Applied Geography 34 (2012) 111–124

Contents lists available at SciVerse ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

A land-use and land-cover modeling strategy to support a national assessment of carbon stocks and fluxes

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Keywords:
Land use
Land cover
Model
Scenario
Carbon

A B S T R A C T

Changes in land use, land cover, disturbance regimes, and land management have considerable influence on carbon and greenhouse gas (GHG) fluxes within ecosystems. Through targeted land-use and land-management activities, ecosystems can be managed to enhance carbon sequestration and mitigate fluxes of other GHGs. National-scale, comprehensive analyses of carbon sequestration potential by ecosystem are needed, with a consistent, nationally applicable land-use and land-cover (LULC) modeling framework a key component of such analyses. The U.S. Geological Survey has initiated a project to analyze current and projected future GHG fluxes by ecosystem and quantify potential mitigation strategies. We have developed a unique LULC modeling framework to support this work. Downscaled scenarios consistent with IPCC Special Report on Emissions Scenarios (SRES) were constructed for U.S. ecoregions, and the FORE-SCE model was used to spatially map the scenarios. Results for a prototype demonstrate our ability to model LULC change and inform a biogeochemical modeling framework for analysis of subsequent GHG fluxes. The methodology was then successfully used to model LULC change for four IPCC SRES scenarios for an ecoregion in the Great Plains. The scenario-based LULC projections are now being used to analyze potential GHG impacts of LULC change across the U.S.

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Introduction

As much as 50% of the Earth's ice-free land surface has been affected directly by land-use and land-cover (LULC) conversion, with most of the rest indirectly affected through LULC change co-effects such as climate change (Turner, Lambin, & Reenberg, 2007). Even in areas where land cover has remained largely static, intensive land-management practices have significantly altered ecological processes (Dale, Archer, Change, & Ojima, 2005). Changes in land cover and land management have considerable influence on biogeochemical cycles, and we have considerable potential to significantly alter emissions of carbon and other greenhouse gases (GHGs) through targeted land-use change. Potter et al. (2007) found afforestation of suitable marginal agricultural lands in the United States has the potential to offset at least one-fifth of annual U.S. fossil fuel emissions, while Smith, Powlson, Smith, Falloon, and Coleman (2000) similarly found potential for sequestering very significant amounts of carbon through long-term woodland regeneration on arable agricultural land in Europe. Grasslands can act as significant carbon sinks with the implementation of improved management techniques (Conant, Paustian, & Elliot, 2001; Lal, 2007). Active use of prescribed burning in fire-dependent forest systems helps increase the rate of carbon sequestration (Wiedinmyer & Hurteau, 2010).

Globally, the Intergovernmental Panel on Climate Change (IPCC) has produced four comprehensive global assessments of climate change since 1990, and IPCC guidelines on agriculture, forestry, and other land uses recommend analyzing GHG emissions from anthropogenically managed lands (Intergovernmental Panel on Climate Change, 2006). Within the United States, the first

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0143-6228/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.apgeog.2011.10.019

state of the carbon cycle report (SOCCR) provided a comprehensive analysis of the effects of LULC change on GHG gas fluxes (U.S. Climate Change Science Program, 2007). The U.S. Environmental Protection Agency (EPA) produces U.S. Greenhouse Gas Inventory Reports on an annual basis (U.S. Environmental Protection Agency, 2010). Within Europe, Nabuurs, Schelhaas, Mohrens, and Field (2003) examined changes in European forest extent from 1950 to 1999, and resultant implications on carbon sequestration. Schwaiger and Bird (2010) examined linkages between land-use change, albedo, and carbon sequestration in southern Europe to determine net effects on regional climate. Tian et al. (2011) simulated the effects of climate and historic LULC change on net carbon balances in the terrestrial ecosystems of China from 1961 to 2005. These reports provide considerable information about historic and current carbon stocks, fluxes, and recent changes related to LULC change.

However, scenario-based projections of LULC change are also needed to inform efforts to mitigate carbon and GHG fluxes. Continental-scale carbon accounting requires modeling frameworks that examine the carbon and GHG flux impacts of changing land use and land management in both a spatially and temporally explicit manner (Richards & Evans, 2004). IPCC's "Good Practice Guidance" (Intergovernmental Panel on Climate Change, 2003) recognizes three "tiers" of methodology for estimating carbon and GHG emissions, and recommends the use of highest possible tier to reduce estimate uncertainties. The IPCC's highest Tier 3 includes modeling frameworks where land-use change can be spatially tracked over time.

In response to section 712 of the U.S. Energy Independence and Security Act (EISA) of 2007 (U.S. Government Printing Office, 2007), the U.S. Geological Survey (USGS) has initiated the LandCarbon project to analyze GHG emissions associated with LULC change and examine potential mitigation strategies under multiple future scenarios (Zhu, 2010).We are using an integrated modeling framework designed to capture the primary ecological processes and interactions that affect GHG fluxes and mitigation potential (Fig. 1).Specifically, the methodology is designed to examine policy- or research-relevant questions including:

1) What are ecological carbon sequestration capacities and GHG fluxes of U.S. ecosystems under different future scenarios, and how do these estimates vary geographically and temporally?
2) How effective are management practices, such as changes in tillage or forest cutting practices, on short- and long-term carbon sequestration?
3) How effective are deliberate changes in land use, such as reforestation or wetland restoration, on carbon sequestration?

The objectives of this paper are to summarize the development and application of a unique LULC modeling framework aimed at addressing a U.S. national assessment of GHG fluxes and potential future mitigation strategies. This paper focuses on the LULC modeling component of the LandCarbon project, including the development of LULC scenarios. We will also briefly look at carbon results from a biogeochemical modeling framework used to analyze terrestrial and aquatic carbon and greenhouse gas fluxes resulting from LULC change (Fig. 1). We will discuss the LULC modeling framework, demonstrate the capability of the framework to inform the biogeochemical model, and provide final LULC projection results for one of the first regions to have been completed.

Background

LULC modeling requirements

The LULC modeling framework was designed to satisfy several requirements of the EISA legislation. Ecological and socioeconomic driving forces of land cover, as well as patterns of resultant LULC change, vary by geographic region (Gallant, Loveland, Sohl, & Napton, 2004; Sohl, Loveland, Sleeter, Sayler, & Barnes, 2010). To better represent regionally specific patterns of LULC change and assist in the identification of effective carbon sequestration mitigation actions, the LandCarbon national assessment uses a regional, spatial framework based on U.S. Environmental Protection Agency (EPA) ecoregions (Omernik, 1987). Ecoregions delineate areas with similar land-use potential and capacity, and are thus very useful for LULC studies (Gallant et al., 2004). The EPA ecoregion framework is hierarchical, with higher-level ecoregions nested within lower-level ecoregions. We are using the 1999 version of the ecoregions (U.S. Environmental Protection Agency, 1999), with 84 level III ecoregions nested within 16 level II ecoregions in the conterminous United States. Level II ecoregions serve as our primary assessment and reporting unit for the LandCarbon project, but much of the land-cover modeling work described in this manuscript is conducted at the Level III ecoregion scale.

A relatively rich level of LULC thematic detail is modeled to better inform the General Ensemble Modeling System (GEMS) (Liu, Bliss, Sundquist, & Huntington, 2003; Liu, Loveland, & Kurtz, 2004), the biogeochemical modeling component (C and GHG fluxes) of the overall framework (Table 1).Given substantial uncertainties inherent in forecasting LULC change (and resultant GHG fluxes), the methodology addresses multiple potential futures through a robust scenario development framework. Spatially explicit modeling for LULC, as well as for biogeochemical process, differentiates this work from many inventory- or sample-based approaches projecting GHG

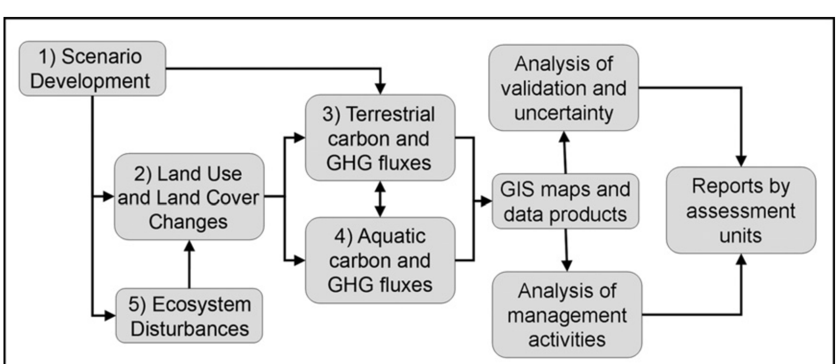

Fig. 1. Conceptual diagram of the major components of the LandCarbon National Assessment. This paper focuses on the LULC modeling component, including both 1) scenario development, and 2) land-use and land-cover changes. The biogeochemical modeling framework discussed briefly in this paper is used to examine 3) terrestrial carbon and GHG fluxes, and 4) aquatic carbon and GHG fluxes. A fifth major modeling component, ecosystem disturbances, focuses on modeling fire, and is not discussed in this paper.

Table 1
LULC classes being modeled from 1992 through 2050. Modeling a relatively high number of thematic LULC classes improves the ability of the linked biogeochemical model to determine GHG fluxes due to LULC change.

Open Water	All areas of open water
Perennial Ice and Snow	All areas with perennial cover of ice and (or) snow
Developed (Urban)	Includes NLCD developed classes with impervious surfaces accounting for > 20% of total cover within a pixel
Barren Land	Barren areas of bedrock, desert pavement, scarps, talus, slides, sand dunes, unconsolidated shoreline, and other naturally barren areas
Surface Mining	Strip mines, gravel pits, and other surface features resulting from mining extraction
Deciduous Forest	Areas dominated by trees > 5 m tall, with > 20% vegetative cover. More than 75% of tree species are deciduous.
Evergreen Forest	Areas dominated by trees > 5 m tall, with > 20% vegetative cover. More than 75% of tree species are evergreen.
Mixed Forest	Areas dominated by trees > 5 m tall, with > 20% vegetative cover. Neither deciduous or evergreen species are more than 75% of tree species.
Clear-cut Forest	Forest disturbed by logging, where more than 80% of trees are removed
Shrub	Areas dominated by shrubs < 5 m tall with shrub canopy greater than 20% of total vegetation.
Grassland	Areas dominated by grammanoid or herbaceous vegetation, generally greater than 80% of total vegetation.
Pasture/Hay	Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops.
Cultivated Crop	Areas used for the production of annual crops such as corn, soybeans, small grains, vegetables, or other crops.
Herbaceous Wetland	Areas where perennial herbaceous vegetation accounts for 75–100% of cover, with soil or substrate periodically saturated or covered with water
Woody Wetland	Areas where forest or shrubland vegetation accounts for 25–100% of cover, with soil or substrate periodically saturated or covered with water

fluxes. Spatially explicit, wall-to-wall LULC and biogeochemical models will facilitate an understanding of geographic distributions of carbon sequestration and GHG flux mitigation potential, as well improve our understanding of modeling uncertainties associated with spatial and non-spatial approaches.

The methodology was designed to allow for an analysis of carbon sequestration mitigation activities associated with either land-use change, or land-management change (Zhu, 2010). LULC change is modeled from 1992 through 2050. 1992 was chosen as the initial baseline year to take advantage of existing data sets that provide important information on general land cover conditions, ecosystem composition and structure, and fire disturbances, including the 1992 and 2001 National Land Cover Database (NLCD) (Homer et al., 2007; Vogelmann et al., 2001), the LANDFIRE database (Rollins & Frame, 2006), and data from the USGS Land Cover Trends project (Loveland et al., 2002). Note that while 2050 marks the end date for Landcarbon analyses, the LULC modeling framework described here examined LULC change through 2100 to potentially support applications other than Landcarbon.

Scenario and LULC modeling framework

A scenario-based framework provides a means to explore uncertainties associated with future LULC conditions and resultant effects on GHG fluxes. A given scenario is not a prediction, but a representation of likely landscape response to scenario-based assumptions in driving forces such as population growth, economic conditions, energy supply and usage, and climate. A suite of scenarios is meant to provide a reasonable approximation of overall uncertainty in future LULC conditions.

A modified version of the Forecasting Scenarios of Land-use change (FORE-SCE) framework (Sohl & Sayler, 2008; Sohl, Sayler, Drummond, & Loveland, 2007) serves our primary system for modeling LULC change. FORE-SCE's modular approach, borrowed from the CLUE series of models (Verburg, Eickhout, van Meijl, 2008; Verburg, Veldkamp, & Fresco, 1999), distinguishes between a non-spatial "demand" component that provides regional proportions of LULC change (a LULC "prescription" consisting of year-by-year areal extent of mapped LULC classes) and a "spatial allocation" component that distributes LULC change on the landscape (Fig. 2). Although no model can address all the complex, multiscale processes affecting LULC change, the modular approach accommodates inclusion of variables representing spatial and non-spatial driving forces operating at multiple scales.

The demand component for this work is provided through a unique scenario development process that qualitatively and quantitatively downscales IPCC Special Report on Emissions Scenarios (SRES) (Intergovernmental Panel on Climate Change,

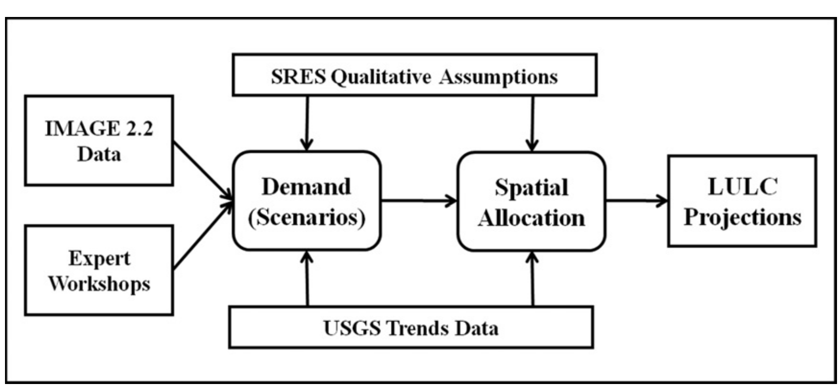

Fig. 2. Conceptual diagram of the LULC modeling framework, with linked demand and spatial allocation components used to produce LULC projections. Scenarios are constructed using qualitative storylines consistent with SRES, quantitative SRES model runs from IMAGE 2.2., and expert opinion. Scenario demand feeds the spatial allocation component which is used to produce spatially explicit LULC maps consistent with each scenario. Historical LULC data from the USGS trends project supports both scenario development, and parameterization of the spatial allocation model.

2000, p. 27) storylines to U.S. ecoregions. The spatial allocation component of FORE-SCE is unique. Land-use change most often occurs at a local scale, with the accumulation of individual patch changes at the local scale resulting in regional patterns of LULC change (Sohl, Gallant, & Loveland, 2004). FORE-SCE's spatial allocation module incorporates a unique patch-by-patch allocation methodology that produces realistic patterns of local and regional land-use change (Sohl & Sayler, 2008; Sohl et al., 2007). Output from FORE-SCE also is compatible for use by the GEMS biogeochemical modeling framework, as demonstrated by previous applications (e.g., Zhao, Liu, Li, & Sohl, 2009; Zhao, Liu, Li, & Sohl, 2010).

Methodology

Scenario development

Four SRES storylines (A1B, A2, B1, B2) serve as our primary scenarios. The scenarios provide a means to explore uncertainties associated with future LULC conditions and resultant effects on GHG fluxes. However, SRES scenarios are general, without a level of specificity to quantitatively inform the required scenario-based demand component of FORE-SCE. We developed our own unique approach to downscale SRES storylines to the U.S. national and regional level, using a mix of existing modeling and scenario research, historical LULC data from the USGS Trends project, and expert knowledge obtained through workshops. LULC modeling starts in 1992 to facilitate model "spin-up" of the linked biogeochemical models. Historical data from the USGS Trends project were used for "demand" for historical LULC proportions for 1992 to 2000, with historical LULC prescriptions developed for each of the 84 Level III ecoregions in the U.S. Similarly, regional LULC proportions from a 2001 to 2006 NLCD change product (Xian, Homer, & Fry, 2009) were used as a LULC demand proxy for the 2000 to 2005 time frame. Scenario projections based on SRES began in the year 2006.

SRES scenario construction consisted of the development of detailed qualitative storylines as well as quantitative proportions of LULC change that could be used as prescribed demand within FORE-SCE. In a workshop setting, the process began with LULC experts who developed qualitative storylines at the U.S. national scale that were consistent with SRES assumptions (Fig. 2). The SRES storylines are oriented along two axes, based on 1) global vs. regional economic, technological, and environmental cooperation, and 2) economic growth vs. environmental conservation. Brief summaries of qualitative scenario characteristics follow:

1) The A1B scenario focuses on economic growth, global economic and technologic development and cooperation, and is the wealthiest of the four scenarios. A convergence of national and global standards of living results in very high per-capita demand for food and energy products. Economic growth and a growing population drive sprawling growth. High technological innovation and strong energy demand result in very strong increases in biofuels, including both traditional and cellulosic-based biofuels.
2) The A2 scenario also focuses on economic growth, but with more regional economic and technologic development. Extremely high population increases globally and resultant pressures on natural resources lower economic growth compared to A1B. Major urban centers increase dramatically in size to accommodate massive population increases. Global demand for foodstuffs drives significant increases in land devoted to agriculture. Biofuels play a smaller role than in the more technologically advanced A1B scenario.
3) The B1 scenario has the same population projections as the A1B scenario, but with a greater focus on environmental conservation. Economic and environmental issues are addressed through global cooperation. Urban growth is moderately less than in A1B, with a focus on more compact urban development. Overall agricultural land use is also less than the A1B scenario, as low per-capita energy demands reduce demand for biofuels. With the environmental focus, attempts are made to limit land-use impacts on natural land covers.
4) The B2 scenario focuses on environmental sustainability and development of local economies. Relatively low population growth, coupled with active management to limit the urban footprint, results in the lowest overall urban expansion. Resource-friendly lifestyles limit pressure on natural resources.

The development of quantitative, national-level LULC proportions for each scenario started with U.S. national-level LULC proportions as modeled by the Integrated Model to Assess the Global Environment (IMAGE), version 2.2 (IMAGE Team, 2001), but concerns about unreasonable regional LULC proportions led to workshop experts modifying IMAGE 2.2 LULC for some LULC sectors. The modified IMAGE 2.2 numbers, as well as the qualitative storylines, were downscaled hierarchically to Level I, Level II, and finally Level III ecoregions (U.S. EPA, 1999), using historical LULC data from the USGS Trends project as well as expert opinion to guide a downscaling process within a spreadsheet accounting model (Sleeter et al., submitted for publication). During the downscaling process, downscaling parameters and methodologies were tailored to the storylines for each scenario. For example, scaling factors were required to convert scenario-based population change to the actual modeled urban footprint. The urban footprint per person was assumed to be smaller in the environmentally conscious B1 scenario than it was in the A1B and A2 scenarios. Thus, more developed land was modeled for A1B than in the B1 scenario, despite those two scenarios sharing the same population assumptions. The resultant LULC trajectories at the Level III ecoregion scale were used to construct tables of "demand" to feed the spatial allocation component of FORE-SCE. Additional details of the scenario construction process can be found in Zhu (2010) and Sleeter et al. (submitted for publication).

Data and probability surface preparation

A starting LULC layer for 1992 was based on the 1992 NLCD (Vogelmann et al., 2001). 1992 NLCD land-cover classes were first collapsed to the LULC classes outlined in Table 1. To populate the baseline LULC layer with disturbed forest patches, we used historical data from the LANDFIRE Vegetation Change Tracker (VCT) product that maps occurrence of forest cutting as well as other disturbance (Huang et al., 2010; Li et al., 2008).

FORE-SCE tracks forest stand age to better mimic regional forest cutting cycles. Two sources of information were used to compile stand-age information for the LULC 1992 baseline layer. The LANDFIRE VCT data was used to identify forest pixels disturbed between 1984 and 1992, which provided the date of last disturbance for pixels clear-cut during that interval. For forest pixels that had not been disturbed since 1984 an interpolated stand-age surface was constructed from U.S. Forest Service FIA data (Woudenberg et al., 2009). The composite stand age image constructed from these two sources was used to initialize forest stand age for 1992.

The spatial allocation component of FORE-SCE relies heavily on historical patterns of LULC conversion for parameterizing how change is modeled on the landscape. Several key parameters governing FORE-SCE's spatial allocation procedure were derived from

USGS Trends project data and from NLCD, such as patch size and shape for each LULC type in Table 1, spatial configuration (including the clumpiness or dispersion of LULC change patches), and historical likelihood of a given LULC conversion occurring (Sohl & Sayler, 2008). These parameters are derived independently for each Level III ecoregion being analyzed. Note that the qualitative storylines developed for an ecoregion were also used to modify baseline model parameters, with the dispersion of patches for a given LULC type, or patch sizes, altered to better represent a given SRES storyline.

Stepwise logistic regression was used to develop empirical models of relationships among spatial data sets representing drivers of LULC change and existing LULC patterns (Sohl & Sayler, 2008). The modified 1992 NLCD serves as the dependent variable, while spatially explicit data sets outlined in Table 2 served as the independent variables. Logistic regression models are used to construct probability-of-occurrence surfaces for each LULC class in Table 1. These surfaces determine relative suitability of the landscape to support a given LULC type, with the "suitability surfaces" used to guide the spatial allocation procedure. Suitability surfaces are independently modeled and constructed by ecoregion. Although the national assessment is based on aggregating information at the Level II ecoregion, we conduct LULC modeling based on finer, Level III ecoregions, which provide a more appropriate scale of stratification for understanding and assembling region-specific information on driving forces linked to LULC change (Gallant et al., 2004).

Spatial allocation procedure

FORE-SCE places change on the landscape patch-by-patch, for each required LULC conversion, until demand from the input scenarios is met for a given year. Placing a patch of change in the landscape is accomplished using the suitability surfaces to guide placement of a "seed" pixel for a specific LULC conversion. A semi-stochastic procedure places seed pixels on the landscape, with higher suitability areas more likely to be selected. Other factors affecting seed placement include the historical likelihood of a given LULC transition in the region, decision rules on protected areas, and in the case of forest pixels, a function of current stand age (to better mimic regional forest cutting patterns). Once a seed pixel is placed, a patch size is assigned by referencing the historical distribution of patch sizes for each LULC transition and stochastically selecting a realistic patch size within this historical range. A patch shape for the assigned patch size is selected from a "patch library" containing a collection of historical patch shapes, as documented by the USGS Trends project (Griffith, Stehman, Sohl, & Loveland, 2003). The patch is placed on the landscape and the process repeats until demand for all LULC types is met. Processing then continues to the next annual time step.

Table 2
Independent variables used in the logistic regression analyses. All independent variables must be spatially explicit.

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	Volume of water available to plants if the soil were at field capacity
Crop Capability Index	Suitability of soils for supporting crop, with decreasing capability as index value increases
Soil Organic Carbon	Soil organic carbon in the top 100 cm of soil
Hydric Soils	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
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
X-Coordinate	Center x-coordinate
Y-Coordinate	Center y-coordinate

Improvements in the newest FORE-SCE modeling framework include the flexibility to accommodate dynamic shifts in demand that mimic temporal changes in policy, economic upheaval, or other "jolts to the system". Demand can now potentially be supplied in varied formats, be it net change between LULC classes, or more detailed, class-by-class transition matrices. In addition, suitability surfaces for each LULC type can be updated as the model iterates, based on LULC change occurring in the previous iteration, and based on projected changes in any of the independent variables used to construct the suitability surfaces (e.g., projected climate change data). FORE-SCE model code is also currently being ported to a more flexible framework to potentially allow for distribution to outside parties. For more details on FORE-SCE model structure, see Sohl et al. (2007) and Sohl and Sayler (2008).

Linkage with GEMS biogeochemical model

Each model run for a scenario produces data stacks of annual LULC change from 1992 to 2100 at 250-m pixel resolution. These data are then passed to GEMS for biogeochemical analysis of carbon and GHG fluxes under each scenario. The two models in concert can simulate and analyze the effects of both land-use change, as well as land-management change. FORE-SCE directly models scenario-specific changes in LULC, and through specific modeling of forest cutting, informs the biogeochemical model on forest structure changes. GEMS handles scenario-specific characterization of land-management practices not addressed by FORE-SCE, including tillage practices, crop rotation, crop fertilization, grazing intensity, and forestry treatments. The LandCarbon project is using a multi-model approach for carbon and GHG modeling to better understand uncertainties between model estimates. Three individual carbon and GHG modeling approaches were used: Spreadsheet (a simple carbon accounting approach), Century (Parton, Schimel, Cole, & Ojima, 1987), and EDCM (Liu et al., 2003). Major output variables included biomass carbon stock, total ecosystem carbon stock, carbon sequestration, and nitrous oxide and methane emissions.

Prototype and LandCarbon application

The methodology was first tested for a prototype region on the U.S. Gulf Coast to determine the ability of the LULC modeling framework to produce LULC scenarios that were consistent with SRES storylines, and to examine the ability of the integrated modeling framework (Fig. 1) to analyze carbon fluxes and potential mitigation strategies. After successful application of the project methodology in the prototype area, the LandCarbon national assessment was initiated. What follows are model results for two prototype ecoregions on the Gulf Coast, including a demonstration of the ability of the LULC modeling framework to support carbon sequestration analyses. This is followed by a more in depth focus on LULC modeling results for one of the first ecoregions to be completed for the LandCarbon national assessment.

Results

Prototype development and testing

A prototype analysis using the SRES A1B scenario and covering two EPA Level III ecoregions (the Mississippi Alluvial Plain and Mississippi Valley Loess Plains) was completed to evaluate the ability of the linked LULC model and carbon model to analyze carbon flux changes due to LULC change. Annual demand prescriptions for LULC change consistent with IPCC SRES scenario A1B were produced for each of the two ecoregions for a reference A1B scenario, as well as an alternative A1B scenario that included alternative land-cover changes designed to increase carbon sequestration. Selected mitigation actions used in the alternative scenario compared to the reference scenario were:

- Restore 8500 km^2 of forested wetland in the Mississippi Alluvial Plain
- Increase forest extent by 2000 km^2 in the Mississippi Valley Loess Plain
- Eliminate deforestation (other than forest harvesting and replanting) across both ecoregions
- Eliminate all wetland conversion to other LULC types
- Increase the typical forest cutting cycle (20 year cutting cycle to 40 year)
- Reduce rates of clear-cutting by 50 percent

Each ecoregion was parameterized and modeled within FORE-SCE using the procedures outlined above for reference and alternative scenarios. Spatially explicit LULC maps for each year from 1992 to 2050 were produced for the reference and alternative A1B scenarios (Fig. 3).

The LULC maps were ingested into GEMS to determine the ability of the modeling framework to measure carbon and GHG flux changes resulting from the inclusion of alternative LULC mitigation strategies. All three carbon and GHG modeling approaches (EDCM, Spreadsheet, and Century) showed a continuous, but slowing rate of sequestration across the study period, with the declining rate primarily due to maturation of forests in the region. Fig. 4 shows the difference in cumulative carbon sequestration rates between the reference and alternatives scenarios for two counties in the pilot area, one in each ecoregion.

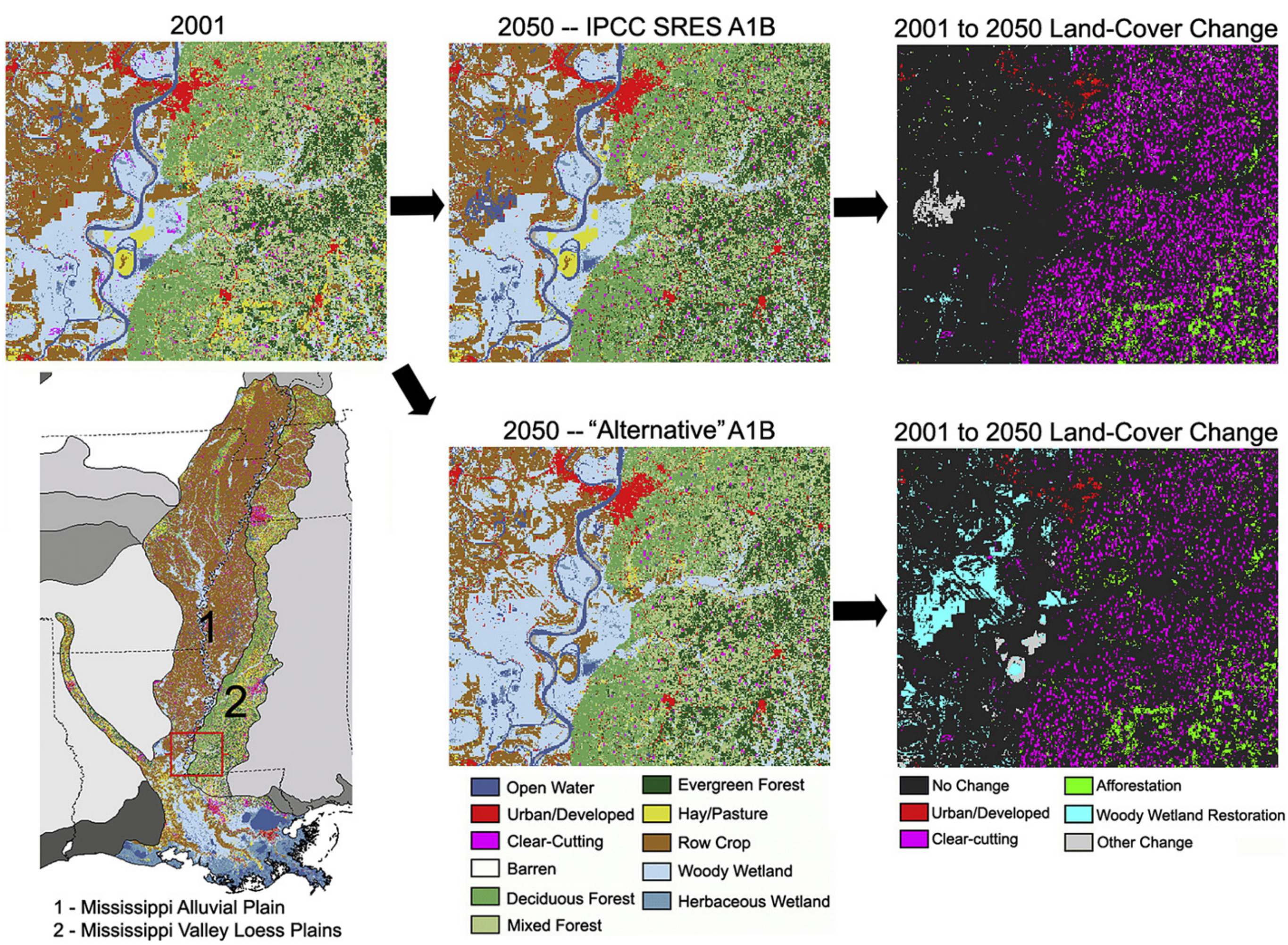

Fig. 3. Net LULC change between 2001 and 2050 for both a reference A1B and an alternative scenario for a portion of two prototype ecoregions. The alternative scenario is marked by wetland restoration in the Mississippi Alluvial Plain, increased afforestation, and lower rates of forest cutting than the reference A1B scenario.

All three approaches estimated consistently higher ecosystem carbon stocks by 2050 for the alternative scenario, relative to the reference scenario, with additional carbon sequestration of 1.64, 1.75, and 1.08 Tg from the Spreadsheet, Century, and EDCM approaches, respectively. This represents about an additional 20 percent, 10 percent, and 23 percent respective increase above carbon sequestered under the reference scenario. While the baseline rates of carbon sequestration differ depending upon modeling approach, overall, the results show the three biogeochemical models are each capable of consistently quantifying additional carbon sequestration using LULC scenarios to spatially map LULC mitigation activities. Additional details of the biogeochemical modeling framework, overall project design, and more detailed biogeochemical modeling results for the prototype region can be found in Zhu (2010). In addition to this prototype work, past research in the southeastern U.S. has shown the ability to link FORE-SCE LULC modeling output with the GEMS biogeochemical modeling framework (Zhao et al., 2009, 2010). Given the demonstrated ability of the modeling framework to quantify the impacts of LULC change on carbon and GHG fluxes, the methodology was then used to initiate an assessment for the entire United States. The following provides a closer look at LULC modeling results for one of the first ecoregions completed for the LandCarbon national assessment.

Central Irregular Plains Ecoregion: LULC modeling

The Central Irregular Plains Ecoregion is one of the first ecoregions with LULC modeled for the LandCarbon national assessment (Fig. 5). Downscaled scenarios were constructed using the methods outlined above and described in Sleeter et al. (submitted for publication). Scenarios for the ecoregion focused on changes in agricultural composition and urban development (Sleeter et al., submitted for publication) (Fig. 6).

Downscaled proportions of LULC shown in Fig. 6 were used to populate the demand component of the FORE-SCE model for each of the four SRES scenarios. FORE-SCE was then run through 2100 for each of the four scenarios, resulting in 250 m, spatially explicit LULC projections with a level of thematic detail consistent with Table 1, and matching scenario-specific LULC proportions shown in Fig. 6.

Spatial LULC modeling results through the year 2100 for a portion of the ecoregion around Kansas City, Missouri are shown in Fig. 7. What follows are some of the highlights of temporal and spatial trends shown in Figs. 6 and 7:

1) The A1B scenario experiences strong economic growth and a growing population. Kansas City and other surrounding urban areas exhibit significant expansion, increasing by over 2200 km^2. The hay/pasture class increases significantly after 2020 in response to a booming cellulosic-based biofuels industry in the region, adding almost 10,000 km^2 by 2100, while cultivated crop increases modestly in response to demand for foodstuffs and for traditional biofuel crops. Natural land covers decline, as nearly 75% of all natural grasslands are lost, with remnants found in only a few scattered locations in the western part of the region by 2100. Nearly 3500 km^2 of forest is lost to urban development, and by conversion to agricultural land.
2) The A2 scenario has weaker economic growth than A1B, but extremely high population increases result in nearly 4500 km^2 of new urban development by 2100. Very high demand for foodstuffs resulted in an increase of 14,500 km^2 for cultivated cropland. Lower biofuels demand and lower technological innovation than the A1B scenario results in relatively low demand for cellulosic ethanol, resulting in only a modest increase in hay and pasture land (1100 km^2). Natural land covers sharply decline as they are converted to urban or agricultural uses, with over 90% of grassland lost, and almost 40% of forest lost.
3) Population projections for the B1 scenario are the same as A1B, yet urban extent only increases by 1250 km^2, as there is more of a focus on compact urban development. Lower per-capita energy demand and more resource-friendly lifestyles also limit agricultural expansion to almost half as much as A1B, with approximately 3800 km^2 of new cultivated cropland and 2000 km^2 of new hay/pasture land. Loss of natural land covers is still significant but is less than A1B, with 6700 km^2 of grassland lost and 350 km^2 of forest lost.
4) Relatively low population growth in the B2 scenario and a focus on environmental sustainability results in the lowest

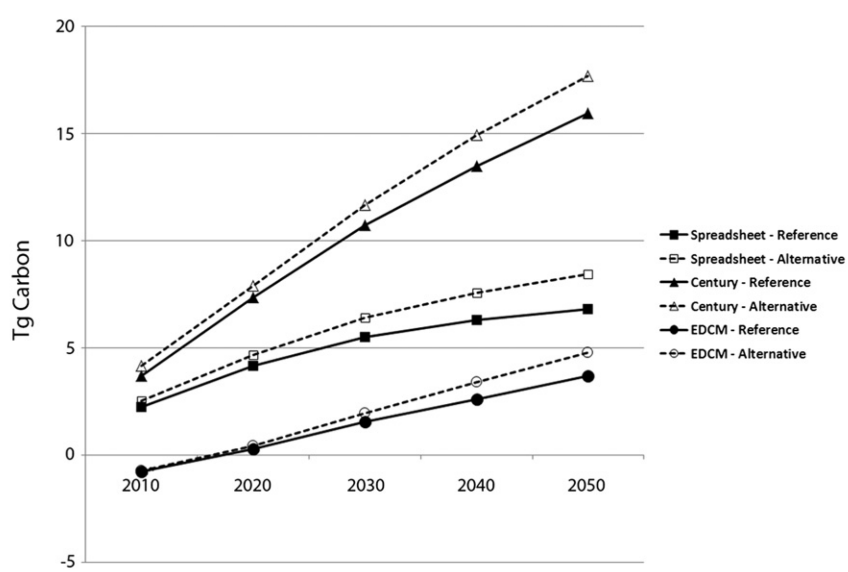

Fig. 4. Cumulative carbon sequestration for the reference and alternative scenarios for two counties in the prototype region, Claiborne County, Mississippi (Mississippi Alluvial Plains ecoregion), and Tensas Parish Louisiana (Mississippi Valley Loess Plains ecoregion). The amount of additional carbon sequestered in the alternative scenario is generally similar for the spreadsheet, Century, and EDCM approaches, but the level and rate of sequestration varies by approach, demonstrating uncertainty between the three modeling approaches.

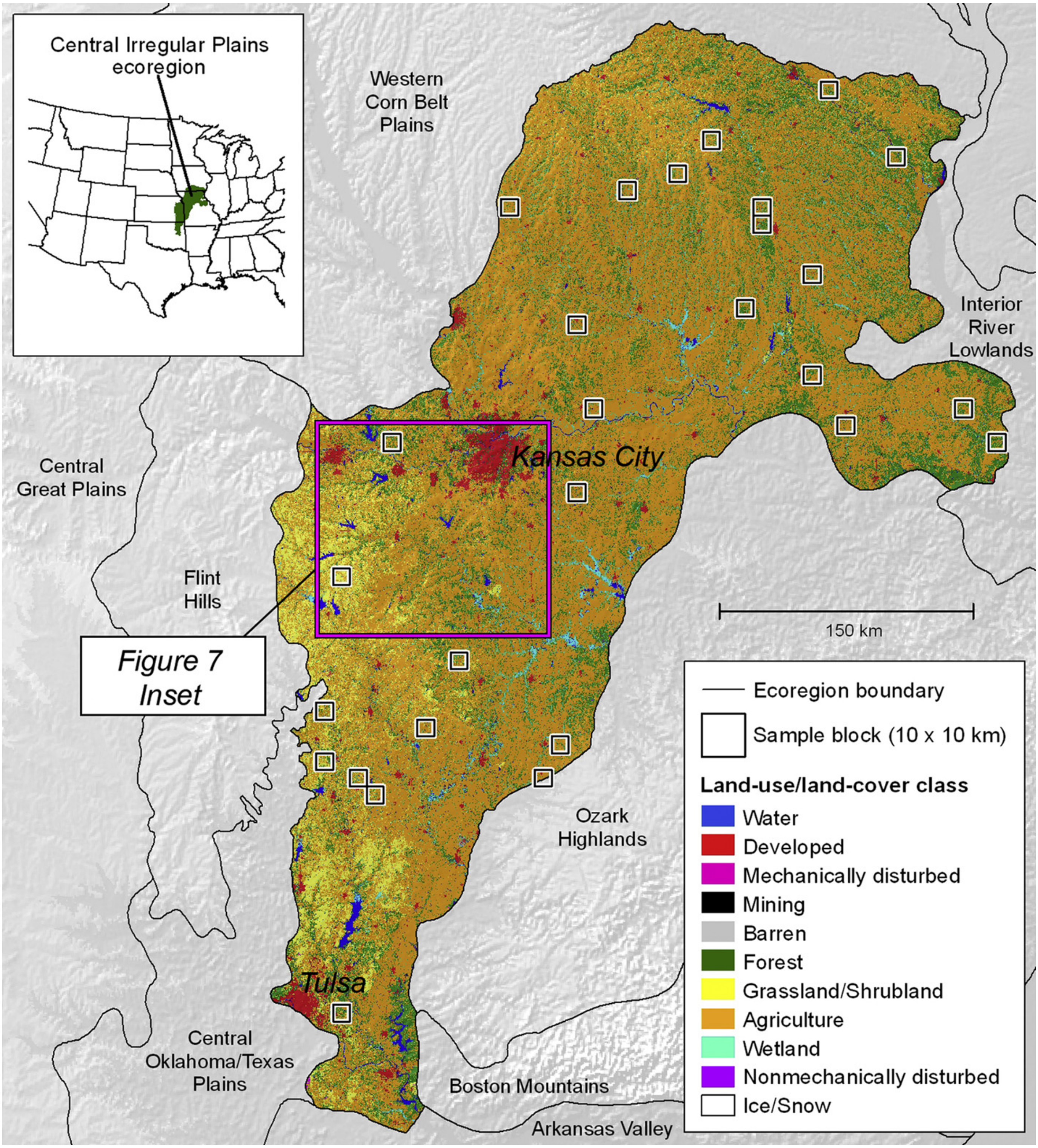

Fig. 5. The Central Irregular Plains exhibit a mosaic of agricultural, forest, grassland, and urban land uses. USGS Land Cover Trends sample blocks for the ecoregion are shown in black.

overall urban expansion, at 950 km^2. B2 is the only scenario with a decline in agricultural land use, with cultivated cropland area dropping by 1500 km^2 and hay/pasture dropping by 1350 km^2. Grassland expands by 1200 km^2, while forest and wetland both experience very slight increases in extent.

Uncertainty and validation of scenario-based results

We examined issues of uncertainty related to the scenario-based projections, as well as issues related to model validation. While the four SRES scenarios are by no means inclusive of all potential landscape futures, the scenario framework itself is used to provide a reasonable bound on overall LULC uncertainty. In our

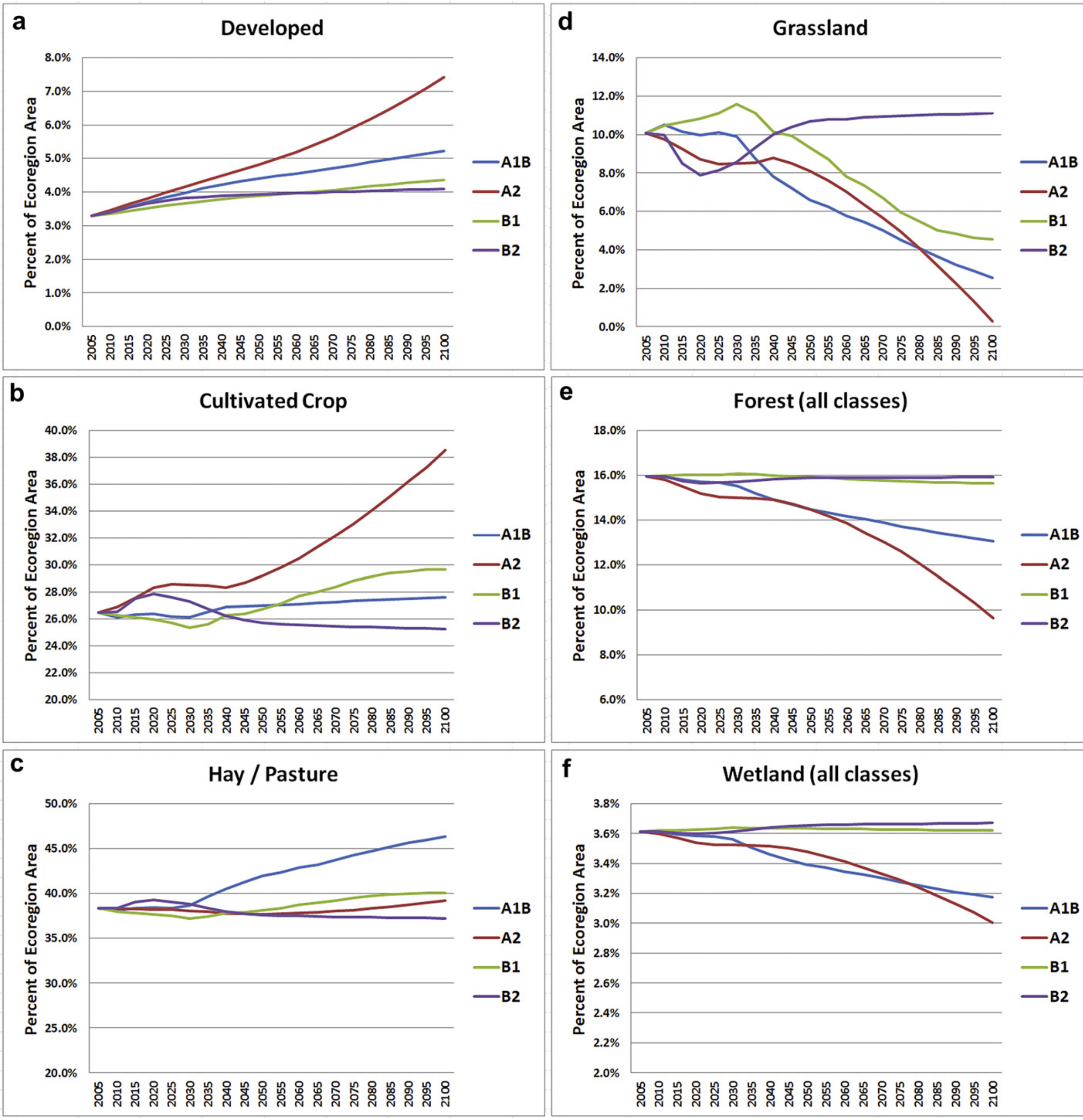

Fig. 6. Trajectories in major LULC classes for each of the 4 scenarios for the Central Irregular Plains ecoregion. These scenario-based LULC proportions were used to provide annual LULC prescriptions for the spatial allocation component of FORE-SCE.

approach, quantitative scenario prescriptions are not modeled, but are dictated by qualitative storylines. As such, the scenario-prescribed proportions of LULC change are treated as an inherent assumption, and quantitative validation of scenario proportions is unwarranted (Pontius & Neeti, 2010). However, we can demonstrate variability and overall uncertainty in future LULC proportions as captured by the scenario framework. Pontius and Neeti (2010) provide a tool to examine "least" and "greatest" differences possible between two scenarios, as a function of the spatial representation of those scenarios. However, theoretical differences due to the spatial allocation of scenario-based LULC proportions may have questionable utility for practical applications, as the spatial characteristics of the landscape are not taken into account. For example, in an approach such as ours, suitability surfaces strongly limit where a given LULC transition may occur, making it very unlikely that any theoretical maximum difference between two scenarios could ever be approached.

We believe it is more useful to examine the actual spatial variability of modeled results. Fig. 8 depicts per-pixel variability between each pair of scenarios, as well as a "diversity" measure which shows the proportion of the overall landscape where differences occur between any two scenarios. The lowest variability

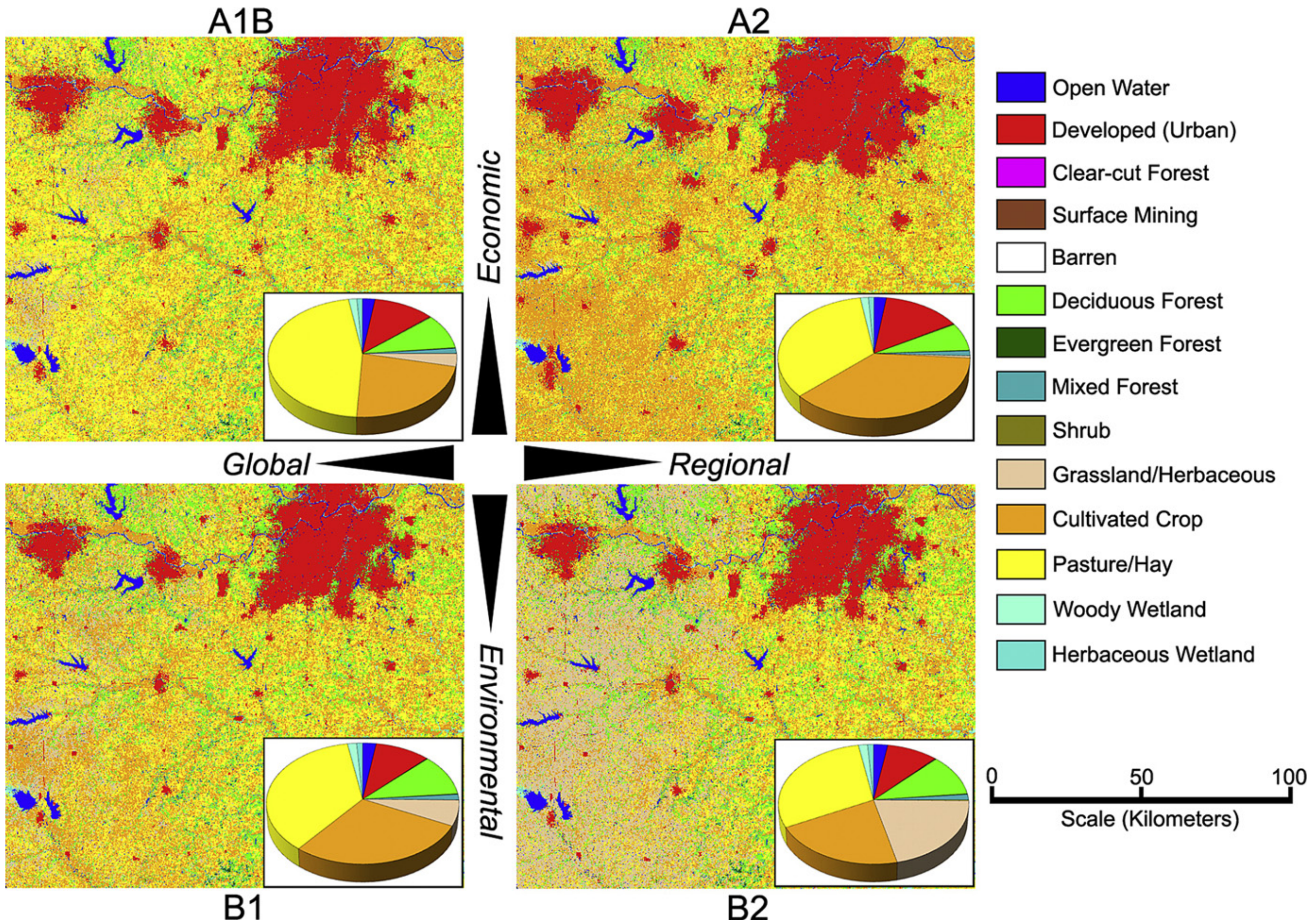

Fig. 7. Spatial LULC projections through the year 2100 for a portion of the Central Irregular Plains around Kansas City (upper-right portion of the images). SRES scenarios oriented along the economic/environmental and global/regional axes show markedly different trajectories in LULC proportions and spatial distribution.

between scenarios is between the two environmentally oriented scenarios with the least amount of overall LULC change (B1 and B2), and between the A1B and B1 scenarios which share the same population assumptions. The highest variability is between the A2 scenario (economic focus) and the B2 scenario (environmental focus), the two scenarios with the greatest difference in population assumptions. The lower and upper bounds on Fig. 8 provide a general "cone of uncertainty" regarding overall uncertainty as represented by the scenarios, but this likely underestimates true overall uncertainty as it ignores within-scenario uncertainty associated with FORE-SCE's spatial allocation of change. Due to computational resources and project timelines, each scenario is currently modeled once. Monte Carlo simulations for each scenario would allow us to better understand uncertainty associated with FORE-SCE's spatial allocation of change, but such simulations were not yet practical for this application.

However, we can examine a "spatial diversity" map to qualitatively examine the spatial variability of change between scenarios. Fig. 9 spatially depicts areas of variability between scenarios. The greatest variability between scenarios is associated with fluxes between grassland, cultivated crop, and hay/pasture (Fig. 6). Spatially, the area of greatest diversity is in eastern Kansas, where the most significant extent of grassland is found at the start of the simulation period. In the A2 scenario, significant expansion of cultivated crop is required to feed global populations of 15 billion by 2100, resulting in conversion of grassland in this area to cultivated corp. In the A1B scenario, technological innovation and very high energy demands result in much of the grassland to be converted hay/pasture to support cellulosic-based ethanol production. In the B2 scenario, environmental priorities restrict conversion of grassland in this area. Other "hotspots" of diversity include a portion of northeastern Oklahoma where significant grassland also exists at the start of the simulation period, the northern portion of the ecoregion where significant conversion of hay/pasture to cultivated crop occurs in the A2 scenario, and in "rings" around urban centers due to variable urban growth between scenarios. When Fig. 9 is examined in conjunction with the scenario storylines, the areas of greatest diversity between scenarios are quite logical. Fig. 9 serves as a proxy both for indicating probability of future LULC change, and uncertainty.

Efforts to validate model results are focused on the model's ability to adequately represent 1) quantity disagreement (ability of the model to match expected proportions of LULC change) and 2) location disagreement (ability to place change in expected locations) (Pontius, 2002). As noted above, scenario-prescribed proportions of LULC change are treated as an assumption and are not subject to analysis of quantity disagreement. However, quantity disagreement could still occur if the FORE-SCE were incapable of representing scenario prescriptions for change. However, FORE-SCE is designed to ensure that spatial map output will very closely match demand for prescribed proportions of LULC change, and quantity disagreement is not a major issue for this work (Table 3). The focus then becomes location disagreement.

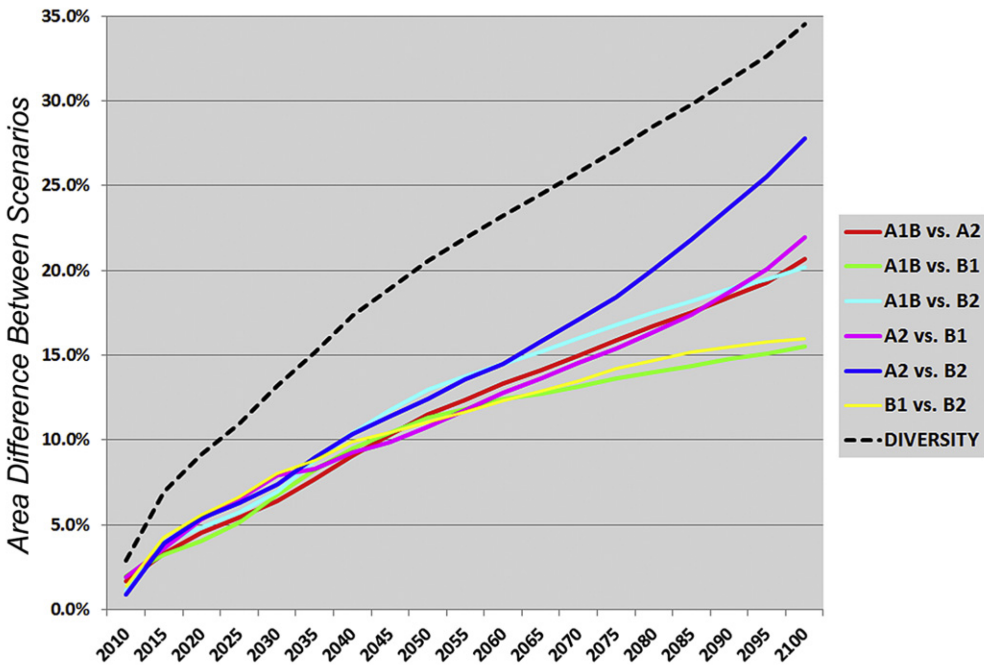

Fig. 8. Variability between IPCC SRES scenarios for the Central Irregular Plains, expressed as a percentage of pixels with different LULC types between scenario pairs. The "diversity" line shows the proportional area of the region where differences occur between any of the four SRES scenarios.

Previous applications of FORE-SCE have produced results that reasonably replicate regional patterns of LULC change (Sohl & Sayler, 2008; Sohl et al., 2007). Despite modeling for this ecoregion including a historical period (1992–2005), a formal analysis of location disagreement is difficult for this ecoregion. The total amount of change modeled for 1992 to 2000, as based on USGS Trends data, is only 2.1% of the total landscape, and is less than 1.0% of the landscape for the 2000 to 2005 period. Pontius et al. (2008) showed that LULC models have difficulty in accurately portraying pixel-level change for time periods where the amount of change is small, while Pontius and Neeti (2010) note that even if we were to attempt a formal validation of this small amount of historical change, validation results for short historical periods offer little value for assessing model performance for future periods, particularly in scenario-based approaches where scenario assumptions and LULC processes are presumed to differ from the historical norm.

Techniques for controlling and evaluating the spatial allocation of change within the Central Irregular Plains thus relied on qualitative evaluation, both before and after model runs were completed. The suitability surfaces created for each modeled LULC class were the primary driving force in the FORE-SCE model of where change is placed on the landscape. For the Central Irregular Plains (and ultimately for all subsequent ecoregions), group consultations were used to ensure the quality of each suitability surface. The review process is designed to ensure consistency between analysts, and improve within-ecoregion spatial representation of change. Similarly, the spatial allocation of each scenario model run was individually critiqued by the entire modeling team, and recommended changes in model parameters or probability surfaces were implemented if the modeling team identified an issue. For example, a "dispersion" factor (Sohl & Sayler, 2008) in FORE-SCE controls the portion of the suitability surfaces that can be used to place landscape change. If a group review finds a given LULC transition is being placed in an unlikely or inappropriate region, the dispersion factor could be reduced to constrict placement of that transition to only the most suitable of locations, or a recommendation could be made to reconstruct the suitability surface itself.

Given the issues related to formal validation procedures as noted by Pontius and Neeti (2010), it is our opinion that comprehensive reviews by a large team of LULC experts provide a much greater benefit to final modeling results than more objective validation procedures, particularly where reference data issues result in questionable validation results. With the examination of uncertainty issues as discussed above, our ability to limit quantity disagreement (Table 3), the quality-control measures implemented within the project, our qualitative assessment of modeling results, and the demonstrated ability of past FORE-SCE applications to replicate landscape pattern, we feel very comfortable using the modeling framework described here for the LandCarbon project.

Discussion

Decision-makers and stakeholders may question the utility of a model if the underlying logic and processes are not communicated clearly (Sohl et al., 2010). The LULC modeling framework shown here, with scenario-based demand and spatial allocation components, is relatively transparent and straightforward. FORE-SCE's ability to successfully match and map prescribed demand from any source gives the framework the flexibility to quickly examine an array of scenarios. Both the scenario-construction component and the analysis of spatial modeling results rely on subjective decisions made by LULC experts, but given the non-stationarity of LULC processes and the human-decision making behind those processes, we believe subjective analysis has an important role to play in scenario-based LULC projections.

The LandCarbon integrated modeling framework was designed to estimate carbon sequestration for multiple potential scenarios, and inform an analysis of future potential sequestration opportunities. The prototype, as well as past research, demonstrates how LandCarbon LULC and biogeochemical models can be integrated for an analysis of the effects of LULC change on carbon and GHG fluxes. Prototype results agree with findings by others that changes in

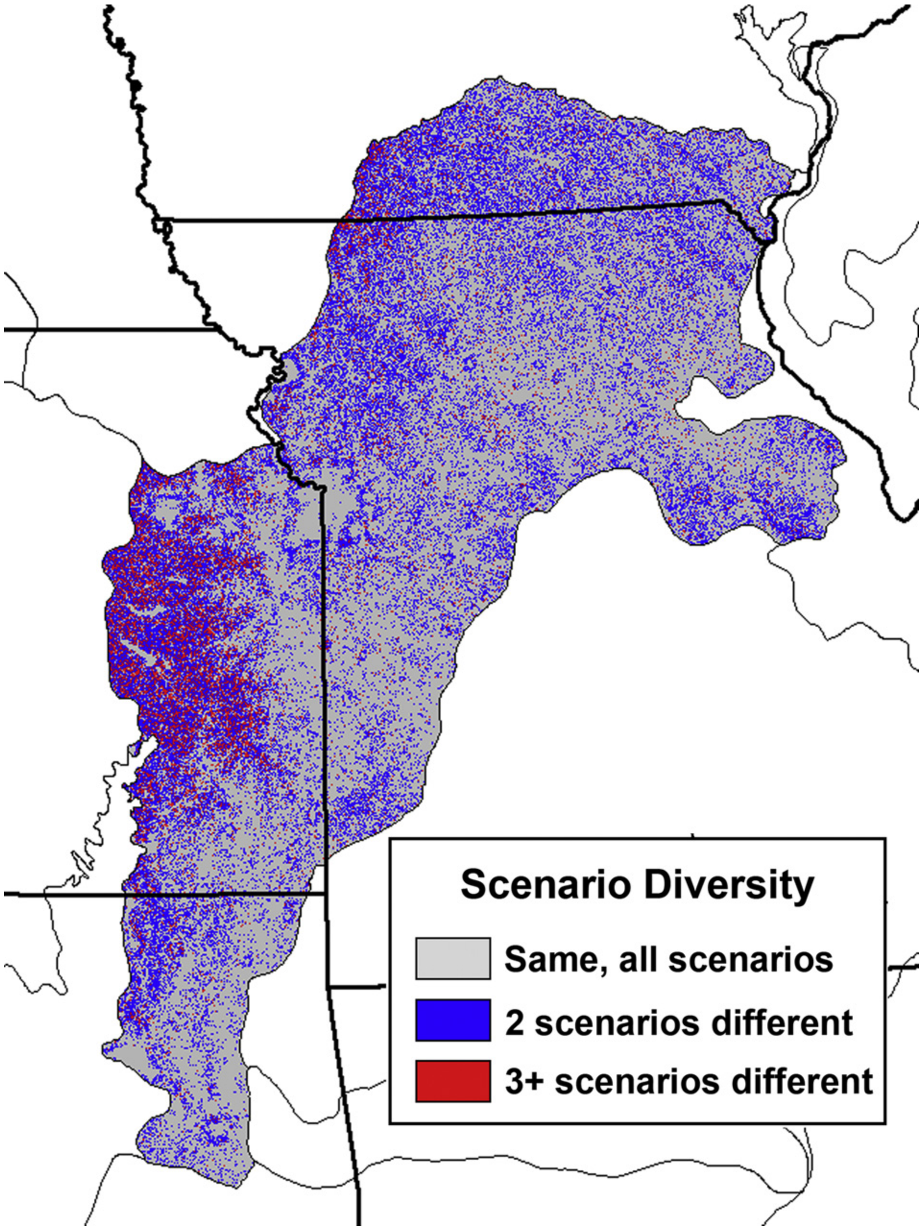

Fig. 9. Spatial representation of "diversity" between IPCC SRES scenarios for the Central Irregular Plains. Hotspots of diversity are concentrated around areas where fluctuations between grassland, cultivated crop, and hay/pasture are most likely to occur.

Table 3
Quantity disagreement for the 4 SRES scenarios for the Central Irregular Plains through 2100. "Demand" refers to the expected proportion for each LULC type by 2100, while "Modeled" refers to the actual modeled proportion.

	A1B		A2		B1		B2	
	Demand	Modeled	Demand	Modeled	Demand	Modeled	Demand	Modeled
1 Water	1.7%	1.7%	1.6%	1.6%	1.9%	1.9%	2.1%	2.1%
2 Developed	5.2%	5.2%	7.4%	7.0%	4.4%	4.4%	4.1%	4.1%
3 Mech Disturbed	0.3%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
4 Mining	0.2%	0.2%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%
5 Barren	0.0%	0.1%	0.0%	0.1%	0.0%	0.1%	0.0%	0.1%
6 Deciduous Forest	11.8%	12.0%	8.5%	8.8%	14.6%	14.6%	14.8%	14.8%
7 Evergreen Forest	0.2%	0.2%	0.1%	0.1%	0.2%	0.2%	0.2%	0.2%
8 Mixed Forest	0.8%	0.9%	0.8%	0.8%	0.9%	0.9%	0.9%	0.9%
9 Shrubland	0.1%	0.1%	0.0%	0.1%	0.1%	0.1%	0.4%	0.4%
10 Grassland	2.5%	2.6%	0.3%	0.8%	4.6%	4.6%	11.1%	11.2%
11 Agriculture	27.6%	27.6%	38.5%	38.3%	29.7%	29.6%	25.3%	25.2%
12 Hay/Pasture	46.4%	46.4%	39.2%	39.2%	40.0%	40.0%	37.2%	37.2%
13 Woody Wetland	2.4%	2.4%	2.2%	2.2%	2.8%	2.8%	2.8%	2.8%
14 Herbaceous Wetland	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%

land-use and land-management activities can provide significant potential carbon sequestration benefits (Conant et al., 2001; Lal, 2007; Potter et al., 2007; Wiedinmyer & Hurteau, 2010). LULC modeling results for the Central Irregular Plains demonstrate our ability to produce scenario-based LULC projections with a relatively high level of spatial and thematic detail.

Given the successful application of the methodology for the prototype, past work successfully linking FORE-SCE and GEMS, and successful application of the LULC framework to the first ecoregions completed for the LandCarbon National Assessment, we are confident that the National Assessment will provide new and valuable information on GHG fluxes and potential mitigation actions. This work is similar to the work of Schulp, Nabuurs, and Verburg (2008) in using regional LULC projections to inform an analysis of future carbon sequestration. However, the approach shown here and in Zhu (2010) goes beyond the use of a spreadsheet or bookkeeping approach for analysis of carbon and links a thematically detailed LULC model and a process-based biogeochemical modeling framework that are both spatially explicit. The unique, spatially explicit approach we are using will allow us to analyze and better understand uncertainties regarding spatial distributions of LULC processes and resultant effects on GHGs. Our modeling framework provides spatial, temporal, and thematic resolutions that meet requirements for a national assessment, and the approach is straightforward and practical for implementing at a national scale. By producing LULC projections across the range of IPCC SRES scenarios, we provide a range of landscape futures for which effects of potential mitigation strategies on carbon and GHG fluxes can be examined.

Conclusions

This paper focuses on the rationale behind the LULC model design being used for the USGS LandCarbon assessment, and the first ecoregion results. This work and past research have shown how the LULC model can interact with the biogeochemical model to analyze the effects of LULC change on carbon and GHG fluxes. Finally, we have demonstrated the use of the LULC modeling framework to produce the first final LULC scenarios for an ecoregion. As the project produces spatially explicit LULC scenarios for the U.S., we anticipate publishing regional summaries of not only LULC modeling results, but also complete integrated modeling results including carbon flux changes due to LULC change, and regional summaries of the most suitable mitigation strategies to adopt region-by-region. The project is due to be completed for the conterminous U.S. by the end of 2012.

We believe the LULC modeling framework discussed here is suitable for a wide range of applications, in addition to carbon and GHG analyses. Longer-term plans for the LandCarbon project include evaluating the effects of LULC change on not only biogeochemical processes, but also a range of other ecosystem services. The results shown in Fig. 7 demonstrate our ability to produce spatially explicit LULC projections consistent with SRES scenario assumptions, relevant at a scale that allows for an analysis of biodiversity, hydrologic processes, climate, and many other natural and anthropogenic processes.

Acknowledgments

This work was funded by the USGS Global Change and Geographic Analysis and Monitoring Programs. The authors thank Alisa Gallant, Joyce Fry, and anonymous reviewers for helpful comments on earlier drafts of this manuscript. Michelle Bouchard and Ryan Reker's participation is supported through USGS contract G10PC00044 with SGT, Inc. Stacie Bennett and Ron Kanengieter's participation is supported through USGS Contract 08PC91508 with ARTS.

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