NLCD) (Vogelmann et al., 2001; Homer et al., 2007). For example, if the composition of a level III ecoregion's agriculture class was 80% cultivated cropland and 20% hay/pasture, all transitions involving agriculture (e.g. agriculture to development) would initially be distributed based on the same ratio (80% of agriculture to development would come from cultivated crops and 20% would come from hay/pasture). In many cases, historical LULC proportions used in the downscaling were altered to better reflect individual scenario and regional storylines, as described in Sleeter et al. (in press). The results of the scenario downscaling process were projections of future, annual LULC proportions from 2005 to 2100, for each level III ecoregion, and for each of the four SRES storylines. Fig. 4 provides an overview of trends in individual LULC classes from 2006 through 2100 for each scenario.

3.2. LULC model

The FORE-SCE model is used to spatially allocate the LULC change provided by the scenarios. FORE-SCE is a geostatistical/empirical modeling framework that uses separate but linked "demand" and "spatial allocation" components, similar to the CLUE modeling framework (Verburg et al., 1999, Verburg and Overmars, 2009), but with a unique patch-based spatial allocation methodology. FORE-SCE has similarly been used in the past to produce regional LULC projections for the Southeastern U.S. (Sohl and Sayler, 2008), and for a western portion of the Great Plains (Sohl et al., 2007). Basic model structure and functioning is similar to past FORE-SCE applications. However, many improvements have been made to the model since the initial application for the western Great Plains, as discussed below.

FORE-SCE initially focuses on identifying site-specific characteristics tied to suitability of the land to support each LULC type being modeled, using empirical relationships between extant LULC type and spatially explicit biophysical and socioeconomic variables. A stepwise logistic regression approach is used, where existing LULC

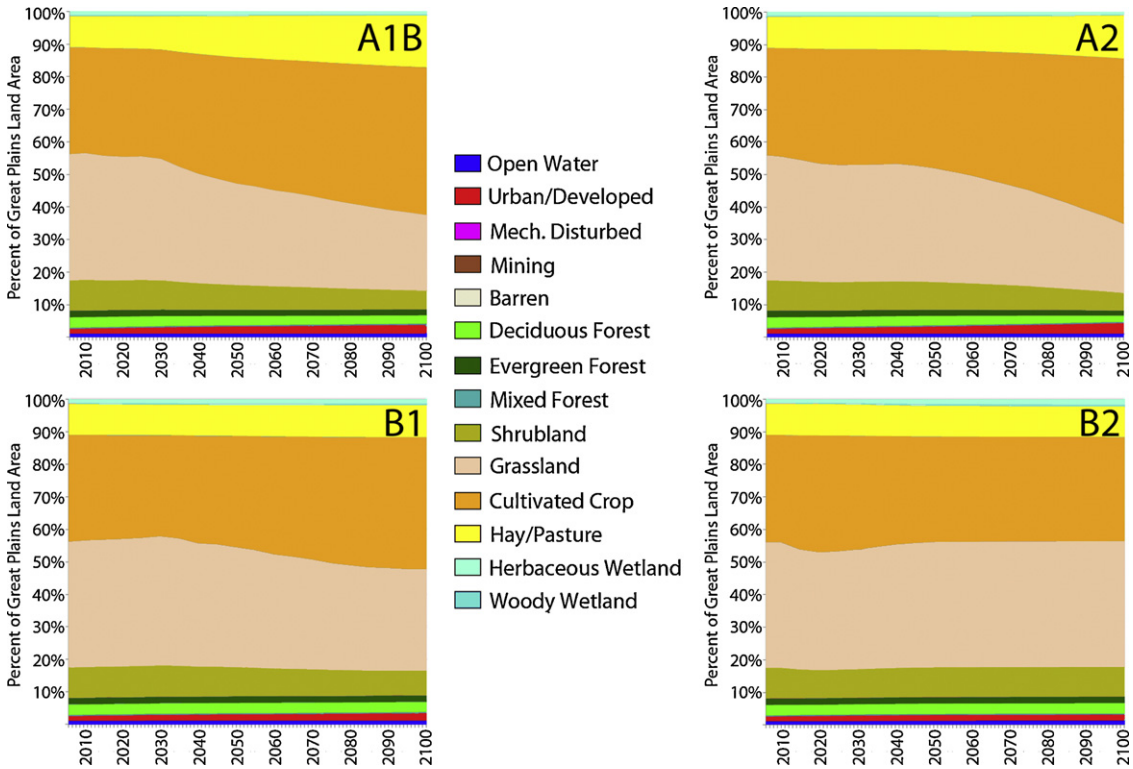

Fig. 4. Great Plains land-cover scenarios. Land-cover trends for each of the downscaled SRES scenarios for the entire Great Plains region. Obvious trends are apparent for both natural and agricultural land cover types, with the greatest scenario divergence occurring after 2050.

patterns for a given LULC type represent the dependent variable, and ancillary variables outlined in Table 2 represent the independent variables. Land cover from the 1992 NLCD (Vogelmann et al., 2001) were modified to the fourteen LULC classes in Table 1, and used as the starting 1992 LULC data for modeling, and as the dependent variable for the logistic regression analyses. Regression analysis identified statistical relationships between dependent and independent variables, but did not necessarily imply causality. While the initial regression for an individual LULC type typically used the majority of variables found in Table 2, project analysts used literature review and expert knowledge to eliminate independent variables in subsequent runs if likely causal relationships with the modeled LULC type could not be identified. The initial stepwise logistic regression was also used to identify multicollinearity issues caused by highly correlated independent variables. We used a simple procedure of examining paired independent variable correlation values, and discarding redundant variables with high correlation coefficients (Kok, 2004; Sohl and Sayler, 2008). Once redundant variables and non-causal variables were identified and discarded, final regression runs were completed and used to construct initial suitability-of-occurrence surfaces for each modeled LULC type in Table 1.

An important methodological improvement for this application was the use of EPA Level III ecoregions as the primary spatial framework for model parameterization and application. Gallant et al. (2004) showed that the abundance, spatial pattern, and temporal trends of individual LULC types are strongly related to ecoregion frameworks which govern suitability for land use. The suitability-of-occurrence surfaces for each modeled LULC type were independently modeled for each of the 16, Level III ecoregions shown in Fig. 2, resulting in 224 individual suitability surfaces for the Great Plains. By producing individual suitability surfaces for each LULC type and for each Level III ecoregion, we minimized heterogeneity across each suitability surface and were better able

Table 2
Independent variables. Independent variables used in the regressions to construct suitability-of-occurrence surfaces for each modeled LULC type. Each of the independent variables must be available as spatially explicit datasets.

Variable	Description
Compound Topographic Index (CTI)	Wetness measure calculated as a ratio of catchment area and slope
Elevation	Elevation in meters
Slope	Mean slope in degrees
Available water capacity	SSURGO-based volume of water available to plants if the soil were at field capacity
Crop Capability Index	SSURGO-based suitability of soils for supporting crop, with decreasing capability as index value increases
Soil organic carbon	SSURGO-based soil organic carbon in the top 100 cm of soil
Hydric soils	SSURGO-based percentage of soil component that is hydric
Annual precipitation	Mean annual average precipitation from 1971 to 2000
Average temperature	Mean annual average temperature from 1971 to 2000
January minimum temperature	Mean average January minimum temperature from 1971 to 2000
July maximum temperature	Mean average July maximum temperature from 1971 to 2000
Population density	Persons per square kilometer (2000)
Housing density	Housing unit density per square kilometer (2000)
Distance to road	Distance from any permanent road (2000)
Distance to stream	Distance to permanent flowing water source
Distance to surface water	Distance to any surface water source
Distance to city	Distance to city center
Urban window count	Urban/developed pixel count within a 5-km neighborhood
Distance to rail	Distance to railroad line (2000)
X-coordinate	Center *X*-coordinate
Y-coordinate	Center *Y*-coordinate

to represent finer, within-ecoregion patterns of LULC change as compared to past FORE-SCE applications. Other model parameters were also specified at the resolution of Level III ecoregions. FORE-SCE uses a patch-by-patch spatial allocation procedure, where patch characteristics for individual LULC types are parameterized using regional, historical LULC databases (Sohl and Sayler, 2008). As with the suitability-of-occurrence surfaces, patch characteristics were parameterized independently for each Level III ecoregion using historical LULC data from the USGS Trends project (Loveland et al., 2002).

In addition to parameterization and independent model runs at the resolution of Level III ecoregions for this work, other key modeling improvements have been implemented. The 2007 work for a portion of the Great Plains was the first application of FORE-SCE, and due to extensive computational demands and model run times, only one projected LULC map was produced, with a starting 1992 LULC map and one projected 2020 LULC map. With improved computational power and more efficient FORE-SCE code, we produced annual LULC maps from 1992 through the end of the projection period (2100). By producing annual LULC maps, we now provide a sequence of realistic maps of gross change throughout the projection period rather than simply representing net change between two temporal endpoints. Other modeling improvements included the use of improved spatial databases for both model parameterization and for construction of suitability surfaces. For example, soils data played an important role in the construction of suitability surfaces in the agriculturally oriented Great Plains, and for this work we utilized the newer, spatially and thematically detailed Soil Survey Geographic Database of the NRCS (SSURGO) soils database for the United States (http://soils.usda.gov/survey/geography/ssurgo).

Model runs were initialized starting in 1992, using the modified 1992 NLCD as the starting LULC map. 1992–2005 was modeled using 1992–2000 USGS Land Cover Trends data and NLCD 2001–2006 data (Xian et al., 2009) to supply historical LULC transitions for each Level III ecoregion. The downscaled IPCC SRES scenarios provided historical LULC transitions from 2006 through 2100. Each IPCC SRES scenario was modeled in turn, with each Level III ecoregion modeled independently for each yearly model iteration. A Protected Areas Database for the United States (PAD-US, 2010) was used to restrict LULC change on currently protected public land. However, restrictions on specific LULC transitions were tailored to each SRES storyline. For example, assumptions were made where environmental protections were relaxed for the economically oriented "A" scenarios, with lands protected in "B" scenarios allowed to undergo LULC change. The spatial allocation process is conceptually straightforward, with individual patches of new LULC placed on the landscape until the scenario-based quantities of LULC change for an ecoregion are met for a given yearly iteration. Processing within an ecoregion is sequential, with quantity demand for one individual LULC transition met prior to proceeding to the next transition. The actual patch placement procedures were similar to past FORE-SCE applications, with the placement of "seed" pixels, assignment of a realistic patch size, and selection of a realistic patch configuration from a "patch library" (Sohl and Sayler, 2008). Individual patches were placed for each transition and for each ecoregion, a process which repeated for each yearly iteration once a given year's LULC quantity demand was met. While only a very minor component of LULC change in the Great Plains, as with past FORE-SCE applications, we also established starting forest stand age and tracked stand age as forests were cleared or established, as the model iterated forward in time.

The net results of the scenario construction process and FORE-SCE spatial modeling were 250 m resolution LULC maps, produced annually from 1992 through 2100 for each of the four SRES storylines, with the thematic resolution as shown in Table 1.

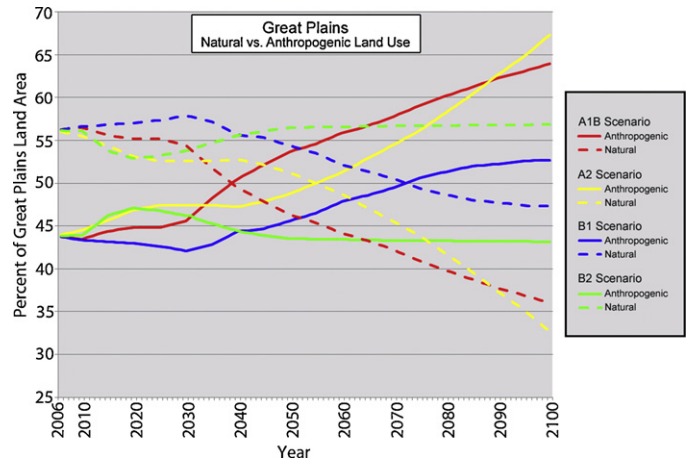

Fig. 5. Natural vs. Anthropogenic Land Uses. Trends in natural and anthropogenic land uses for the four scenarios through 2100. "Anthropogenic" land uses include urban, mechanically disturbed, mining, hay/pasture, and cultivated crop, while "natural" land uses are other modeled land-use types. Only the B2 scenario maintains the current proportion of natural land covers by 2100. The A1B and A2 scenarios experience dramatic shifts in land-use proportions, with once dominant natural land covers only comprising 36.0% and 32.7% of the Great Plains by 2100, respectively.

4. Results and model assessment

4.1. Modeling results

The quantitative downscaling of the SRES storylines, along with the FORE-SCE based spatial allocation of change, were used to construct spatially explicit LULC maps for each scenario from 1992 to 2100. The major storylines for the four scenarios were primarily reflected in major shifts between anthropogenic and natural land cover classes (Fig. 5). The economically oriented A1B and A2 scenarios showed dramatic increases in anthropogenic land covers and corresponding declines in natural land covers. The environmentally oriented B1 and B2 scenarios showed less movement towards anthropogenic land covers. Population pressures in the B1 scenario (same global population assumptions as the A1B scenario) drove modest increases in anthropogenic land covers in the latter half of the study period. Only the B2 scenario managed to maintain current proportions of natural land covers by 2100.

Fig. 6 depicts the spatial patterns in major LULC types for each of the four scenarios. High standards of living and technological innovation in the A1B scenario led to high demand for agricultural land use, including both cultivated crops for food and feed, and land devoted to biofuels, with a large amount of land devoted to cellulosic biofuels after 2025 (shown by expansion in the "hay/pasture" class). Only limited agricultural expansion was possible in the eastern Great Plains as the area was already heavily cultivated, resulting in most new agricultural land appearing in more marginal lands in central Great Plains ecoregions. The A2 scenario similarly underwent agricultural expansion, although scenario assumptions of higher population pressures and lower use of biofuels resulted in less hay/pasture expansion and more cultivated crop expansion than the A1B scenario. Both the A1B and A2 scenarios showed similar patterns of grassland, shrubland, wetland, and forest loss, although the magnitude of losses differed by scenario. The B1 scenario also showed expansion of agricultural land by 2100, although at a much lower magnitude than the A scenarios. With less demand for agriculture, agricultural expansion was concentrated in a few central Great Plains ecoregions. The B2 scenario showed far less change than the other scenarios. Both the B scenarios even showed expansion (restoration) of wetlands,

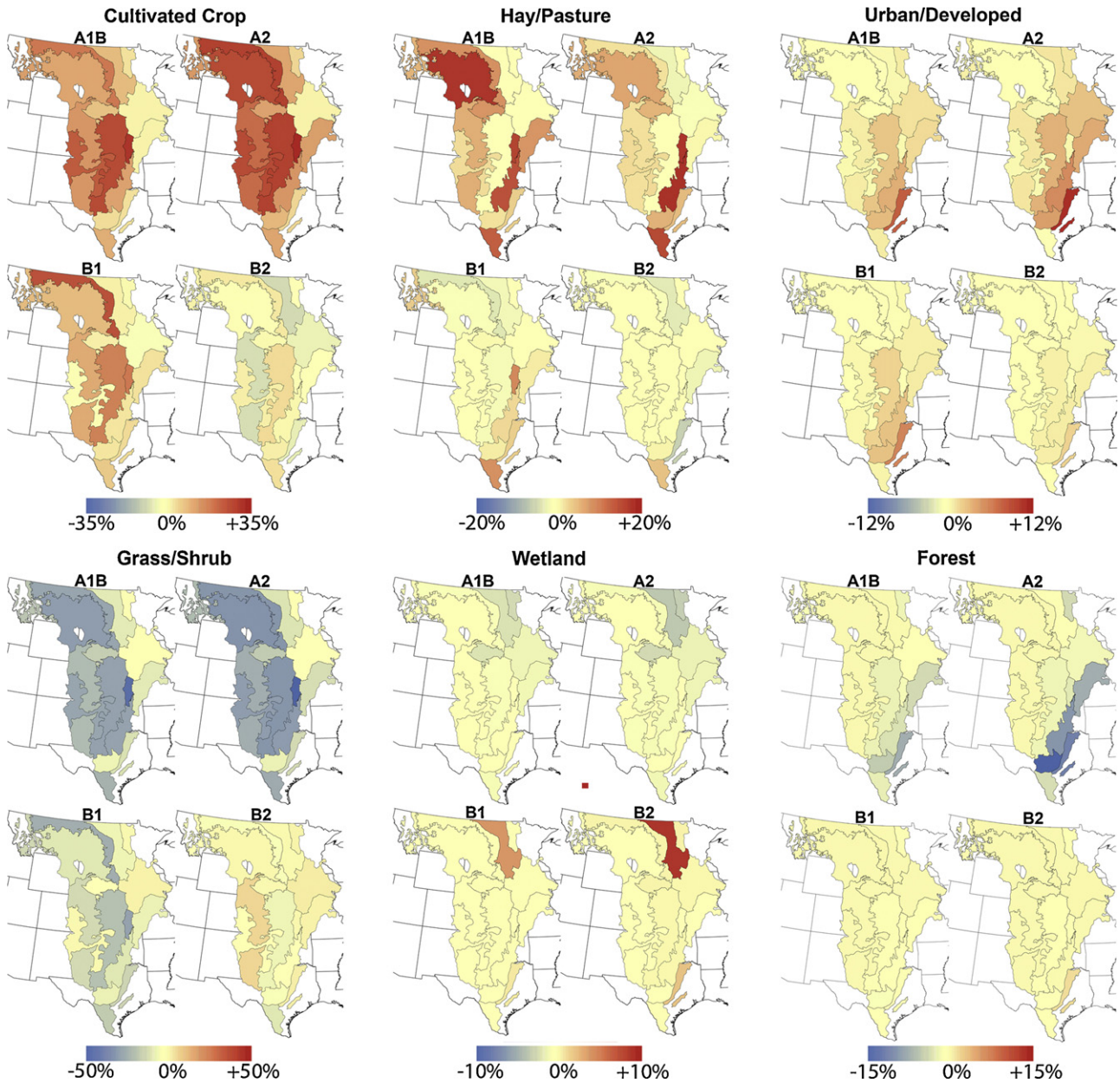

Fig. 6. Land-cover change per scenario. Gain or loss of major land cover classes for each Level III ecoregion, by scenario, between 2005 and 2100. Anthropogenic land covers are shown in the top row, while natural land covers are shown in the bottom row. Values are percentage of total ecoregion area, with each land cover class individually scaled to better highlight spatial variability. Blue tones represent losses while red tones represent gains.

primarily in the northern Great Plains, and the B2 scenario shows expansion of grassland and shrubs in parts of the western Great Plains.

Fig. 7 depicts the full-resolution spatial data for an area around Dallas/Fort Worth, Texas, showing the region at the start of the simulation period, and for the four scenarios at year 2100. At the start of the period, grassland and forest habitat was widely scattered throughout the area northwest of Dallas/Fort Worth. Forest cover only experienced modest reductions for any of the scenarios, but grassland sharply declined in the northwestern quarter of the area in the A scenarios as it was converted to cultivated crop and hay/pasture. Dallas/Fort Worth expanded in all scenarios, as did select other urban areas, but expansion was clearly most pronounced in the A scenarios, especially the highly populated A2 scenario.

4.2. Assessment of modeling results

When judging a LULC modeling framework, the primary evaluation criteria for validating a model are based on assessing whether the models produced the correct quantity of LULC change, and if the model placed LULC change in the correct allocation (Chen and Pontius, 2010; Pontius and Millones, 2011). In association with model validation is an understanding of modeling uncertainty, which can result from a lack of knowledge about the processes being modeled, or by inaccuracies in the model's representation of the processes. Here we focus on assessing performance of our modeling framework by examining both the scenarios themselves, and the spatial representation of the scenarios. As noted in the scenario discussion, the primary reason for the use of a scenario-based framework is to capture the uncertainty associated with

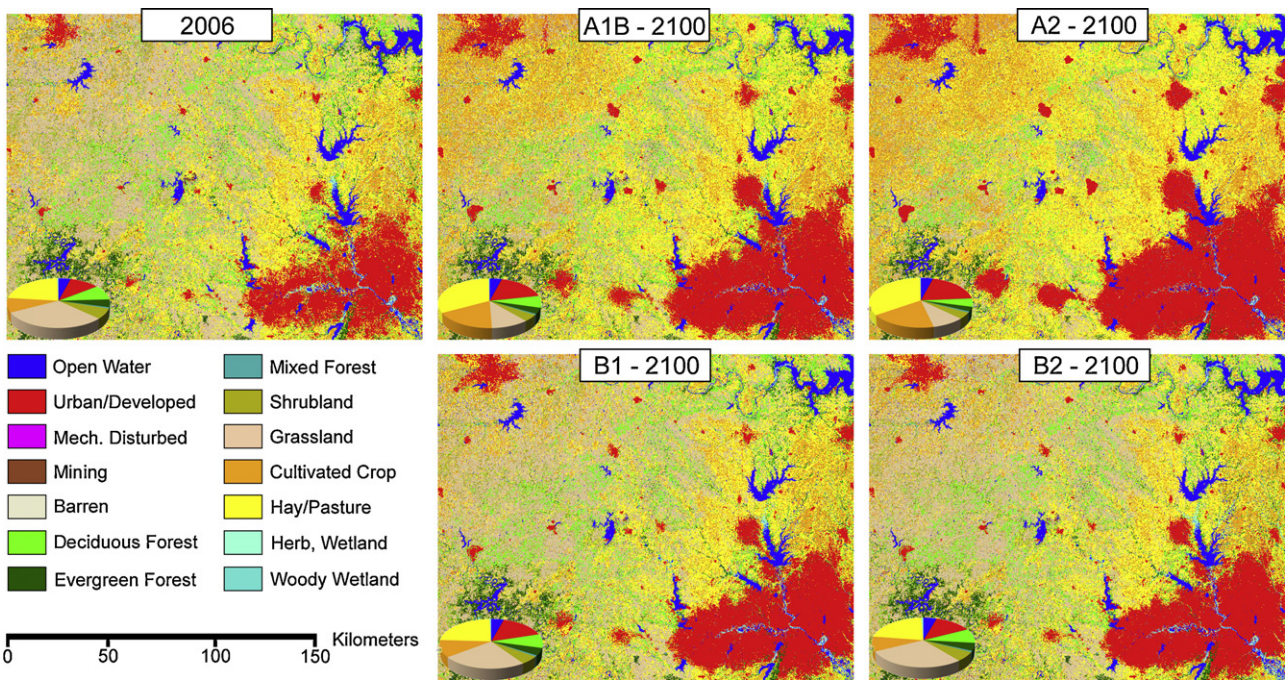

Fig. 7. LULC projection results. FORE-SCE LULC projection results for the four IPCC SRES scenarios for a portion of the study area around Dallas, Texas. Both B scenarios maintain high amounts of natural land cover, whereas increases in cultivated crop, hay/pasture, and urban/developed result in severe decreases in natural cover types by 2100 in the A scenarios.

future LULC projections. For this work, SRES scenarios are used to represent uncertainty in the future driving forces affecting LULC change. The scenarios we have constructed are but one interpretation of LULC response to conditions in each IPCC SRES storyline. However, Pontius and Neeti (2010) note that there is little value in attempting to validate quantified scenarios that are based on qualitative storylines, and no such attempt to formally validate the quantified scenarios will be made here. However, we can demonstrate variability between quantified scenarios, and demonstrate the uncertainty in future LULC conditions as captured by our scenario-based modeling framework.

Pontius et al. (2008) and Pontius and Millones (2011) recommend the use of two simple parameters when comparing map pairs: quantity disagreement and allocation disagreement. Quantity disagreement is defined as the difference between two maps due to an imperfect match in overall proportions of all mapped LULC categories (Pontius and Millones, 2011). Allocation disagreement is defined as the difference between two maps due to an imperfect match between the spatial allocation of all mapped LULC categories (Pontius and Millones, 2011). The two measures can be used to evaluate both validity of a modeled map (comparing to a historical reference map) or for evaluating differences between two scenarios. Fig. 8 provides quantity disagreement, allocation disagreement, and total disagreement for each paired set of scenarios, at 10-year increments from 2010 through 2100. The lowest total disagreement between scenarios was between the pair of economically oriented scenarios (A1B and A2) and the pair of environmentally oriented scenarios (B1 and B2), while the greatest disagreement was between the A2 and B2 scenario. Depending upon scenario pair, per-pixel comparison shows total disagreement ranged between 13.2% and 28.0% by 2100, with 34.2% of all pixels differing between any of the four scenarios.

The proportion of quantity disagreement vs. allocation disagreement in Fig. 8 varied by scenario pair. Overall, quantity disagreement composes a higher percentage of total disagreement than did allocation disagreement. This was especially true towards the end of the simulation period, as the greatest variability in scenario-defined LULC proportions occurred in 2100. However, allocation disagreement often composed the highest proportion of total disagreement early in the simulation period, and even remained highest throughout the simulation period when comparing A1B and A2. In short, differences between scenario maps in the long-term were primarily due to differences in the scenarios themselves, while in the short-term, both the scenarios and the spatial modeling were important contributors to map differences. This suggests that in our framework, scenario variability is best examined through long-term simulation, as short-term differences in scenario maps may simply be due to the vagaries and stochasticity of the spatial modeling procedure. However, key parameters driving the spatial allocation of change in FORE-SCE may vary depending upon scenario assumptions. For example, assumptions regarding more compact urban development in the environmentally conscious “B” scenarios led to a tightening of a patch-dispersion variable for new urban pixels. Also, additional lands were assumed to be managed for environmental purposes in the “B” scenarios, resulting in a higher proportion of the landscape “protected” from widespread LULC change. Thus, some of the differences attributed to allocation disagreement in Fig. 8 are likely due to strategic, scenario-specific model parameterization rather than stochastic allocation results.

In the modeling framework, it is the scenarios themselves that are designed to frame overall uncertainty associated with future landscapes. Fig. 8 thus represents an important component of overall uncertainties associated with the scenario framework. However, Fig. 8 undoubtedly underestimates overall uncertainty and scenario variability, as results for each scenario were only simulated once within FORE-SCE. Monte Carlo simulations within each scenario would allow us to better quantify uncertainty associated with FORE-SCE’s spatial allocation of scenario-based LULC change, but computational resources and model run times made Monte Carlo simulations not feasible for the entire Great Plains. However, we can look at the spatial output of FORE-SCE for the four scenarios to qualitatively examine uncertainty based on SRES storylines, identifying areas where future LULC is more certain (i.e.,

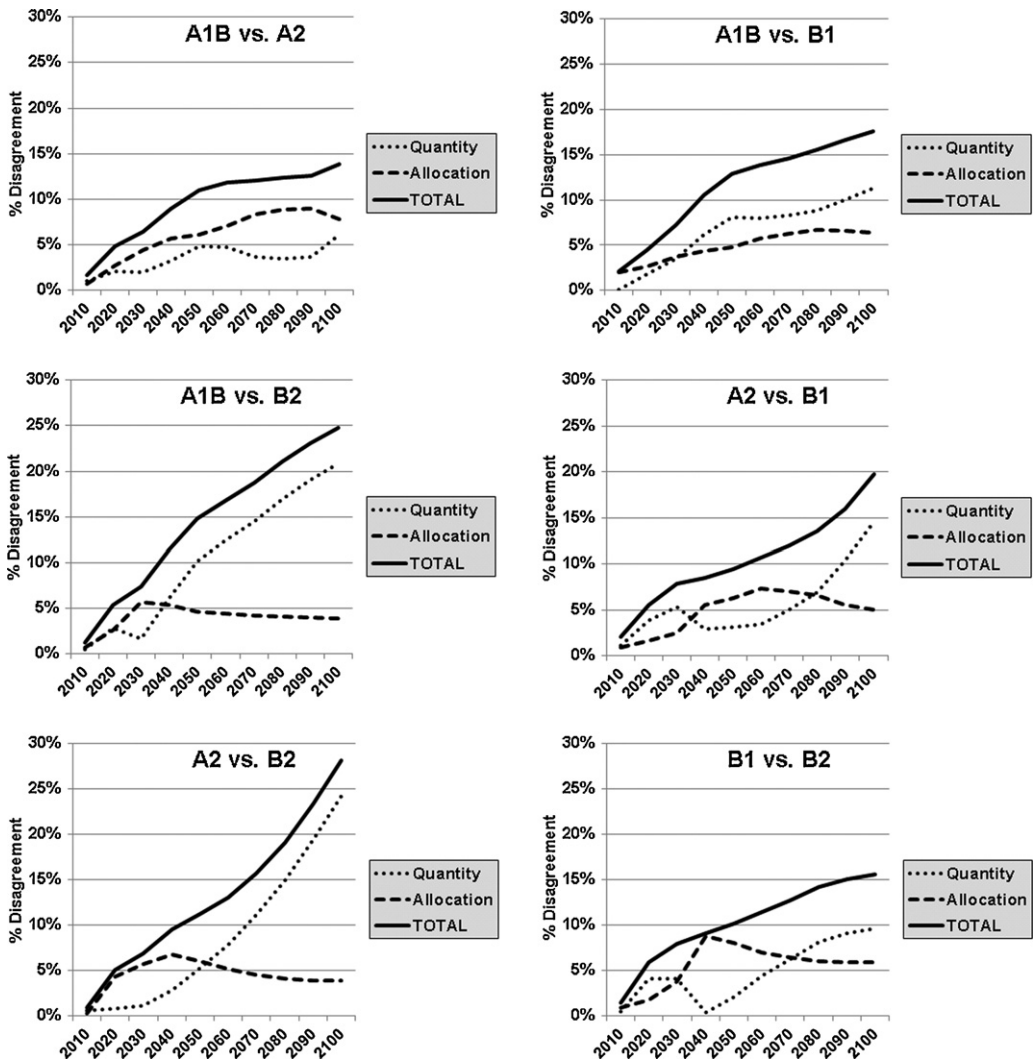

Fig. 8. Quantity and allocation disagreement – quantity, allocation, and total disagreement for each modeled pair of IPCC SRES scenarios from 2010 through 2100. Variation in the spatial allocation of change as modeled by FORE-SCE represents a large portion of total disagreement in the first few decades of the simulation, but quantity disagreement driven by scenario characteristics dominates total disagreement by the latter portion of the simulation period.

relatively stable regardless of scenario), and areas where different storylines produce different LULC patterns. Fig. 9 represents a "spatial diversity" representation of modeled LULC change through 2100. "Core" agricultural ecoregions such as the Central Corn Belt Plains, the Lake Agassiz Plain, and the Central Great Plains were already dominated by cultivated cropland at the start of the simulation period, and future LULC stayed relatively stable through the simulation period for all scenarios. Ecoregions with more marginal agricultural lands, such as those in the Northwestern Glaciated Plains, the Northwestern Great Plains, and the High Plains were considerably more variable between scenario simulations. Variability in these ecoregions was driven by scenario-specific levels of demand for cultivated crop and hay/pasture, with markedly different patterns of agricultural land, grassland, and shrubland between scenarios. Other hotspots of variability include the Flint Hills ecoregion, the western portion of the Central Irregular Plains, and the Cross Timbers ecoregions, ecoregions where considerable pressure for agricultural land use resulted in high loss of remaining grassland habitat, particularly as hay/pasture expanded in response to increased demand for biofuels in the A1B scenario. The diversity map in Fig. 9 serves as a spatial representation for indicating both probability of future LULC change, and uncertainty.

The same concepts and tools for map comparison as advocated by Pontius and Millones (2011) that are used for examining scenario pairs can be used to validate modeling results, determining the degree to which the modeling framework accurately predicted empirical conditions. Quantity disagreement is of little interest for validating quantified scenarios based on qualitative storylines, as noted above. Quantity disagreement for our modeled LULC results thus focuses on a verification of the FORE-SCE model's ability to adequately match scenario-defined proportions of LULC change. Table 3 shows that FORE-SCE is able to very closely match scenario-defined proportions of LULC change, even through a nearly 100-year simulation period. The highlighted cells in Table 3 show a handful of cases where modeled proportions for individual LULC classes are slightly off (>0.2% or more). With additional model iterations, the level of match could be tightened even further, but at the cost of additional processing time. Model iterations are continued until the level of match between "demand" and "modeled" LULC proportions meets user-specified requirements.

Allocation disagreement is typically analyzed by comparing reference LULC data to modeled LULC data for a historical period (Pontius et al., 2004; Pontius and Millones, 2011). However, historical LULC data sources with a compatible spatial extent, spatial resolution, and temporal resolution are difficult to obtain for

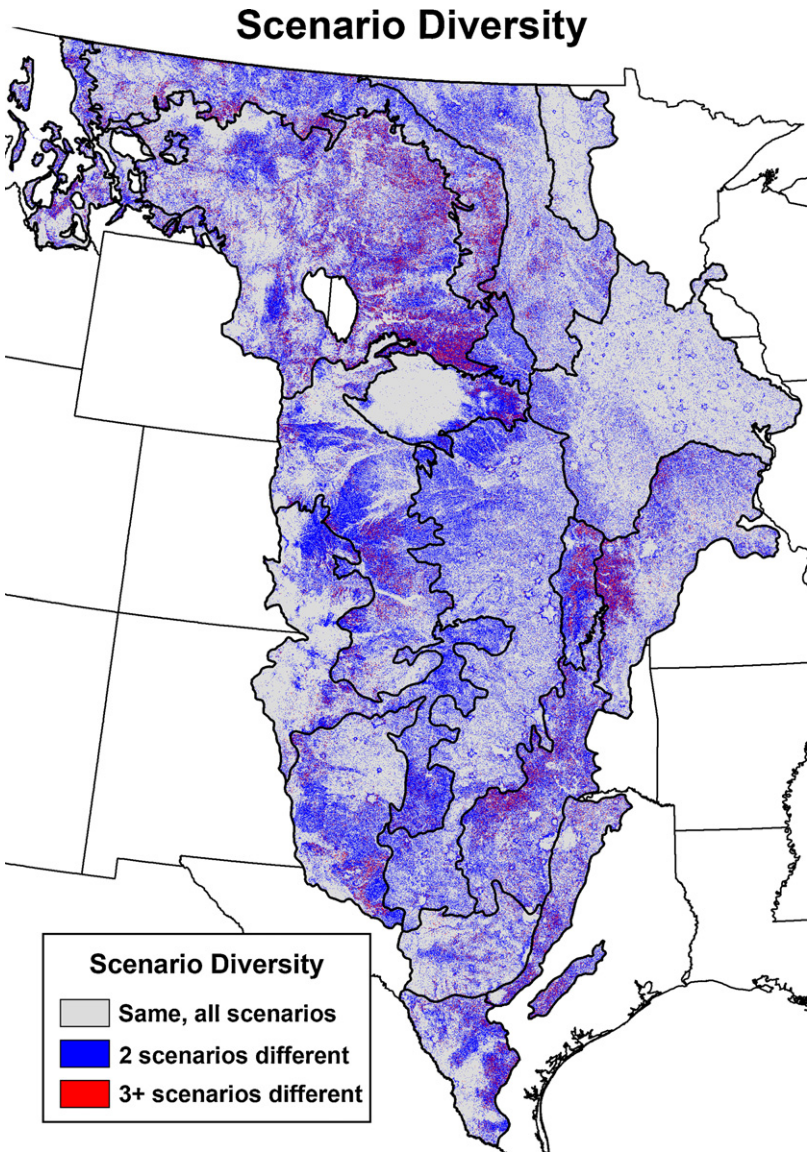

Fig. 9. Scenario diversity. Per-pixel diversity between IPCC SRES scenarios. Differences between scenarios are concentrated in hotspots including irrigated agricultural areas in the High Plains, the agricultural and grassland boundary in the Northwestern Glaciated Plains and Northwestern Great Plains, and the Flint Hills and western part of the Central Irregular Plains.

regional- to national-scale LULC modeling applications. Due to the issues with the suitability of available historical data sources, a formal quantitative validation of the spatial allocation was not performed.

5. Discussion

The framework we have developed allowed us to produce LULC projections for multiple scenarios in the Great Plains, projections which have several desirable characteristics. The value of future projections is not for pure prediction, but through our ability to examine LULC impacts across a range of potential future economic and policy contexts (Riebsame et al., 1994). The scenario-based framework we have developed allows us to assess potential future LULC trajectories in the Great Plains based on a specific set of predefined socioeconomic and biophysical driving force assumptions. This in turn allows for the analysis of impacts on carbon and greenhouse gas fluxes as part of the USGS Biological Carbon Sequestration Project, as well as for analyses of other ecological processes related to LULC change.

One of the biggest advantages of the approach is the construction of spatially explicit LULC maps for each year through the projection period. Local land-use pattern has a strong influence on environmental processes, including biodiversity, water quality, and ecological function (Wimberly and Ohman, 2004; Lee et al., 2009; Polasky et al., 2011). Thus, representing spatial patterns of land use is important for analyzing the impacts of LULC change (Brown et al., 2002; Veldkamp and Verburg, 2004). Samson et al. (2004) note that proper conservation planning for the Great Plains must be based on availability of sophisticated geospatial information. The projections we have produced are spatially explicit, and also provide a representation of the entire landscape, modeling all lands in the Great Plains, and covering a wide range of thematic LULC types. Our approach thus overcomes the limitations of many modeling approaches that examine only a portion of the landscape (e.g., econometric approaches that only modeling private land) or approaches that only model specific components of LULC change (e.g., urban models or agricultural models).

The approach also attempts to avoid potential pitfalls with overdesign and model complexity. A difficulty in LULC modeling

Table 3
Verification-modeled quantity disagreement. Percentage of the total landscape for each of 14 mapped land-cover classes through 2100, as quantified by the scenario ("demand"), and as actually modeled. Land cover percentages at the start of the simulation period are shown for comparison purposes. FORE-SCE is able to match the scenario-defined proportions of overall LULC change to a very high degree, with the exact level of match dictated by user requirements and the need to limit the number of modeled iterations. Areas of slight mismatches greater than 0.2% are highlighted in gray cells.

	Starting	A1B			A2		
	2006 LULC	2100 Demand	2100 Modeled	2100 Difference	2100 Demand	2100 Modeled	2100 Difference
Water	1.2	1.2	1.2	0.0	1.1	1.1	0.0
Developed	1.4	2.6	2.7	0.1	3.1	3.4	0.3
Mechanically disturbed	0.0	0.0	0.2	0.2	0.0	0.2	0.2
Mining	0.1	0.1	0.1	0.0	0.1	0.1	0.0
Barren	0.3	0.3	0.3	0.0	0.3	0.3	0.0
Deciduous forest	3.2	2.5	2.5	−0.1	1.9	1.8	−0.1
Evergreen forest	2.0	1.8	1.6	−0.1	1.5	1.4	−0.1
Mixed forest	0.2	0.1	0.1	0.0	0.1	0.1	0.0
Shrubland	9.2	5.7	5.6	−0.1	5.3	5.2	−0.1
Grassland	38.8	23.3	23.2	−0.2	21.4	21.2	−0.3
Agriculture	32.8	45.2	45.3	0.1	50.8	50.9	0.1
Hay/pasture	9.6	16.0	16.0	0.0	13.3	13.3	0.0
Woody wetland	0.4	0.3	0.3	0.0	0.3	0.2	0.0
Herbaceous wetland	1.0	0.8	0.8	0.0	0.7	0.7	0.0
	Starting	B1			B2		
	2006 LULC	2100 Demand	2100 Modeled	2100 Difference	2100 Demand	2100 Modeled	2100 Difference
Water	1.2	1.2	1.2	0.0	1.3	1.3	−0.1
Developed	1.4	2.2	2.3	0.1	1.7	1.8	0.1
Mechanically disturbed	0.0	0.0	0.1	0.1	0.0	0.2	0.2
Mining	0.1	0.1	0.0	0.0	0.1	0.1	0.0
Barren	0.3	0.3	0.3	0.0	0.3	0.3	0.0
Deciduous forest	3.2	3.1	3.1	0.0	3.2	3.1	0.0
Evergreen forest	2.0	2.0	1.9	−0.1	2.0	1.9	−0.1
Mixed forest	0.2	0.2	0.2	0.0	0.1	0.1	0.0
Shrubland	9.2	7.5	7.5	0.0	8.9	8.9	0.0
Grassland	38.8	31.3	31.2	−0.1	38.8	37.9	−0.8
Agriculture	32.8	40.5	40.5	0.0	31.9	32.9	1.0
Hay/pasture	9.6	9.9	9.9	0.0	9.4	9.6	0.2
Woody wetland	0.4	0.5	0.5	0.0	0.6	0.6	0.0
Herbaceous wetland	1.0	1.3	1.3	0.0	1.6	1.3	−0.3

is achieving a balance between accounting for the major processes and feedbacks affecting LULC change, and developing models that are too complex to be practical, or too complex to analyze model uncertainties (Verburg et al., 2004; Van Rompaey and Govers, 2002). There is no guarantee that building complex models and expending high levels of effort will result in LULC results that are useful (Pontius and Spencer, 2005). Decision-makers, as well as external project collaborators, may be reluctant to use LULC projections if the logic and processes cannot be clearly and transparently communicated (Schiller et al., 2001; Sohl et al., 2010). Murray (2007) noted that more generalized "top-down" models help to facilitate insight into the impacts of driving forces of a phenomenon. We have taken the approach that a simple and straightforward framework can have tremendous value for research applications related to LULC change. The USGS Biological Carbon Sequestration project had very stringent and aggressive timelines for completion of this work, which provided additional pressure to develop a straightforward and efficient modeling framework. Rather than relying solely on complex, integrated modeling frameworks for constructing scenarios, we also incorporated historical LULC information and the expertise of regional LULC experts in a story-and-simulation approach (Alcamo, 2001, 2008). For construction of scenarios, we chose to trade objective, quantitative modeling for a more subjective process that has "buy-in" and confidence from project stakeholders, as advocated by past modeling applications (Theobald et al., 2000; D'Aquino et al., 2003; Hulse et al., 2004; Castella et al., 2005). For this application, workshop participants included stakeholders from across the USGS Biological Carbon Sequestration Project, including those involved in the modeling of biogeochemical processes. This framework, with the inclusion of project stakeholders in the scenario construction process, could similarly be used for future applications. Our transparent, straightforward approach to both scenario development and spatial modeling enable collaborators and potential users of the LULC projections to easily judge suitability for their own applications.

We recognize, however, that there is no single "correct" approach to LULC modeling, and that a number of factors may limit the practicality of our framework for other applications. The framework relies heavily on spatially explicit biophysical and socioeconomic data, both for the construction of suitability-of-occurrence surfaces, and for model parameterization (e.g., parameterization of patch characteristics based on historical LULC data). Use of the framework is problematic in regions that are less "data rich" than the United States. The framework also can be labor intensive, as substantial investments in personnel and time are required to model at this level of thematic and spatial resolution for a region as large as the Great Plains. The scenario-based framework allows for analysis of multiple landscape futures, but the predetermination of a handful of generalized scenarios may limit the utility for ecological or social applications attempting to investigate specific landscape processes. In addition, our scenario-construction process relies heavily on subjective input from LULC experts. While inclusion of LULC experts and project stakeholders in the scenario-construction process may internally increase confidence in modeling results, potential users and decision-makers outside of the project team may feel less confident in our reliance on subjective input. Decision- and policy-makers with a focus on

modeling the human decision-making process through an agent-based approach may also feel less comfortable using an approach that relies on empirically based modeling in combination with our scenario-construction process.

A formal validation of the spatial modeling results remains problematic due to characteristics of available historical data. By starting model runs in 1992, two LULC data sources offered the potential for validating our modeling results, but difficult issues existed with each. NLCD data offer historical LULC data that are potentially useful for validation. We used 1992 NLCD as our starting land cover, and 2001 and 2006 NLCD products were used to drive quantity demand for the 2000–2005 modeling period. However, the original 1992 NLCD and the 2001 and 2006 NLCD data used different mapping methodologies and thematic classification systems, and are not directly comparable. The only available, consistent, wall-to-wall LULC data for multiple historical dates for the Great Plains is the 2001 and 2006 NLCD data. Our mapping, however, did not use the 2001 NLCD as a starting LULC product, and we thus cannot directly compare our results to the 2001 and 2006 NLCD. The 2001–2006 NLCD change product also is itself not yet validated, making its utility as a reference data source questionable. In addition, the total amount of LULC change mapped in the Great Plains between 2001 and 2006 by NLCD was only 0.75% of the landscape. This brings into question whether basing a validation on the short 2001–2006 time period with little LULC change is a true measure of a model's performance, as Pontius et al. (2008) demonstrated a very strong relationship between the amount of change being mapped, and a model's ability to correctly place change. The USGS Land Cover Trends data that was used to construct quantity demand for the 1992–2000 period also offers some potential for validation. However, the data are based on a sampling framework, with samples randomly distributed and covering only 3.1% of the Great Plains landscape. Issues also exist with mapping methodologies and the thematic differences between our modeled LULC classes and the more generalized classes mapped by the USGS Land Cover Trends project. For all of these reasons, we have not used the NLCD or USGS Land Cover Trends data products to validate model's performance. In addition to past applications that have examined validation issues for the model (Sohl et al., 2007; Sohl and Sayler, 2008), we are currently working on LULC "backcasting" modeling for historical periods, work that will provide a long validation period (1950 to present) and enable validation using historical agricultural census data at the county level, population census data, and other historical data sources related to land use and land cover.

Beyond quantitative validation of LULC modeling results, Pontius et al. (2004) state that visual inspection is important, as the mind can detect patterns that statistical procedures might miss. There is no single standardized methodology for validating all LULC models (Rykiel, 1996; Pontius et al., 2004), and it is not useful to judge a model as valid or invalid based solely on quantitative validation results (Verburg et al., 2006). For future projections, the issues with allocation disagreement boil down to the question of whether change is being placed in suitable locations. Attention was thus focused on ensuring the quality of the suitability surfaces used in this work. With 16 ecoregions and 14 land-cover types being mapped, 224 individual suitability surfaces were constructed for the Great Plains. For every suitability surface, a group review of all project scientists was used to examine and assess the quality of the surface and the fidelity of the regressions used to create those surfaces. In addition, the use of the suitability surfaces within FORESCE ensures the placement of change patches only on the higher suitability locations, as a "clumpiness" parameter is used to limit the portion of the suitability surface used to place change (Sohl and Sayler, 2008). For example, for the placement of cultivated crop, hay/pasture, grassland, or shrub patches of change, the clumpiness parameter typically limited placement to the highest 10–20% of suitability values, ensuring LULC change is placed in suitable locations. Visual inspection of modeling results for each scenario was also used to ensure LULC change patches were being placed in suitable locations, with adjustment of model parameters or base suitability surfaces if issues were detected. In sum, assessment and control of model performance thus was based on examining uncertainty, quantity disagreement, location disagreement (as much as possible), restriction of placing change patches to highly suitable locations, and subjective analysis of model results.

6. Conclusion

The scenario-based LULC projections described here are the first spatially explicit, fine spatial and thematic resolution land cover projections that have been produced for the Great Plains of the United States. The spatially explicit, scenario-based LULC projections will prove invaluable for understanding the spatial and temporal relationships between LULC change and carbon and greenhouse gas dynamics in the Great Plains, and reduce uncertainties in greenhouse gas estimates compared to studies using accounting or other non-spatial approaches. The fine spatial and temporal resolution also make the scenario-based projections useful for analyzing impacts of projected LULC change on other biophysical processes. By the end of 2012, we expect to have completed scenario-based LULC projections for the conterminous U.S., projections which will be made readily available to any research application.

The work described here is just a start to providing timely, flexible, spatially explicit, and scenario-based LULC projections for these and other applications. Our ongoing research is moving towards integrated modeling environments, where spatially explicit LULC models are tightly linked with spatially explicit hydrologic, climate, and biogeochemical models so we can examine and realistically model feedbacks between LULC change and water availability, temperature and precipitation changes, and soil biogeochemistry. Integrated modeling frameworks involving these additional components will improve our ability to accurately model the landscape's changing suitability to support different LULC types. When linked with exogenous economic models, such a modeling framework will also allow for more dynamic scenario development, where modeled data on biophysical constraints for different LULC types inform models of economic opportunities that drive the scenario framework.

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