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Scenarios of land use and land cover change in the conterminous United States: Utilizing the special report on emission scenarios at ecoregional scales

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ABSTRACT

Global environmental change scenarios have typically provided projections of land use and land cover for a relatively small number of regions or using a relatively coarse resolution spatial grid, and for only a few major sectors. The coarseness of global projections, in both spatial and thematic dimensions, often limits their direct utility at scales useful for environmental management. This paper describes methods to downscale projections of land-use and land-cover change from the Intergovernmental Panel on Climate Change's Special Report on Emission Scenarios to ecological regions of the conterminous United States, using an integrated assessment model, land-use histories, and expert knowledge. Downscaled projections span a wide range of future potential conditions across sixteen land use/land cover sectors and 84 ecological regions, and are logically consistent with both historical measurements and SRES characteristics. Results appear to provide a credible solution for connecting regionalized projections of land use and land cover with existing downscaled climate scenarios, under a common set of scenario-based socioeconomic assumptions.

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1. Introduction

A major scientific challenge in global change research is connecting coarse-scale global assessments, particularly those involving the projection of land use, to scales relevant and useful for analysis and management (Wilbanks and Kates, 1999). For example, Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) results (including land use) were reported for four macro-scale world regions. Strengers et al. (2004) note that while SRES scenario development was a landmark achievement, the treatment and poor resolution of land use and land cover (LULC) information has frustrated attempts to use these data for other studies. The coarseness of these reporting units, combined with the coarseness of the thematic land use, makes utility at sub-national scales difficult. Conversely, the resolution of many global circulation model outputs based on SRES is conducive to regional scale applications. The result is a paradigm where projected climate variables, are used in absentia of corresponding socio-economic scenario outputs (i.e. future land use), which often are equally or more important drivers of regional environmental impacts (Arnell et al., 2004; Holman and Loveland, 2001; Parry et al., 2001; Johns et al., 2003; Holman et al., 2005). The IPCC reports emissions from land use, primarily deforestation, account for 23% of global CO_2 emissions and 74% of CH_4 (Nakicenovic and Swart, 2000). Similarly, Casperson et al. (2000) found that land-use change was the dominant factor contributing to carbon accumulation in eastern U.S. forests, while Zaehle et al. (2007) found that under future scenarios in Europe carbon fluxes from land-use change were of similar magnitude to fluxes attributed to climate change. To overcome the disconnect between coarse scale treatment of LULC and the relatively fine resolution of GCM outputs, we have developed a method to downscale LULC outputs from global

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integrated assessment models to level III ecoregions of the conterminous United States (see http://www.epa.gov/wed/pages/ecoregions.htm).

Scenarios have emerged as useful tools to explore uncertain futures in ecological and anthropogenic systems. Scenarios differ from predictions, forecasts, and projections in that they describe alternative futures under different sets of assumptions given our current understanding of the way drivers of land-use and land-cover (LULC) interact to affect ecosystems. Scenarios typically lack quantified probabilities (Nakicenovic and Swart, 2000; Swart et al., 2004) instead functioning as alternative narratives or storylines that capture important elements about the future (Nakicenovic and Swart, 2000; Peterson et al., 2003; Swart et al., 2004). Alcamo et al. (2008, p. 15) define scenarios as "descriptions of how the future may unfold based on 'if-then' propositions." Scenarios are used to assist in the understanding of possible future developments in complex systems that typically have high levels of scientific uncertainty (Nakicenovic and Swart, 2000; Raskin et al., 1998). Plausible scenarios generally require knowledge of how drivers of change have acted to influence historical and current conditions. For many Earth systems, especially those at the confluence of physical and social sciences, the information and quantitative variables needed to make future forecasts are limited. In these cases, scenarios provide a structured framework for exploration of alternative future pathways (Alcamo et al., 2008).

An important element of scenarios is the capability to capture both qualitative and quantitative elements that define future conditions. A general characteristic of global environmental scenarios is the use of narrative storylines to represent qualitative scenario elements (Raskin et al., 1998; Nakicenovic and Swart, 2000; Alcamo et al., 2008). Narrative storylines provide descriptive detail and increased explanatory power to scenario results. Raskin (2005, p. 134) writes "the narrative gives voice to the qualitative factors that shape development, such as values, behaviors, and institutions, while modeling offers empirically based insights into the subset of socioeconomic and biophysical factors that are amenable to quantification." Scenarios based on narrative alone lack the theoretical foundation from which environmental assessments are often conducted. Quantitative scenarios provide the information needed for empirical study, however, due to data limitations their utility and acceptance can be limited due to the numerous assumptions that often accompany empirical modeling. Quantitative scenarios by themselves often appear to users; both scientific and otherwise, as "black boxes", if model assumptions and structure are not clearly articulated, potentially creating some reluctance to use within decision making processes (Couclelis, 2002). Combining both qualitative and quantitative scenario components, in the form of narrative storylines and empirical modeling results, has become a common approach in global environmental change assessments (Nakicenovic and Swart, 2000; Alcamo et al., 2008) and sustainability science (Swart et al., 2004).

Land use is characterized by human practices such as cropping, grazing, logging, mining, and processes such as urbanization. Land cover is the manifestation of land use into a set of discrete classes such as forest, grassland, and wetlands (IPCC, 2000). Because land cover is changed primarily by human uses land-use change is a critical determinant of land-cover change (Turner et al., 1995). Future changes in LULC are a function of numerous driving force variables. Biophysical conditions, population change, economic activity and growth, societal attitudes, governance, and regulatory regimes are all important drivers of change, interacting to create unique and dynamic LULC mosaics functioning at a range of geographic scales. Driving forces occur and interact at a wide range of both temporal and spatial dimensions, making long-term prediction and forecasting nearly impossible with any reasonable degree of certainty. For this reason, scenarios have emerged as a useful framework for investigating alternative futures of land use and land cover.

This research was initiated as part of the U.S. Geological Survey's (USGS) Biological Carbon Sequestration assessment (Zhu et al., 2010). The USGS is conducting an assessment of carbon sequestration and greenhouse gas (GHG) fluxes for ecosystems of the United States. Multiple scenarios of LULC change are required to analyze potential carbon sequestration mitigation strategies under a range of possible future landscapes (Sohl et al., 2012). To accomplish this we incorporated a modular approach to projecting LULC change, with unique "demand" and "spatial allocation" components. Scenario demand was developed using the land use accounting model described in this paper, while the FOREcasting SCEnarios (FORE-SCE) geostatistical/empirical model was used to allocate scenario demand on the landscape (see Verburg et al., 2002; Sohl et al., 2007, 2012).

This paper presents an approach using high resolution LULC models to downscale changes from macro-scale global environmental change assessments to the ecoregion and landscape level. Projections of changes between major LULC classes consistent with IPCC-SRES are developed at a range of hierarchically nested ecoregion scales and allocated to the landscape at a 250 m pixel resolution. Following the description of methods, we present results and discussion of the downscaling at national and ecoregional scales. We conclude with a section on the major findings of this project, and suggestions about future applications and development.

2. Methods

2.1. Land-use and land-cover scenario downscaling

Spatial downscaling describes the effort to translate scenarios developed at coarse scales to a finer geographic scale, while maintaining consistency with the original dataset (van Vuuren et al., 2007, 2010). Depending on the intended purpose and application of the downscaled scenarios, characteristics of the downscaling process may be quite different. For example, downscaling may only apply to certain scenario parameters (e.g. land use or population) or for a limited geographic coverage (e.g. a single country). Despite different characteristics associated with scenario downscaling, certain important cross-cutting fundamentals are important to consider. In a review of socioeconomic scenario downscaling efforts, van Vuuren et al. (2007, 2010) identified four primary characteristics that should be present in any downscaling efforts. They are:

- some form of consistency with existing local scale data (e.g., with the historical period),
- consistency with the original source (the scenario data at the much coarser scale),
- transparency and internal consistency in a well-defined methodology, and
- plausibility of the outcome.

For review purposes, we discuss two general categories of spatial downscaling: (1) gridded downscaling and (2) thematic downscaling. A selected review of relevant IPCC-SRES downscaling efforts is provided in Table 1. Gridded downscaling describes the effort to translate global and macro-scale scenario parameters (e.g. population) to a spatial grid where each cell contains a parameter value with the sum of all cells within a region adding up to the original scenario total. Gaffin et al. (2004) and van Vuuren et al. (2007) downscaled population and GDP to national and spatial grids. Arnell et al. (2004) described the use of these downscaled scenarios for a range of climate impact assessments, including food

Table 1
Selected literature on downscaling land use and land cover for the IPCC Special Report on Emission Scenarios.

Research	Study area	Primary driver or LULC sector	Description
Gaffin et al. (2004)	Global	Population, GDP	National and gridded ($0.25^\circ \times 0.25^\circ$)
van Vuuren et al. (2007)	Global	Population, GDP, GHG emissions	National and gridded ($0.5^\circ \times 0.5^\circ$)
EPA (2009) ICLUS	United States	Developed	Changes in housing and impervious cover based on projected demographic change
Solecki and Oliveri (2004)	New York City	Developed	Downscaled SRES for use in modeling urban growth using the SLEUTH model in New York
Abildtrup et al. (2006)	Europe	Agriculture	Participatory approach used to incorporate expert opinion in downscaling of SRES for European agriculture
Busch (2006)	Europe	Agriculture	Review of existing quantitative land use scenarios including SRES and the impact on European agriculture
Ewert et al. (2005)	Europe	Agriculture productivity	Estimated potential changes in crop productivity based on climate, atmospheric CO_2, and technological development (ATEAM project)
Rounsevell et al. (2005)	Europe	Agriculture, grasslands	Projections constructed for 2020, 2050, and 2080 at 10×10 min resolution (ATEAM project)
Rounsevell et al. (2006)	Europe	Developed, cropland, grassland, forest	Used a combination of experts, literature review, and modeling to downscale LULC to 250 m grid
Kankaanpaa and Carter (2004)	Europe	Forest	Projections of forest land use and cover under alternative future scenarios
Reginster and Rounsevell (2006)	Europe	Developed	Projections of developed land use under alternative future scenarios
Rounsevell et al. (2006)	Europe	Agriculture	Description of the 'Assessing Climate Change Affects on Land Use and Ecosystems: From Regional Analysis to the European Scale' project (ACCELERATES)
van Meijl et al. (2006)	Europe	Agriculture, others	Assessment of the impact of globalization, trade, and climate on land use in Europe
Verburg et al. (2006)	Europe	Agriculture, developed, others	Translation of European level scenarios to spatially explicit projections for 25 EU countries

scarcity (Parry et al., 2004), water stress (Arnell, 2003), exposure to malaria (Van Lieshout et al., 2003), coastal flooding and wetland loss (Nicholls, 2004), and terrestrial ecosystems (Levy et al., 2003). Thematic downscaling are those efforts that have typically focused on a narrow range of land-use types. These efforts generally focus on a sub region, rather than attempt to downscale globally. Sectoral downscaling has been most widely applied to agricultural land use, with several studies undertaken in Europe. While significant effort has been given to downscale land use in Europe based on IPCC-SRES, few examples exist in the United States. One example was work done by the United States Environmental Protection Agency's Integrated Climate and Land-Use Scenarios (ICLUS) project (EPA, 2009) which used demographic and spatial allocation models and produced projections of housing density and impervious cover based on the IPCC-SRES scenarios. At the local scale, Solecki and Oliveri (2004) downscaled IPCC-SRES for use in an application of the SLEUTH urban growth model to the New York metropolitan region. However, to date, no comprehensive effort to downscale a wide range of LULC types has been undertaken in the U.S.

2.2. Downscaling approach and scenario framework

Our methods to develop comprehensive LULC scenarios for the conterminous United States (CONUS) downscaled from IPCC-SRES scenario assumptions had thematic, spatial, and temporal elements. Thematically, downscaling was designed to span a wide range of primary LULC classes which are described in Table 2. In the spatial domain results were developed at several geographic scales based on a hierarchical ecoregion framework developed by Omernik (1987) (Fig. 1). Ultimately, the goal of the downscaling effort was to produce bi-decadal projections of changes in major LULC classes at national and ecoregional scales consistent with IPCC-SRES.

For this paper our chosen scenario framework was guided by criteria established for the USGS biological carbon sequestration assessment described in Zhu et al. (2010). The criteria dictated that the scenario framework includes the following key elements:

- To better communicate future LULC scenarios, the scenario framework should include qualitative and quantitative components. In addition to quantitative projections of LULC, IPCC-SRES provides detailed narrative storylines which are used to add a sense of "realism" to the scenarios. Narratives are a useful tool for describing future pathways of major driving forces which are not readily quantified or easily understood using numbers and models alone. They also help in the communication of results to a wide range of users and decision makers, a critical aspect of the USGS carbon assessment.
- The scenario framework should have a foundation based on alternative future socioeconomic pathways. Drivers of LULC change are most often based on underlying socioeconomic conditions. Scenarios of emissions, radiative forcing, or climate alone would not have provided the needed foundation to project future changes in LULC because they do not address the major underlying driving forces of LULC change. Because the USGS assessment was instigated primarily to address the role of LULC change on carbon and GHG fluxes, it was necessary to develop scenarios that were responsive to a range of future socioeconomic driving forces.

Table 2
Land use and land cover class definitions and conversion characteristics used in national and ecoregional downscaling.

LULC sector	Class description[a]	Source of future demand	LULC change
Developed (LU)	Areas of intensive use with much of the land covered with structures or anthropogenic impervious surfaces (e.g., high-density residential, commercial, industrial, roads, etc.) or less intensive uses where the land cover matrix includes both vegetation and structures (e.g., low-density residential, recreational facilities, cemeteries, parking lots, utility corridors), including any land functionally related to urban or built-up environments (e.g., parks, golf courses).	IMAGE 2.2 U.S. population change	Changes between all land use and cover classes.
Mining (LU)	Areas with extractive mining activities that have a significant surface expression. This includes (to the extent that these features can be detected) mining buildings, quarry pits, overburden, leach, evaporative, tailings, or other related components.	IMAGE 2.2 coal production	Demand for conversions to and from developed supplied by developed class; otherwise changes between all land use and cover classes.
Agriculture (LU) (cultivated crops, hay/pasture)	Land in either a vegetated or an unvegetated state used for the production of food and fiber. This includes cultivated and uncultivated croplands, hay lands, pasture, orchards, vineyards, and confined livestock operations. Note that forest plantations are considered forests regardless of the use of the wood products.	IMAGE 2.2 agriculture projections	Demand for conversions to and from developed and mining provided by developed and mining, respectively; otherwise all changes between land use and cover classes.
Forest harvest (LU)	Areas impacted by forest harvest activities.	IMAGE 2.2 forest regrowth (harvest) projections	Transitions include conversions from and to forest.
Water (LC)	Areas persistently covered with water, such as streams, canals, lakes, reservoirs, bays, or oceans.	USGS Trends	Only conversions due to demand from land use sectors.
Wetland (LC) (herbaceous, woody wetlands)	Land where water saturation is the determining factor in soil characteristics, vegetation types, and animal communities. Wetlands usually contain both water and vegetated cover.	USGS Trends	Conversions due to demand from land use sectors; historical rates of conversion to and from barren, forest, and grassland/shrubland.
Forest (LC) (deciduous, evergreen, mixed)	Tree-covered land where the tree cover density is greater than 10%. Note that cleared forest land (i.e., clear-cuts) is mapped according to current cover (e.g., mechanically disturbed or grassland/shrubland).	USGS Trends	Conversions due to demand from land use sectors; historical rates of conversion from grassland/ shrubland due to agricultural abandonment.
Grassland/shrubland (LC) (grassland, shrubland)	Land predominately covered with grasses, forbs, or shrubs. The vegetated cover must comprise at least 10% of the area.	USGS Trends	Conversions due to demand from land use sectors; historical rates of conversion to and from barren.
Barren (LC)	Land comprised of soils, sand, or rocks where less than 10% of the area is vegetated. Barren lands are usually naturally occurring.	USGS Trends	
Snow/Ice (LC)	Land where the accumulation of snow and ice does not completely melt during the summer period (e.g., alpine glaciers and snowfields).	IMAGE 2.2	Only natural conversions to and from barren.
Fire[b]	Areas impacted by wildfire.	Exogenous modeling	All transitions allowed.

[a] LULC class definitions from the USGS Trends project (Loveland et al., 2002).
[b] Wildland fire modeling provided by Todd Hawbaker in conjunction with the USGS biological carbon sequestration assessment (Zhu et al., 2010).

- The scenario framework should serve as reference conditions from which potential future mitigation strategies can be assessed. The USGS carbon assessment had the added goal of assessing potential mitigation strategies to increase ecosystem carbon stocks. To evaluate potential mitigation actions it was necessary to base the assessment on a range of reference conditions which do not include integrated assumptions related to climate change mitigation.
- The scenario framework must include associated projections of changes in future climate. Other aspects of the USGS assessment include the coupled modeling of future projections in LULC and climate to assess disturbance regimes, biogeochemical cycling, aquatic systems, and mitigation potential. For this reason it was necessary to select a scenario framework which included corresponding climate simulations from a range of general circulation models.
- The USGS assessment is charged with assessing carbon and GHG stocks and fluxes across a range of ecosystems for the United States. For this reason the scenario framework had to be adaptable at multiple spatial scales, be consistently implemented across a range of ecological regions, and cover all major ecosystem types. The development of multi-scale scenarios extending from landscape to global scales is recommended to increase scenario credibility and relevance (Alcamo et al., 2008).
- The nature of the USGS assessment dictated that the underlying scenario framework be well vetted and have undergone an extensive peer review. In addition, there should be broad transparency in the use of underlying assumptions regarding the major drivers of LULC change.
- Due to the large uncertainties associated with future environmental change, it was determined that the scenario framework

Fig. 1. Ecoregion map of the conterminous United States.

chosen for the assessment not be predictive; rather the scenarios should encompass a wide range of future potential LULC pathways based on the unique interaction of a range of socioeconomic driving forces.

Based on these criteria, and following an analysis of a range of global scenario frameworks and existing scenario literature, it was decided that the IPCC-SRES set of scenarios would best serve the needs of the USGS carbon assessment. IPCC-SRES scenarios were developed for the IPCC 3rd assessment (IPCC, 2001). The scenario framework was developed to explore the consequences of future potential greenhouse gas (GHG) emissions based on assumptions of interactions of the major driving forces of change, such as population, economic development, technological innovation, societal attitudes, governance, energy systems, and the importance of environmental regulation. The scenarios were comprised of qualitative descriptions of future conditions, often referred to as narrative storylines, and quantitative modeling, including projections of land use. Projections were made for four macro-scale world regions for a small number of major land-use types. Four unique scenario families were developed and were oriented along two axes with the 'A' scenarios emphasizing economic development and the 'B' scenarios oriented towards environmental sustainability. In the other dimension, the '1' scenarios are globally oriented while the '2' scenarios are regionally focused. The basic defining characteristics of IPCC-SRES have been presented in a number of reports and are summarized here in Fig. 2. It is important to note that the SRES scenarios are in no way intended to represent the complete range of future potential conditions, nor are they intended to be construed as being favorable. Furthermore, for any scenario there exists a wide range of interpretations of the interaction of major driving forces which could lead to dramatically different future conditions. For this reason, the downscaled SRES scenarios presented here should be considered only as four unique and equally not improbable futures of LULC change in the conterminous United States.

As a first step in the downscaling process it was necessary to develop national and regionalized narrative storylines consistent with the IPCC-SRES alternative futures. The interpretation of downscaled narratives is critical for developing quantitative scenarios because they are rich in descriptive attributes which add explanatory power to future possible outcomes. Expert opinion was used, in conjunction with a review of IPCC-SRES literature, to develop initial draft narratives. These were then refined throughout the quantitative downscaling process so as to add thematic and ecoregion-specific detail, and to ensure overall consistency with national and global storylines.

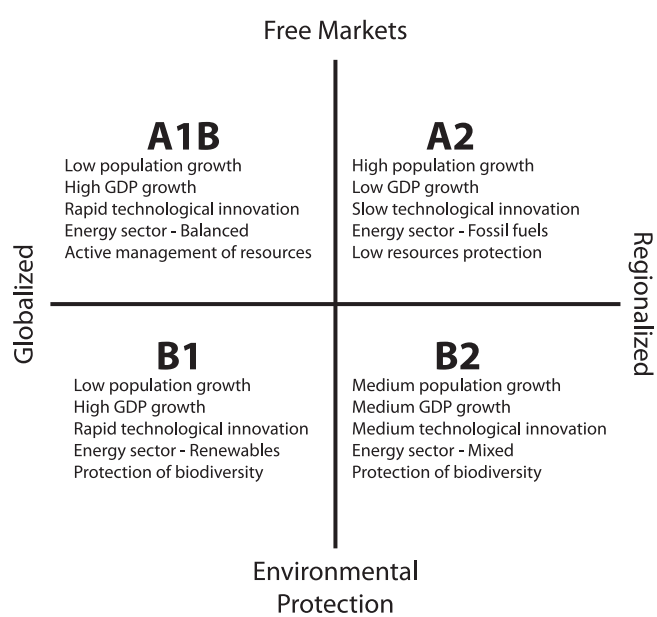

Fig. 2. Characteristics of the major driving forces behind the IPCC Special Report on Emission Scenarios four scenario families.

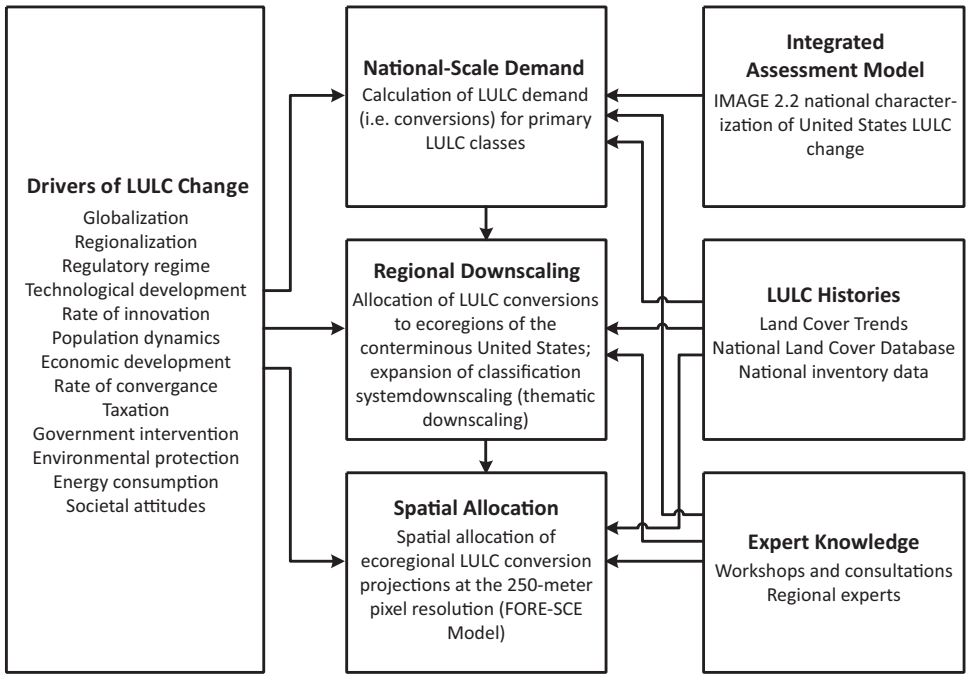

Fig. 3. Conceptual diagram of the major components used to downscale IPCC-SRES scenarios.

For this effort it was necessary to develop a model capable of downscaling projections of future LULC change across increasing spatial and thematic resolutions. A spreadsheet accounting model was developed to handle all aspects of the downscaling process. To drive demand for future land use we leveraged empirical modeling results from the Integrated Model to Assess the Global Environment 2.2 (IMAGE) implementation of the SRES marker scenarios (IMAGE Team, 2001). However, IMAGE data alone were not sufficient to develop scenarios as there are large discrepancies between the demands from the coarse-scale macro-economic model and current and historical baseline LULC inventories (Verburg et al., 2006). For this reason, LULC histories from the U.S. Geological Survey's Land Cover Trends Project (USGS Trends) (Loveland et al., 2002) were used to scale IMAGE inputs, as well as guide the distribution of LULC conversions at the ecoregion scale. Land-use change experts were consulted to assist in the development, interpretation, and implementation of narrative storylines and downscaling parameters at national and ecoregion scales. Below we briefly describe the role of these three important sources of scenario information, followed by an explanation of how they were incorporated at various steps in the downscaling model. Fig. 3 shows how the various elements used to construct and downscale scenarios were integrated.

2.3. Sources of data and information to construct national and regional LULC scenarios

2.3.1. Integrated model to assess the global environment (IMAGE)

While we would like to leverage as much available SRES-specific LULC information as possible, the majority of the modeling frameworks used by the SRES modeling teams did not explicitly account for LULC change or resultant GHG emissions. The exceptions were the AIM (Kainuma et al., 2002) and IMAGE (IMAGE Team, 2001; Strengers et al., 2004) models, with IMAGE providing the greatest level of thematic and spatial detail. IMAGE was improved further after the IPCC's third assessment (IPCC, 2001), with IMAGE 2.2 model data for the world readily available. IMAGE 2.2 consists of numerous linked modules, including modules focused on demographics, global economics, energy production and consumption, and climate. The integrated modeling framework interacts with a land-use module to produce LULC information for 17 world regions (with the U.S. represented as an independent region), with LULC distributions between regions based on socioeconomic factors such as demand for food products. IMAGE 2.2 also provides LULC information for half-by-half degree grid cells globally (approximately 55 km $\times$ 43 km at 40° north), with the spatial distribution of LULC based on biophysical factors such as climate and soils (Strengers et al., 2004).

National-level LULC projections from IMAGE served as a starting point for regional downscaling. Overall trends in major land use classes were logically consistent with SRES scenario assumptions, but absolute LULC proportions were unreasonable in some scenarios for certain LULC types (e.g., a near-doubling of agricultural land extent, or improbable rates of forest cutting). Thus, while national-level quantities and trajectories of LULC change from IMAGE are used as a basis for downscaling, they are modified according to methods discussed below. IMAGE provides data on population growth, energy resources, agricultural land use, and forest cutting; information used to drive demand for developed lands, mining, agriculture, and forest disturbance, respectively. Other IMAGE model outputs, such as biofuels demand and crop productivity, were incorporated into the narrative storylines to help inform scenario development and add thematic context to the final downscaled results.

2.3.2. Land-use and land-cover histories

The USGS recently completed a comprehensive assessment of CONUS land change. Utilizing the Landsat data archive, the USGS Trends project provides estimates of land change across 11 LULC classes for 5 dates between 1973 and 2000 (nominally, 1973, 1980, 1986, 1992, 2000). CONUS land change estimates were based on a random sample of 100 km^2 or 400 km^2 sample blocks developed for each of its 84 Level III ecoregions. For a complete discussion of the USGS Trends methodology see Loveland et al. (2002) and Stehman et al. (2003). Results from the USGS Trends assessment reveal a complex mosaic of LULC change patterns (Fig. 4), with high

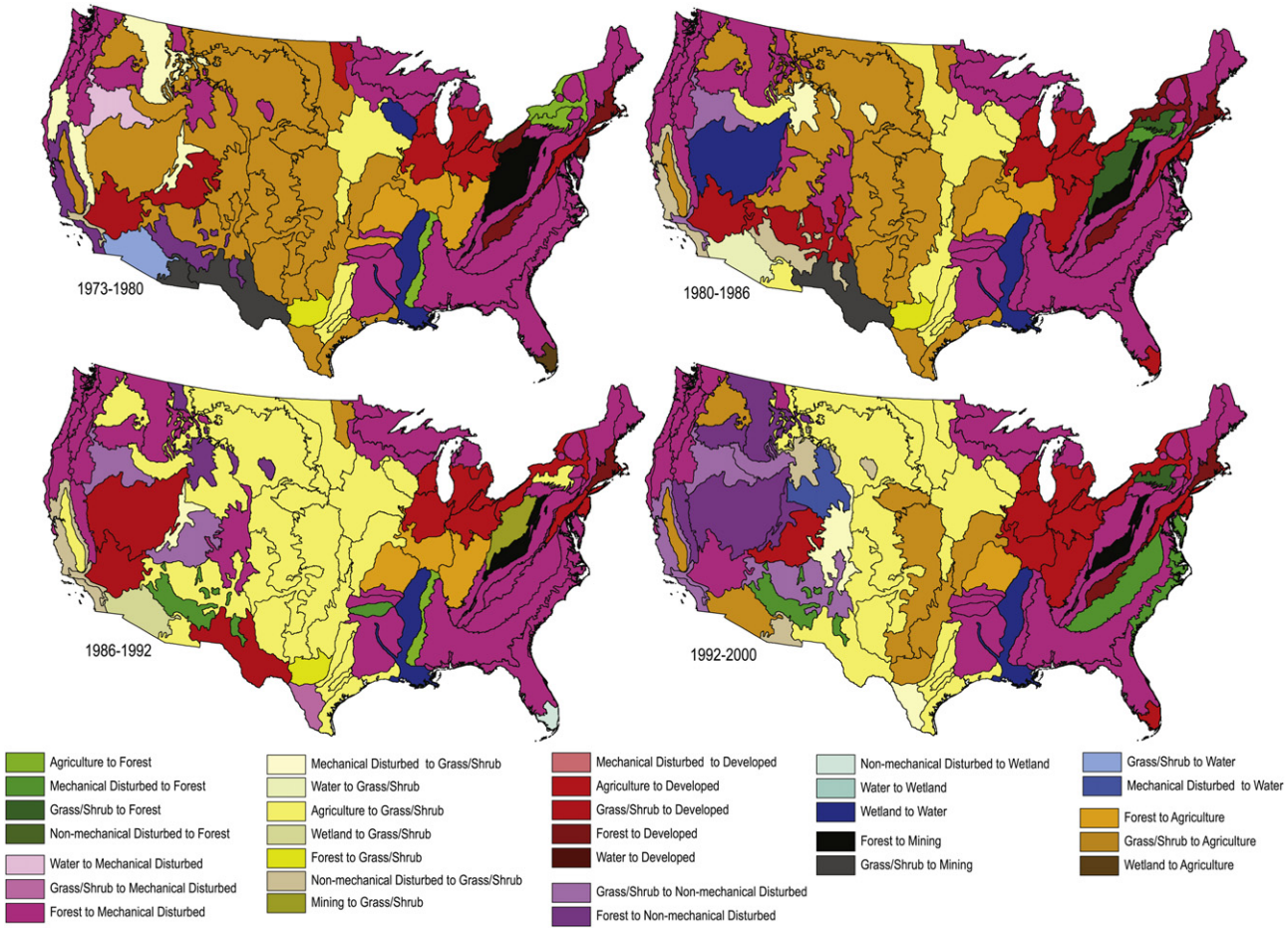

Fig. 4. Most common LULC conversion by ecoregion and temporal period from the USGS Land Cover Trends project.

rates of change typically found in regions with an active forestry. Unidirectional changes were common in areas where urbanization was the leading LULC change, although the originating LULC class varied by region. Agriculture was dynamic, both spatially and temporally. Agriculture intensified in some regions, often in response to technological changes, or declined in other areas as a result of competition for other land uses and policy implementations. For an in-depth discussion about USGS Trends results see Drummond and Loveland (2010), Sleeter et al. (2011), Napton et al. (2010), and http://landcovertrends.usgs.gov.

Comprehensive LULC histories provided by the USGS Trends project were the primary source for scenario downscaling parameters. Furthermore, LULC histories provided qualitative insights into the recent historical changes experienced in ecoregions. Qualitative elements were used to develop scenario narratives, specifically to describe ecoregion biophysical and socioeconomic conditions and potential, how they interacted to create historical and baseline LULC conditions, and the potential for future changes based on SRES scenario characteristics.

2.3.3. Expert knowledge

Computer models are often constrained by data availability; more so in highly complex socio-environmental systems. Human judgment, however, can be used to interpret the context of the narrative storylines and their major elements and driving forces assumptions, and adapt or shift parameters to more closely meet the desired intent of the scenarios. We incorporated judgment from land-change experts into the downscaling process to improve the relevance, credibility, legitimacy, and creativity (Alcamo et al., 2008) of scenario outcomes. Experts were used to provide interpretations of major driving forces of land change, not easily quantified by empirical or statistical models, using a combination of experience, knowledge, judgment, and ancillary data.A workshop was held in January 24–28, 2011, consisting of a mix of 20 topical and regional LULC experts spanning a range of expertise from coarse scale LULC trends mapping and analysis to regionally oriented and class specific specialists. Also participating in the workshop were authors of the ecoregion framework used for this project. Their expertise was invaluable as they were able to call upon their years of experience in the identification and delineation of ecoregion boundaries which generally reflect the range of potential land uses available. The goal of the workshop was to elicit knowledge about the major driving forces of land change in U.S. ecoregions. Prior to the workshop, attendees were provided information about SRES scenarios and narrative storylines, IMAGE model results, land-use histories, and assumptions from LULC downscaling literature. The structure of the workshop was unique to this project. Experts were divided into two groups, with one group focusing on regional scenarios (A2, B2) and another on global scenarios (A1B, B1). Working groups were asked to: (1) evaluate and document the major driving forces of change to LULC in the United States, consistent with IPCC-SRES storyline characterizations, (2) create downscaled LULC narrative storylines at national and ecoregional scales consistent with IPCC-SRES, and (3) to evaluate and adjust parameters used in the LULC downscaling model. Experts were encouraged to draw on their own experiences and knowledge, as well as their familiarity with other external sources of information, which could serve to inform scenario development (e.g. other national inventory programs). Participants

were able to iteratively manipulate a range of input parameters in the land-use scenario downscaling model (described in Section 2.4) and view the end-result of their downscaled scenario in real-time. The workshop was followed by a series of ad-hoc consultations to refine downscaling parameters and results. Due to their involvement throughout the scenario development process, many of the experts that participated in the workshop and follow up consultations are included as co-authors of this paper. In following sections, any reference to "expert opinion or judgment" includes those of the authors and others listed in the acknowledgments section.

2.4. Land-use scenario downscaling accounting model

A downscaling accounting model was developed to produce LULC change prescriptions for ecoregions of CONUS for four IPCC-SRES scenarios (A1B, A2, B1, and B2). This effort was designed to simulate a comprehensive set of land change conditions, thus it was necessary to model change between both use and cover. The downscaling model consists of two primary modules. The first module is used to develop national scale LULC change scenarios across major LULC classes, based on land use projections from IMAGE. The second module takes the LULC conversions specified at the national scale and downscales them to ecoregions of the U.S. The downscaling module is applied to progressively higher resolution ecoregion stratifications, first allocating conversions from the national scale to Level I ecoregions, then from Level I to Level II ecoregions, and finally from Level II to Level III ecoregions. During the final step when LULC conversions are allocated from Level II to Level III ecoregions, the classification system was expanded from 9 to 16 classes. Although not discussed in detail in this paper aside from some illustrative examples, Level III ecoregion scenarios, specified in the form of LULC conversions, are then allocated on the landscape using the FORE-SCE spatially explicit model. (e.g. see Sohl and Sayler, 2008; Sohl et al., 2007, 2012). Following is a description of the different elements of the scenario development and downscaling process.

2.4.1. Baseline conditions

Baseline LULC change conditions were established at 5-year intervals for the period 1970–2000 using results from the USGS Trends project. LULC histories were used to provide current and historical information on LULC composition and various measurements of land change (e.g. gross, net, conversions). Historic and baseline conditions were used to provide an initialized point of departure for the LULC projections and to serve as a consistency check for future change. Scenario projections with large departures from the historical ranges were carefully analyzed for logical consistency and to ensure the projections were plausible and consistent with storyline characteristics.

The FORE-SCE model used a modified version of the 1992 National Land Cover Dataset (NLCD) (Vogelmann et al., 2001), resampled to 250 m resolution, to initiate model runs. LULC change was modeled forward from 1992 through 2006 using rates of change from USGS Trends for the period 1992–2000, and rates of change from the 2001 to 2006 NLCD (Homer et al., 2004; Xian et al., 2009). Data from the Vegetation Change Tracker (VCT) (Huang et al., 2010) was used to provide annual areas of forest harvest which was "burned-in" on the modeled LULC.

2.4.2. National scale LULC scenarios

The goal of the national scale scenario development process was to provide projections of *conversions* between LULC classes at the national scale. LULC conversion projections were calculated along with a number of other land change variables, including *composition*, *net change*, *gross change*, *gains*, and *losses*. These are defined as:

- *Composition* – The amount, in either percent or area, of a LULC class at any given point in time.
- *Net change* – Expressed as the difference in area of a LULC classes between two dates.
- *Gross change* – The sum of all gains and losses in a class between two dates.
- *Gains* – The amount of area that converts into a given classes between two dates, irrespective of the amount of area lost.
- *Losses* – The amount of area that converts out of a given classes between two dates, irrespective of the amount of area gained.
- *Conversions* – The amount of area that converts between two classes between two dates.

National scenario development was a simple and straightforward process. For the four major land uses we calculate the percent change at five-year intervals from the IMAGE model. Rates of change are then applied to baseline conditions to project LULC composition and net change into the future. USGS Trends data are used to convert net change into gross change based on historical measurements. Gains and losses are calculated as a function of having projections of net and gross change, while USGS Trends data are used to allocate gains and losses to LULC conversions. Changes between land-cover classes (e.g. water converting to wetlands) were either extrapolated into the future from USGS Trends data or not addressed in this research. Here we discuss the model parameters used to calculate national scale LULC conversions.

2.4.2.1. Developed. IMAGE does not include developed land use as one of its modeled outputs, so it was necessary to use a proxy to drive developed land-use demand. IMAGE population projections for the U.S. were used to calculate population change at 5-year intervals; these change amounts were then used to drive changes in developed lands. However, using only population would assume a static one-to-one relationship between population growth and the demand for new developed lands, ignoring the role of economic growth, technology, and societal attitudes that influence the characteristics and pattern of developed land use. As a means to include these other important scenario characteristics, the model was developed to allow freedom to manipulate the population change projections in an effort to better reflect scenario characteristics. For example, experts concluded that while the A1B and B1 scenarios share the same population projections, the impact on developed land use would be significantly different due to the economic and environmental preferences established in the SRES narratives (Nakicenovic and Swart, 2000). Thus, scaling factors were applied to reflect this interpretation of storyline narratives, resulting in differences in the demand for new developed areas between scenarios with the same population projections. Furthermore, experts concluded there would be limitations on the sources of new developed lands under some scenarios (e.g., restricting new development originating from wetlands in environmentally focused scenarios). Therefore, composition of developed land use was calculated as:

$$Dev^{P}_{t1\ldots tn} = B_{dev} * (Pop\Delta^{P}_{p1\ldots pn} * EIF) \quad (1)$$

where Dev^{p} is the projected amount of developed land area, t is a point in time, B_{dev} is the baseline starting composition from USGS Trends measurements, $Pop\Delta^{P}$ is the projected percent change in population from IMAGE at 5-year intervals, p is a 5-year time period, and EIF is an expert modifier used to adjust the rates of change based on unique scenario storyline characteristics. In the A1B scenario, experts increased the rate of developed by 40% through year 2050 and then by 15% through 2100. In the A2/B2 and B1 scenarios the change rate was decreased by 5% and 10%, respectively.

Net change was calculated as:

$$N\Delta^{P}_{p1\ldots pn} = Dev^{P}_{t1\ldots tn} - Dev^{P}_{t-1} \quad (2)$$

where $N\Delta^{P}_{p1\ldots pn}$ is the projected net change in a class during time period p, Dev^{P} is the composition of developed land in time t, and Dev^{P} is the amount of developed land in time $t-1$.

Gross change in developed was calculated using the following formula:

$$G\Delta^{P}_{p1\ldots pn} = (N\Delta^{P}_{p1\ldots pn}) * \left(\frac{G\Delta^{H\mu}_{1973-2000}}{N\Delta^{H\mu}_{1973-2000}}\right) \quad (3a)$$

where $G\Delta^{P}$ is projected gross change in time period p, $N\Delta^{P}$ is projected net change in time period p, $G\Delta^{H\mu}_{1973-2000}$ is the historic measurement of gross change from USGS Trends for the period 1973–2000, and $N\Delta^{H\mu}_{1973-2000}$ is the historic measurement of net change from USGS Trends also for the period 1973–2000. Therefore, projected gross change in developed was calculated as:

$$G\Delta^{P}_{p1\ldots pn} = (N\Delta^{P}_{p1\ldots pn}) * (1.02) \quad (3b)$$

Losses were calculated as:

$$Losses^{P}_{p1\ldots pn} = \left(\frac{G\Delta^{H\mu}_{1973-2000} - N\Delta^{H\mu}_{1973-2000}}{2}\right) \quad (4)$$

Gains were calculated as:

$$Gains^{P}_{p1\ldots pn} = G\Delta^{H\mu}_{1973-2000} - Losses^{P}_{p1\ldots pn} \quad (5)$$

Allocation of gains and losses to LULC conversions was based on USGS Trends data for the period 1973–2000 and modified by experts to reflect scenario characteristics (e.g. the protection of wetlands).

2.4.2.2. Mining. Similar to developed land use, IMAGE 2.2 does not produce projections of land devoted to mining. However, IMAGE produced projections of energy production from coal, which were used as a proxy for mining demand under the assumption there is a general correlation between coal mining activity and overall surface mining land-use demand under the alternative scenarios. Composition and net changes were calculated using Eqs. (1) and (2). Conditional statements were developed to calculate gross change. When net changes were low it was necessary to increase the scaling factor to adequately represent landscape changes that were still occurring, despite relatively little change in overall LULC composition. Conversely, when net changes were high (i.e. large increases or declines in a particular class), the gross change scaling factors were reduced to avoid placing an unrealistic amount of demand for LULC change on the landscape. To calculate gross change for mining we use following equations:

$$\text{IF} \quad N\Delta^{P}_{p1\ldots pn} \geq N\Delta^{H\mu}_{1973-2000} \ \text{ THEN } \ G\Delta^{P}_{p1\ldots pn} = (N\Delta^{P}_{p1\ldots pn}) * \left(\frac{G\Delta^{H\mu}_{1973-1980}}{N\Delta^{H\mu}_{1973-1980}}\right) \quad (6a)$$

$$\text{IF} \quad N\Delta^{P}_{p1\ldots pn} < N\Delta^{H\mu}_{1973-2000} \ \text{ THEN } \ G\Delta^{P}_{p1\ldots pn} = (N\Delta^{P}_{p1\ldots pn}) * \left(\frac{G\Delta^{H\mu}_{1973-2000}}{N\Delta^{H\mu}_{1973-2000}}\right) \quad (6b)$$

where $N\Delta^{P}$ is the projected net change in period p, $N\Delta^{H\mu}_{1973-2000}$ is the mean net change measured by USGS Trends, $G\Delta^{P}$ is the projected gross change in period p, $G\Delta^{H\mu}_{1973-1980}$ is the measured gross change for the period 1973–1980 from USGS Trends, $N\Delta^{H\mu}_{1973-1980}$ is the net change for the period 1973–1980. Therefore, we get the following calculations:

$$\text{IF} \quad N\Delta^{P}_{p1\ldots pn} \geq N\Delta^{H\mu}_{1973-2000} \ \text{ THEN } \ (N\Delta^{P}_{p1\ldots pn}) * 3.68 \quad (6c)$$

$$\text{IF} \quad N\Delta^{P}_{p1\ldots pn} < N\Delta^{H\mu}_{1973-2000} \ \text{ THEN } \ (N\Delta^{P}_{p1\ldots pn}) * 7.39 \quad (6d)$$

Losses and gains in mining were calculated using Eqs. (3a), (3b) and (4), respectively; distribution between LULC classes was based on the Trends data and modified by experts.

2.4.2.3. Agriculture. The IMAGE 2.2 model produces explicit projections of agricultural land use, and serves as a starting point for development of LULC scenarios. Trajectories of changes in agricultural land use were generally consistent with scenario assumptions; however, the magnitude of change was higher than could reasonably be expected to be accommodated nationally. Agriculture composition projects were calculated by:

$$Agric^{P}_{t1\ldots tn} = B_{agric} * (Agric\Delta^{P}_{p1\ldots pn} * 0.7) \quad (7)$$

where $Agric^{P}$ is the amount of projected agricultural land area at a point in time t, B_{agric} is the baseline starting composition from USGS Trends measurements, and $Agric\Delta^{P}$ is the percent change in agriculture composition projected by IMAGE for time period p. IMAGE projections were reduced by 30% for all scenarios resulting in scenarios that were generally within the range of historical measurements, with the exception of the A2, and to a lesser extent A1B, post 2050, where the rate of agricultural increase is exceptionally high.

Gross change in agriculture was calculated similar to mining, using a simple conditional statement and a range of historical ratios from the Trends data.

$$\text{IF} \quad N\Delta^{P}_{p1\ldots pn} \geq N\Delta^{H\mu}_{1973-2000} \ \text{ THEN } \ G\Delta^{P}_{p1\ldots pn} = (N\Delta^{P}_{p1\ldots pn}) * \left(\frac{G\Delta^{H\mu}_{1986-1992}}{N\Delta^{H\mu}_{1986-1992}}\right) \quad (8a)$$

$$\text{IF} \quad N\Delta^{P}_{p1\ldots pn} < N\Delta^{H\mu}_{1973-2000} \ \text{ THEN } \ G\Delta^{P}_{p1\ldots pn} = (N\Delta^{P}_{p1\ldots pn}) * \left(\frac{G\Delta^{H\mu}_{1973-2000}}{N\Delta^{H\mu}_{1973-2000}}\right) \quad (8b)$$

where $N\Delta^{P}$ is the projected net change in period p, $N\Delta^{H\mu}_{1973-2000}$ is the mean net change measured by USGS Trends, $G\Delta^{P}$ is the projected gross change for period p, $G\Delta^{H\mu}_{1986-1992}$ is the measured gross change for the period 1986–1992 from USGS Trends, $N\Delta^{H\mu}_{1986-1992}$ is the net change for the period 1986–1992. Therefore, we get the following calculations:

$$\text{IF} \quad N\Delta^{P}_{p1\ldots pn} \geq N\Delta^{H\mu}_{1973-2000} \ \text{ THEN } \ (N\Delta^{P}_{p1\ldots pn}) * 1.5 \quad (8c)$$

$$\text{IF} \quad N\Delta^{P}_{p1\ldots pn} < N\Delta^{H\mu}_{1973-2000} \ \text{ THEN } \ (N\Delta^{P}_{p1\ldots pn}) * 3.5 \quad (8d)$$

Losses and gains in agricultural land use were calculated based on Eqs. (4) and (5), respectively.

2.4.2.4. Forest harvest. Similar to the agricultural class, IMAGE 2.2 provides projections of forest regrowth from harvest for the U.S. The contribution of cutting from Alaska was isolated using the gridded spatial data provided by IMAGE. Data for CONUS were used to develop future projections. Based on USGS Trends data, areas of forest cutting ranged from a low of 14,000 km^2 in 1970, to a high of 48,000 km^2 in 1990 while IMAGE had projections of as much as ten times the highest measured amount. The USGS Trends definition of "mechanically disturbed" results in only clear-cutting of forest as being explicitly mapped. Forest thinning and other

partial cutting measures were not explicitly mapped by USGS Trends. Forest product measures as provided by IMAGE include all timber products produced, and a conversion of timber volume to forest cutting area thus is very likely to provide a total reported area that is much higher than the mapped USGS Trends estimate. Our primary use of IMAGE forest cutting measures is to examine relative trends in forest cutting, between scenarios and over time. The trends are thus relevant to the downscaling, but the overall quantity provided by IMAGE is not compatible with USGS Trends results (in an effort to downscale scenarios for Europe, Verburg et al. (2006, p. 43) encountered a similar problem related to agricultural land use and applied a "correction factor" to utilize IMAGE data at the regional scale). We therefore used USGS Trends estimates of clear-cut logging to scale the IMAGE data using the following formula:

$$MD^{P}_{t1\ldots tn} = MD\Delta^{P}_{p1\ldots pn} * 0.2 \tag{9}$$

where MD^P is the amount of mechanically disturbed area in time t and $MD\Delta^P$ is the amount of forest regrowth from logging from IMAGE in period p. Because the mechanically disturbed class is used as a transitory class for disturbed forest land, the calculation of gains and losses is different from other land-use classes. Gains in mechanical disturbance are equal to the composition as calculated using Eq. (9). By rule, all areas classified as mechanically disturbed are transitioned back to forest, therefore, losses in time t are equal to the gains in time $t-1$. The only LULC class allowed to change in or out of mechanically disturbed was the forest class.

2.4.2.5. Land-cover classes. Once demand for all four land-use types was met, demand was calculated for the remaining land-cover classes. Because land-use demands on the remaining land-cover classes had been satisfied from the prior land-use demand calculations, the only remaining conversions were transitions between land-cover types (e.g., forest encroachment into grasslands). To satisfy demand for these classes we applied historical rates of change based on the USGS Trends land-use histories. It is important to note that while the effects of future climate conditions were not incorporated into modeling of changes in vegetation structure, which could potentially lead to shifts in land cover, the use of the ecoregion framework isolates the potential for these changes. Thus, future changes in precipitation or temperature can subsequently be incorporated within a spatially explicit LULC model (see Sohl et al., 2007; Sohl and Sayler, 2008) to simulate "natural" changes in land cover (Zhu et al., 2010).

2.4.3. Eco-regionalization of scenarios

The second phase of the downscaling model was to allocate national level LULC conversions to ecological regions (Fig. 3) (EPA, 1999). Ecoregions are areas of general similarity in ecosystems and in the type, quality, and quantity of environmental resources. They are designed to serve as a spatial framework for the research, assessment, management, and monitoring of ecosystems and ecosystem components. The spatial framework is based on the premise that ecological regions are hierarchical and can be identified through the analysis of the spatial patterns and the composition of biotic and abiotic phenomena that affect or reflect differences in ecosystem quality and integrity (Omernik, 1987, 1995, 2004). Such phenomena include geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology. These general purpose regions are critical for structuring and implementing ecosystem management strategies across federal agencies, state agencies, and nongovernment organizations that are responsible for different types of resources within the same geographical areas (Omernik et al., 2000).

Regionalization of scenarios was accomplished by downscaling LULC conversions specified at the national scale. Using the USGS Trends data, projected LULC conversions were downscaled to Level I ecoregions based on the recent historic distribution of conversions. In some instances, experts modified these distributions to emphasize aspects of storylines characteristics. As noted prior, this was a multi-step process, with national LULC conversions downscaled to Level I ecoregions, followed by downscaling of Level I ecoregion conversions to Level II and Level II ecoregions to Level III.

Level I ecoregions were aggregated to four main regions of CONUS: the Eastern U.S., the Great Plains, the Western Mountains and Forests, and the Western Deserts and Mediterranean California (Fig. 3). Initially, LULC conversions were downscaled proportionally to these regions based on historical LULC conversion data from the USGS Trends project. Downscaling of LULC conversions to ecoregions was done based on the average distribution of LULC conversions across ecoregion stratification between 1973 and 2000. For example, if the conversion of agriculture to development was distributed equally across all four Level I ecoregions, then future amounts of the same conversion would be initially distributed equally. More temporally detailed data on the distribution of LULC conversions was available from USGS Trends, and was incorporated by experts based on storyline characteristics. Experts reviewed the resultant four regionalized scenarios for logical consistency with the IPCC-SRES storylines, iteratively modifying LULC trajectories to ensure general consistency with storylines. The formula used to downscale conversions from national to Level I ecoregions was:

$$PCV^{L1}_{1\ldots n} = PCV^{N}_{1\ldots n} * \left(\frac{MCV^{L1}_{1\ldots n}}{\sum MCV^{L1\ldots n}_{1\ldots n}}\right) \tag{10}$$

where $PCV^{L1}_{1\ldots n}$ is a projected conversions for a Level I ecoregion, $PCV^{N}_{1\ldots n}$ is the total amount of a conversion projected at the national scale, $MCV^{L1}_{1\ldots n}$ is the total measured conversions in a Level I ecoregion from USGS Trends, and $\sum MCV^{L1\ldots n}_{1\ldots n}$ is the totaled measured conversion for all Level I ecoregions from USGS Trends data. A second phase of scenario regionalization occurred with Level I conversions being allocated to their respective nested Level II ecoregions (Fig. 3). The same process was applied where conversions were allocated to Level II ecoregions based on recent historical distributions, therefore:

$$PCV^{L2}_{1\ldots n} = PCV^{PL1}_{1\ldots n} * \left(\frac{MCV^{L2}_{1\ldots n}}{\sum MCV^{L2\ldots n}_{1\ldots n}}\right) \tag{11}$$

where $PCV^{L2}_{1\ldots n}$ is the projected conversion in a Level II ecoregion, $PCV^{PL1}_{1\ldots n}$ is the projected conversion amount in the parent Level I ecoregion as calculated in Eq. (10), and $MCV^{L2}_{1\ldots n}$ is the historical measured conversion in the Level II ecoregion from USGS Trends. The goal of this nested approach was to reduce the number of ecoregions that had to be considered at any given time, allowing scenario developers to think more coherently about the range of outcomes occurring across a limited number of regions.

Downscaling LULC conversions from the 15 Level II ecoregions to 84 Level III ecoregions was a two-tiered process. First, projected conversions were allocated from parent Level II ecoregions to nested Level III's:

$$PCV^{L3}_{1\ldots n} = PCV^{PL2}_{1\ldots n} * \left(\frac{MCV^{L3}_{1\ldots n}}{\sum MCV^{L3\ldots n}_{1\ldots n}}\right) \tag{12}$$

where $PCV^{L3}_{1\ldots n}$ is the projected conversion in a Level III ecoregion, $PCV^{PL2}_{1\ldots n}$ is the projected conversion amount in the parent Level II ecoregion as calculated in Eq. (11), $MCV^{L3}_{1\ldots n}$ is the measured amount of a conversion in a Level III ecoregion from USGS Trends, and

$\sum MCV_{1\ldots n}^{L3\ldots n}$ is the sum of a conversion across all nested Level III ecoregions.

The second tier of Level III downscaling was the expansion of the classification system from 9 to 16 classes (Table 2). The forest class was subdivided into evergreen, mixed, and deciduous classes, grassland/shrubland was divided into grassland/herbaceous and shrublands, wetlands were divided into woody and herbaceous classes, agriculture was divided into cultivated cropland and hay/pasture, and mechanical disturbance was divided into three ownership classes: national forest transitional, other public transitional, and private transitional. With the exception of the transitional/disturbance class, we used measurements of LULC composition from the 2001 NLCD to subdivide the classes. For example, if cultivated crops accounted for 70% of the total area classified as 'agriculture', then an equal percentage of all conversions involving the agriculture class would be allocated to cultivated cropland while 30% would be allocated to the hay/pasture class. Therefore,

$$\text{IF} \quad PC = \sum SC_{1\ldots n} \ \text{ THEN } \ PSC_{1\ldots n} = PCV_{1\ldots n}^{L3} * \left(\frac{MSC_{1\ldots n}}{\sum MSC_{1\ldots n}} \right) \qquad (13)$$

where PC is the parent class, SC is the subclass, $PSC_{1\ldots n}$ is the projected conversion of a subclass, $PCV_{1\ldots n}^{L3}$ is the projected conversion between two parent classes for a Level III ecoregion, and $MSC_{1\ldots n}$ is the measured area of a subclass from the 2001 NLCD.

Ownership and management of forests often results in different rates and patterns of LULC change. To better represent these differences we used remote sensing data from the Vegetation Change Tracker (VCT) dataset (Huang et al., 2010) to characterize disturbance rates across three categories of land ownership (National Forests, other public lands, and private lands).. VCT data provides annual, spatially explicit maps of vegetation disturbance from both anthropogenic and natural causes. Using the spatially explicit Monitoring Trends in Burn Severity data (Eidenshink et al., 2007) we masked out known areas of wildfire and summarized disturbances for the three ownership classes using the USGS/GAP Protected Areas Database. Future demand for forest harvest was then initially distributed to the three ownership classes based on the distribution of cutting in VCT for the year 2005.

2.5. Spatial allocation

The scenarios developed here serve as input to the spatial model Forecasting Scenarios of Land Change (FORE-SCE) (Sohl and Sayler, 2008; Sohl et al., 2012). FORE-SCE uses a modular approach, with "demand" for overall regional proportions of LULC change modeled independently from a "spatial allocation" component that spatially maps LULC change. The scenarios described here provide demand for FORE-SCE, with FORE-SCE mapping transition-by-transition LULC change based on the scenario specifications. FORE-SCE uses a patch-based spatial allocation procedure. Patch characteristics are based on regional, historical LULC data, with individual parameterization of patch sizes for each LULC type. Patch placement is dictated by the development of spatially explicit surfaces providing relative suitability of a region to support a given LULC type. Suitability surfaces are constructed using logistic regression, examining empirical relationships between extant LULC types and spatially explicit biophysical and socioeconomic variables. A protected area database (PAD-US, 2010) is used to restrict the placement of LULC change on certain types of protected lands. The spatial modeling proceeds with individual patches of new LULC placed on the landscape until the scenario-provided demand is met. Qualitative storylines accompanying the quantitative scenarios are also used to inform the spatial modeling, as patch size characteristics, parameters on patch dispersion, or lands protected from change may vary depending upon characteristics of the underlying scenario storylines.

3. Results and discussion

3.1. National scenario characteristics and results

Scenario downscaling results in two primary data sources: (1) ecoregion-based projections of LULC change, and (2) annual spatially explicit maps of LULC at 250 m resolution for the conterminous United States. The process of producing spatially explicit maps is ongoing; therefore we focus the discussion of results on ecoregion-based projections while highlighting completed areas for illustrative purposes. Ecoregion-based projections provide important insights into a range of future LULC conditions that could be expected under alternative scenarios and are discussed below.

3.1.1. A1B

The A1B scenario is marked by strong economic growth, high levels of technological innovation, international mobility of people, ideas, and technology, and high rates of LULC change. The focus of the storyline is on wealth accumulation, with a convergence of global standards of living; environmental concerns are secondary to economic growth. Urban growth is strong, particularly in and around major urban centers and in coastal regions, and has a large impact on other land uses and covers (e.g. agriculture and forests). Large increases in demand for biofuels and food production to meet national and global needs offset expected gains in crop productivity through technological innovation, resulting in large increases in agricultural land use. A focus on wealth accumulation and achieving and maintaining a high standard of living, results in high pressure on forest resources, with a continuation of recent trends towards intensification of forest land management through expansion of plantation forestry. Traditional areas used to produce forest products are expected to intensify, such as the Pacific Northwest and southeastern United States. In some regions with well-developed infrastructure and abundant natural resources, pressure from competing land uses are expected to result in increased fragmentation of natural covers.

3.1.2. A2

In the A2 scenario rapid population growth is combined with low per capita income. Technological change is slow, as low economic growth limits research investment, and an emphasis on regional and local policy results in slow diffusion of new technologies. Large population gains result in the highest rates of conversion of lands for developed uses; an absence of policies to restrict growth result in a sprawling pattern of development. Existing urban areas are the primary destination for new developed areas although growth around agricultural "hubs" is also common. Increases in agricultural productivity follow recent historical trends and are primarily the result of increased use of fertilizers as opposed to advances in bioengineering and cultivation practices. Federal environmental and conservation programs are reduced and there is strong governmental support to maintain overproduction. These actions result in a strengthening of core agricultural regions and an expansion into marginal areas limited only by the physical capacity of the resource base. High population growth increases overall forest area harvested. With decreased emphasis on protecting the environment, logging increases on public lands. Forest cutting intensifies, with large stands of monoculture becoming increasingly common. Large areas of fast growing species are needed for pulp and paper production, and locally, for woody biomass for biofuels. Natural land covers, such as

wetlands and grasslands are vulnerable to conversion to meet land use demands.

3.1.3. B1

The B1 scenario is characterized by the same moderate population growth as the A1B scenario, with similarly high economic growth. A central element of the scenario is a high level of environmental and social consciousness, with a globally coherent approach to sustainable development and a focus on resource-friendly lifestyles. Increases in development and impervious covers are relatively slow due to the environmental orientation of the scenario. The "sprawling suburbia" characteristic of economically oriented scenarios is replaced by a pattern of compact development, as low-density residential suburbia is discouraged through regulation, and by choice of a population focused on environmental protection. The B1 scenario is marked by technological advancement resulting in higher crop yields. However, productivity increases are balanced against environmental concerns which restrict many intensive farming practices. For both crop and livestock production, more environmentally friendly methods are utilized, including organic farming, open range grazing, and a reduction in intensive "landless" livestock operations. A trend towards dematerialization results in lower overall demand for wood products. Forestland restoration occurs on marginal agricultural lands as efforts are made to preserve biodiversity and water quality. Management of forest land changes with rising concerns about the environmental implications of intensively managed forest monocultures. Efforts are made to significantly increase "natural" forests and reduce the areal extent of heavily managed plantation forestry. Increasing the amount of forest land for protection of biodiversity is a common objective. Natural land covers are protected and restoration is a common objective of land management.

3.1.4. B2

The B2 scenario is often described as the "dynamics-as-usual" scenario and is characterized by gradual changes and less extreme developments (Nakicenovic and Swart, 2000). It describes a future that is based on regional solutions to economic, social and environmental sustainability. Due to low population growth and a societal focus on environmental sustainability, expansion of development and impervious covers is slowest in the B2 scenario. Increased local environmental awareness results in high density construction. Technological energy advances are limited because of the lack of shared global development resulting in continued use of current oil and natural gas reserves. An increase in environmental awareness, coupled with concerns over food security, shift dietary patterns towards local products and reduced meat consumption. Environmental concerns lead to reclamation of degraded lands, increasing forests, grasslands, and wetlands, and improving local and regional environmental quality. Agricultural commodity exports are low and production is focused on the highest productivity and least vulnerable lands. Demand for biofuels is high due to a local and regional emphasis on environmental and socioeconomic sustainability. The combination of storyline characteristics results in the largest declines in agriculture of any of the scenarios. Forest area is relatively stable but demand for modern biofuels contributes to increased rates of forest disturbance.

3.2. Comparison of scenarios and regions

Future projections in the demand for development, mining, agriculture, forest harvest, and environmental protection interact in unique combinations across the four SRES scenarios and ecoregions resulting in highly variable landscapes. Land change rates were calculated for 5-year periods based on the sum of all conversions occurring within the period. The highest rates were most commonly associated with the economically oriented scenarios and typically ranged from 2% to 3% of the CONUS land area changing every 5 years (Fig. 5). Regionally, the Eastern U.S. accounted for the largest proportion of overall change, followed by the Western Mountains and Forests and Great Plains regions. The Western Deserts and Mediterranean California had the lowest rates of land change in all scenarios. At the Level II ecoregion scale the highest rates of change were in the Marine West Coast Forests, Mixed Wood Shield, Southeastern Plains, and Mississippi Alluvial and Southeastern Coastal Plain ecoregions. These regions are generally characterized by high rates of forest disturbance coupled with a dynamic agriculture and/or developed landscape. Low rates of change were common in ecoregions where land resources were being utilized at their highest use, such as in the Central USA Plains, Mixed Wood Plains, and Temperate Prairies, or where environmental conditions limit the potential of resource development such as in the Warm and Cold Deserts ecoregions.

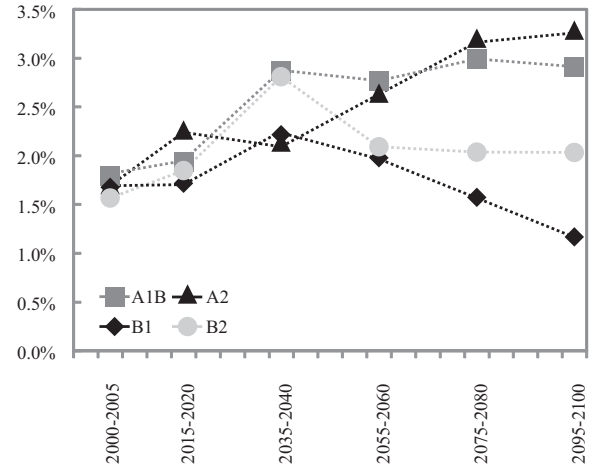

Fig. 5. Percent of the conterminous United States projected to experience LULC change under each of the IPCC-SRES scenarios.

The net change in individual LULC classes is an important indicator of overall regional trends. Results of the downscaling model project higher demands and intensification of land uses in the economic oriented scenarios with large areal increases in the developed and agricultural classes. The impact of high land use demands results in large declines in natural land covers, primarily forests, grasslands/shrublands, and wetlands. Conversely, the environmentally oriented scenarios have relatively less demand for land use and therefore the impact on natural covers is lessened. Fig. 6 shows the net change between 2000 and 2100 in major land use (developed, mining, agriculture, and logging) and land cover (water, wetlands, forest, and grassland/shrublands) classes for each Level II ecoregion.

Although accounting for a relatively small portion of the landscape (approximately 4% of CONUS in 2000), developed land use is expected to experience the largest changes by 2100. The largest change was an increase of 115% in A2, followed by an increase of 92% in A1B. The B1 and B2 (environmental oriented) scenarios were projected to be considerably lower with increases of 57% and 28%, respectively (Fig. 6). Population growth was the major driving factor; however, assumptions about policies to restrict or govern growth were also important and reflected in the A1B and B1 scenarios which share the same population projections (and similar economic growth assumptions). Depending upon scenario, between 1.1% and 4.5% of the U.S. is projected to convert into developed uses by 2100, with the majority of the converted

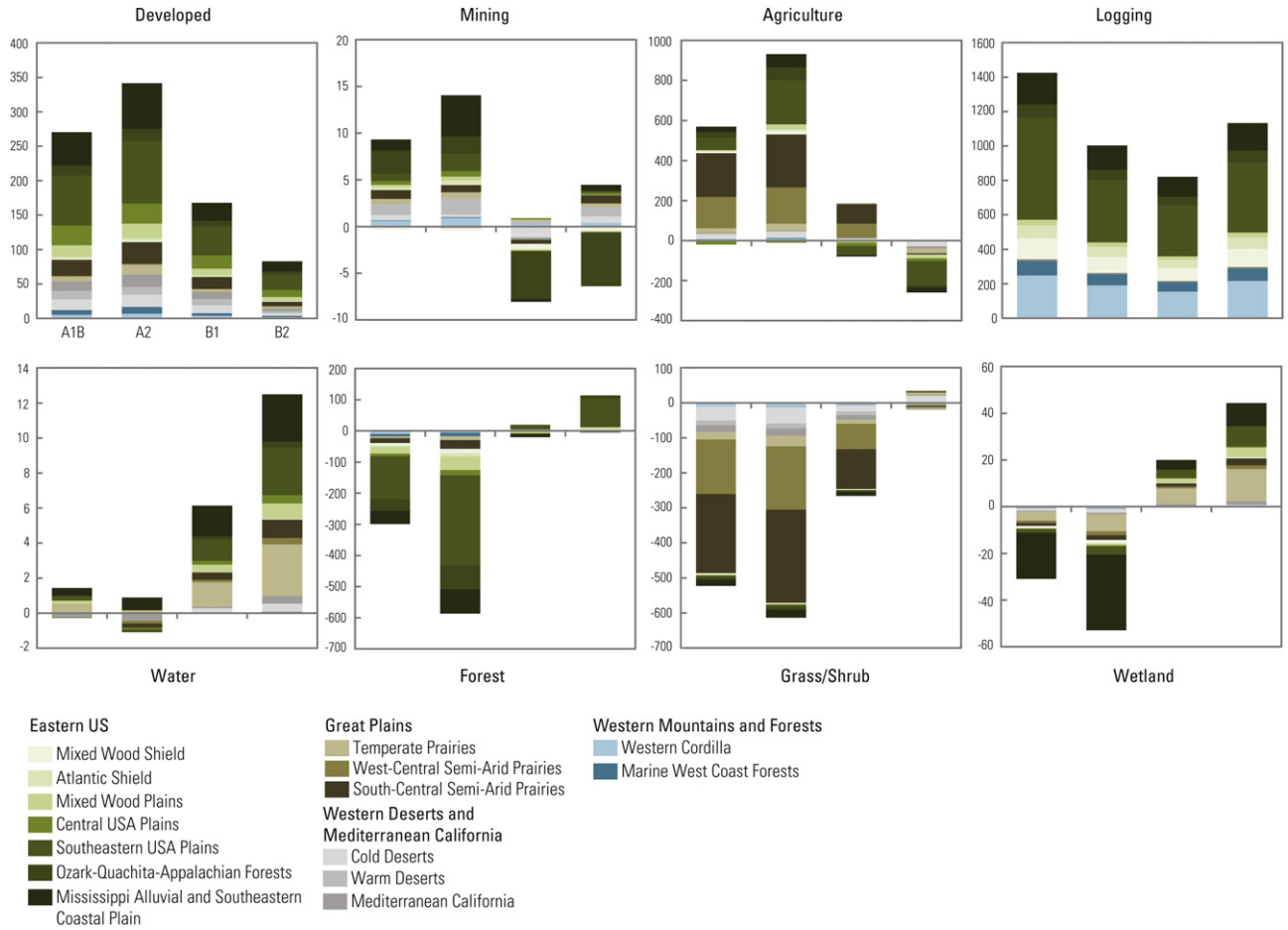

Fig. 6. Projected net change in each of the 15 Level II ecoregions between 2000 and 2100 for each of the major land use (top row) and land cover (bottom row) classes. The logging class (top right) reflects the cumulative total area of clear cut logging over the 100 year projection period. The vertical axis is thousands of km^2.

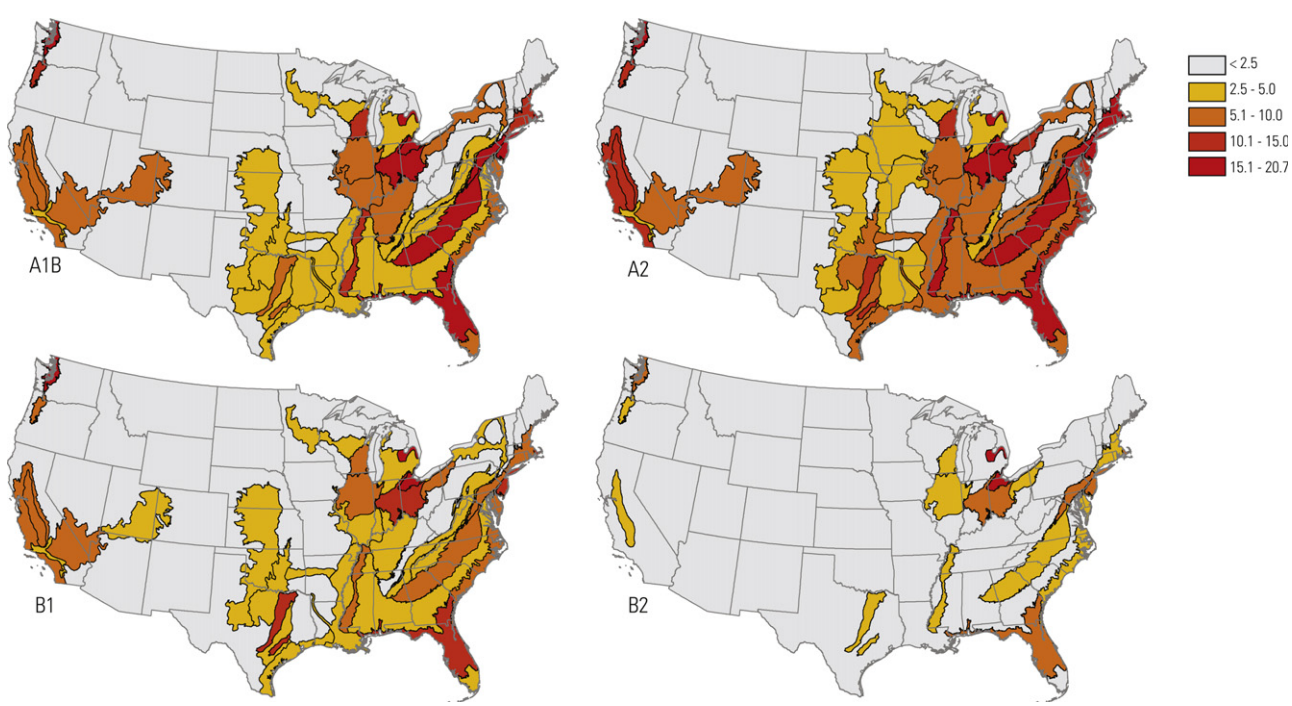

Fig. 7. Distribution of net change in developed land use (2000–2100) by Level III ecoregion. Units are percent of ecoregion area changed.

land coming from the Eastern U.S. At the Level 2 ecoregion scale the most important areas, irrespective of scenario, were the Southeastern Plains, the Mississippi Alluvial and Southern Coastal Plain, Central USA Plains, and the South-Central Semi-Arid Prairies. At the Level III scale, results of the scenario downscaling process indicate the Puget Lowlands, Willamette Valley, and Central California Valley as being hot-spots of urban change in the west, while the Eastern Corn Belt, Central Corn Belt, Southern Coastal Plain, Mississippi Loess Plains, Texas Blackland Prairies, and Piedmont ecoregions are common destinations in the Great Plains and East (Fig. 7). Fig. 8 shows an example of increased demand for development in the Texas Blackland Prairies and adjacent ecoregions.

Like developed, mining land use accounts for a small proportion of the total landscape. However, due to the intensity of use there are often important local to regional scale ecological implications to consider. Mining experiences overall net gains in the two economic scenarios, with gains in A2 totaling nearly 15,000 km^2 by 2100. The global environmental scenario (B1) has the largest net decline with a loss of approximately 7700 km^2. Across scenarios, the Eastern U.S. has the most variability with mining projected to range between a 71% decline in B1 to an increase of 123% in A2. Generally, the Quachita-Ozark-Appalachian Mountains ecoregion was the most important ecoregion for mining change, followed by the Mississippi Alluvial and Southern Coastal Plain, the Cold Deserts and the Warm Deserts ecoregions. In general there was more variability in mining change across ecoregions and scenarios than in developed use.

In year 2000, approximately one-quarter of the conterminous United States was classified as agriculture. Downscaling results in the four scenarios covering a range of future trends in agriculture, with the economic oriented scenarios ranging from 28% to 48%

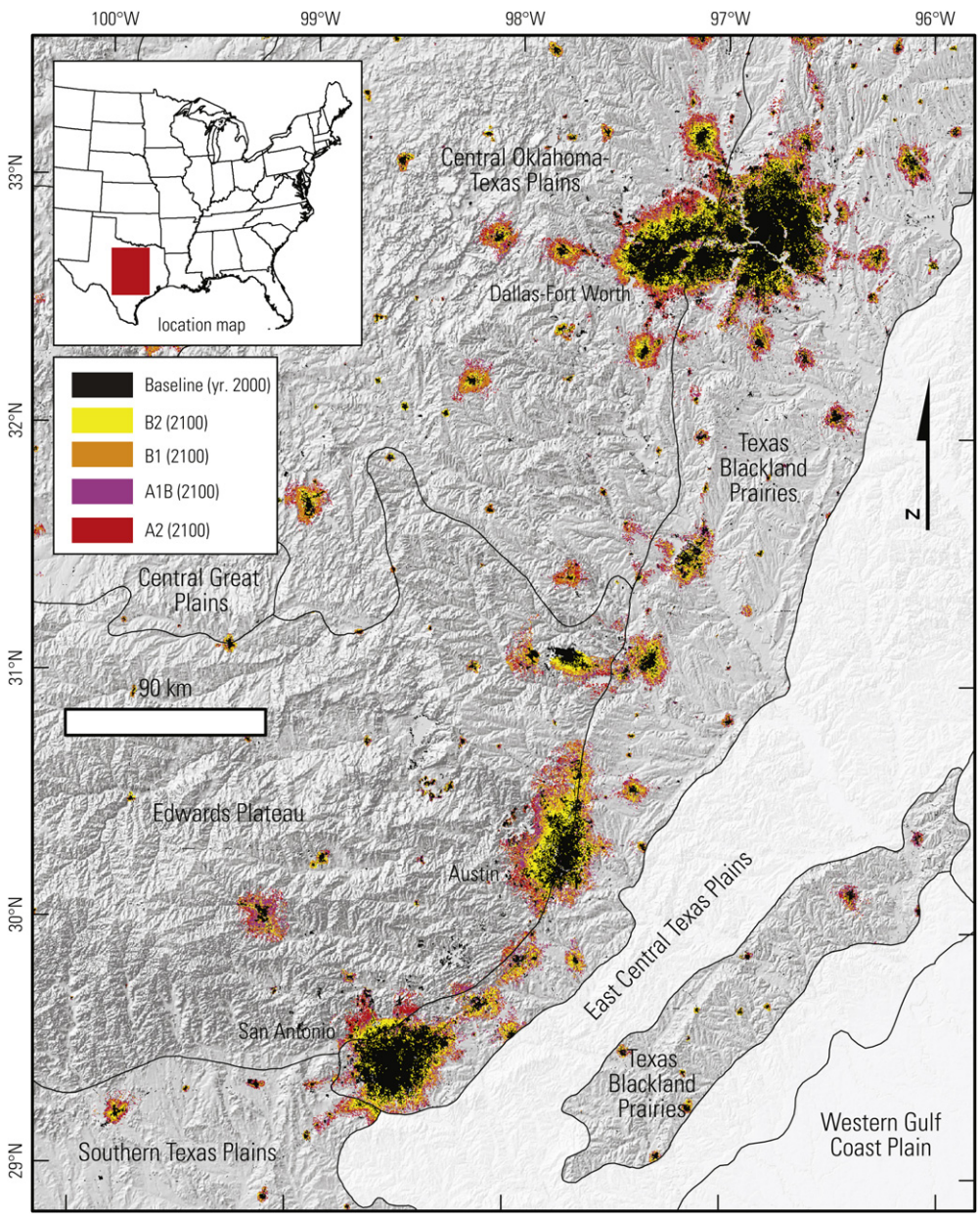

Fig. 8. Spatially explicit projection of developed land-use change in and around the Texas Blackland Prairies ecoregion. The map shows the spatial extent of developed lands in 2100. Black areas represent the baseline extent of developed land in year 2000; yellow areas are the spatial extent in the B2 scenario; orange areas are the spatial extent in the B1 scenario; magenta areas are the spatial extent in the A1B scenario; red areas are the spatial extent in the A2 scenario.

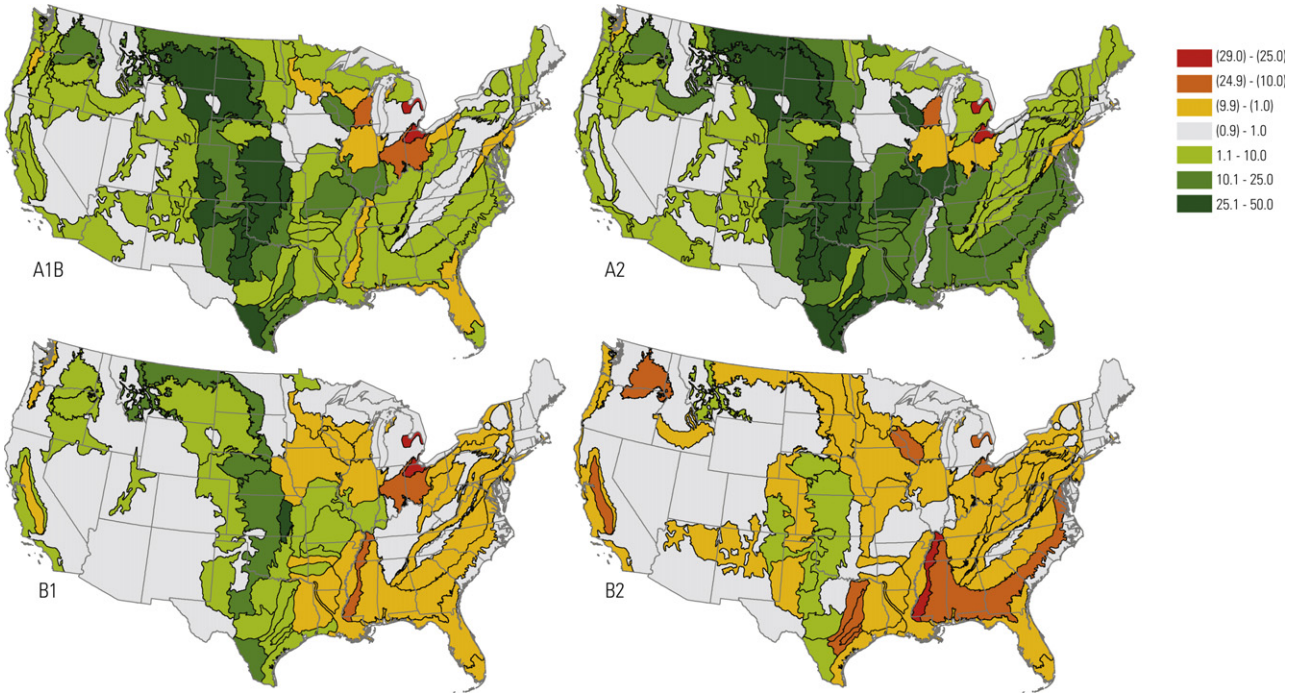

Fig. 9. Distribution of change in agricultural land use (2000–2100) by Level III ecoregion. Units are percent of ecoregion area changed.

increases in area and the environmentally oriented scenarios ranging from a 5% increase in B1 to a 12% decline in B2 (Fig. 6). With the exception of locally suitable areas in the west (i.e. Central California Valley, Columbia Plateau, Willamette Valley, and Snake River Plain ecoregions), agricultural change was most prominent in the Great Plains and Eastern U.S. regions. Due to competing land use pressures in the A1B scenario, agricultural gains in the East were below the national average (gain of 14% by 2100). Despite small increases nationally in the B1 scenario, the Eastern US experiences a decline of 8% as efforts are made to preserve natural landscapes. Conversely, the Great Plains region becomes increasingly important in terms of agricultural land use with gains of 42% in A1B, 51% in A2, and 18% in B1; the B2 scenario remains relatively stable with a decline of 3% by 2100. Despite strong gains in the economic scenarios, some ecoregions, such as the Central Plains, and to a lesser extent the Mixed Wood Plains are projected to lose agricultural land in all scenarios, primarily as a result of increased pressure to meet needs for new urban lands (Fig. 9). Biofuels are projected to be a major driver of change, more so in some scenarios and regions than others. Fig. 10 shows an example of agricultural change in the Northern Great Plains Ecoregion in the A1B and B2 scenarios. The rapid expansion of new generation biofuels, resulting from high per capita demand for energy and rapidly emerging technologies, results in wide spread expansion of land devoted to agriculture throughout the ecoregion when compared to the relative stability associated with the B2 scenario.

At the national scale, forest disturbance from logging was highest in the A1B and B2 scenarios with a cumulative total of 1.47 million km^2 and 1.32 million km^2, respectively (Table 3). The lowest amounts were associated with the globally oriented B1 scenario (0.95 million km^2) (Fig. 6). USGS Trends data show that more than 99% of all logging demand was allocated to the Western Mountains and Forests (22.2%) and Eastern US regions (77.3%) between 1973 and 2000, a pattern preserved in the scenario projections. In the Western Mountains and Forests cumulative logging totals accounted for 0.21 million km^2 (B1) to 0.33 million km^2 (A1B) for the period from 2000 to 2100; a range of 1.0–2.1% of the region during any 5-year period. In the Eastern US, logging accounted for a cumulative 0.74 million km^2 in B1 and 1.13 million km^2 in A1B; a range of 1.0–2.4% of the regions area over a 5-year period. The Southeastern Plains ecoregion was the primary destination for the nations logging with 35–41% of cutting allocated across all scenarios. The Western Cordillera was second with 17–19% of all cutting followed by the Mississippi Alluvial and Southern Coastal Plain ecoregion with 12–14%. The Mixed Wood Shield accounted for between 8% and 10% of cutting while the Marine West Coast Forest, despite accounting for only approximately 1% of the nation's land area, accounted for between 5% and 7% of the logging.

Changes in land cover (i.e. forest, grassland/shrubland, and wetland) are the result of competition for competing land uses. Land covers experience the strongest declines in the economic oriented scenarios (Fig. 6). In A1B, an area equivalent to 4.5% of the conterminous US converts out of forest while 6.6% and 0.5% convert out of grassland/shrubland and wetland, respectively. In A2, net declines are even more dramatic with areas equivalent to 8.6%, 7.1%, and 0.8% of the conterminous US moving out of forest, grassland/shrubland, and wetland, respectively. Forest declines were most typically associated with the Southeastern Plains, Quachita-Ozarks-Appalachian Mountains, and Mississippi Alluvial and Southern Coastal Plain ecoregions while net losses in grassland/shrubland were most abundant in the West-Central and South-Central Semi-Arid Prairies ecoregions (Fig. 11); wetland losses were primarily located in the Mississippi Alluvial and Southern Coastal Plain although net loss in the Prairie Pothole region of the Temperate Prairies was also a significant contributor (Fig. 6). The environmentally oriented scenarios had less loss in natural covers when compared to the economic scenarios. Forests experienced virtually no net change in the B1 scenario and a net increase of 110,000 km^2 in B2, while grassland/shrublands were projected to decline by 265,000 km^2 in B1 and increase by 15,000 km^2 in B2. Wetlands increased in both B1 (20,000 km^2) and B2 (44,000 km^2).

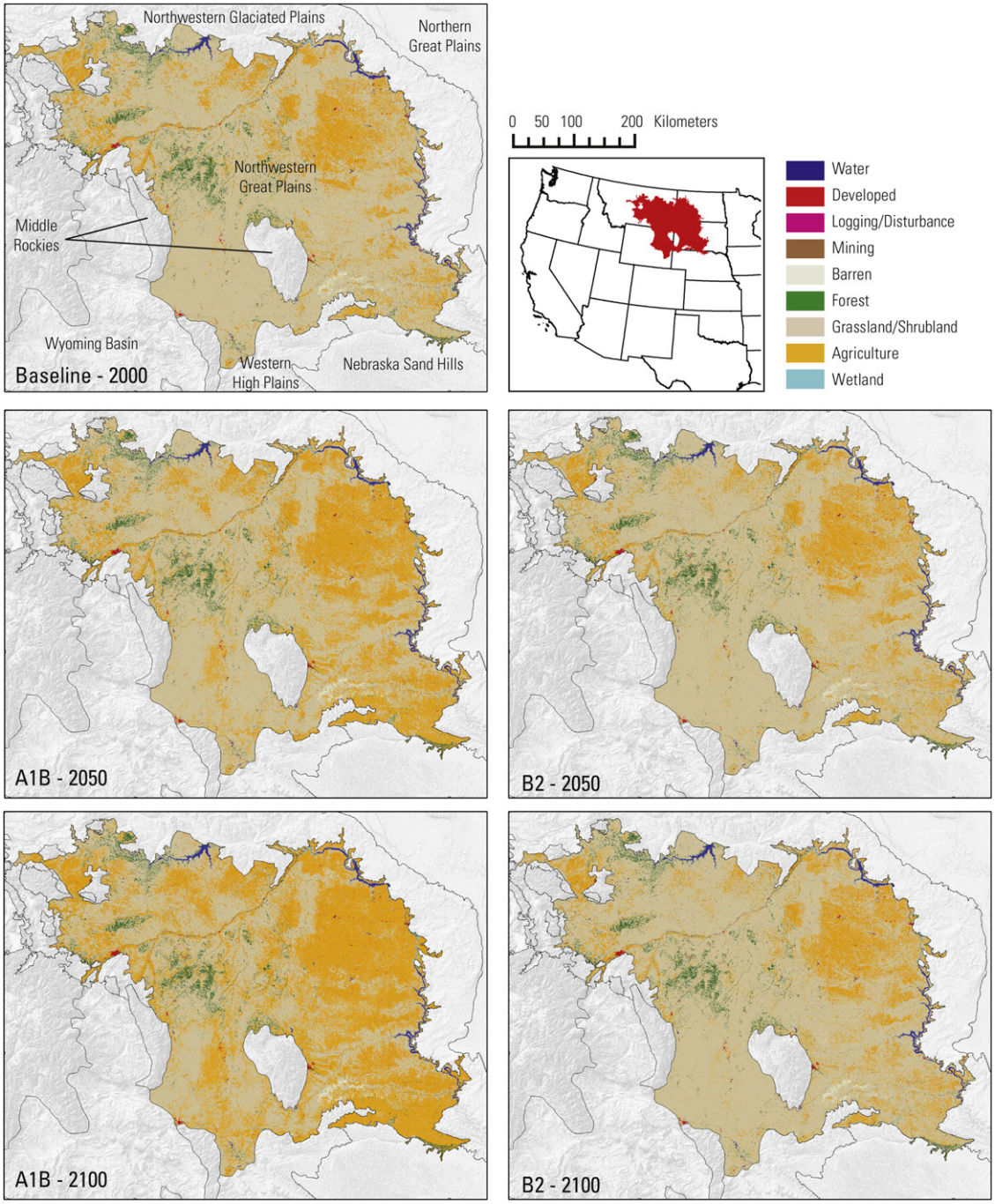

Fig. 10. Spatially explicit projection of agricultural land use change in the Northwestern Great Plains ecoregion for the A1B and B2 scenarios.

Table 3
The cumulative area of forest disturbance from logging (km^2). Note that the areal extent of logging may be less as a result of areas being harvested in more than one date.

Region	A1B	A2	B1	B2
CONUS	1,473,406	1,168,909	954,647	1,321,891
Level I/Level II				
East	1,132,159	906,318	740,324	1,024,836
Mixed Wood Shield	120,571	92,863	75,859	105,003
Atlantic Highlands	74,819	57,555	46,960	65,119
Mixed Wood Plains	35,600	27,409	22,382	30,998
Central USA Plains	933	755	646	833
Southeastern Plains	590,565	489,221	399,627	553,191
Quachita-Ozarks-Appalachian Forests	117,734	90,474	73,746	102,418
Mississippi Alluvial Southern Coastal Plain	191,937	148,041	121,104	167,274
Great Plains	5392	4361	3728	4813
Temperate Prairies	458	331	292	372
West-Central Semi-Arid Prairies	1920	2163	1255	2435

Table 3 (*Continued*)

Region	A1B	A2	B1	B2
South-Central Semi-Arid Prairies	3013	1867	2181	2005
West Deserts	2122	1947	1840	2024
Cold Deserts	424	371	339	394
Warm Deserts	1058	1041	1030	1048
Mediterranean California	640	535	471	581
West Mountains	333,733	256,283	208,755	290,218
Western Cordillera	248,637	190,549	154,903	216,001
Marine West Coast Forests	85,096	65,734	53,852	74,218

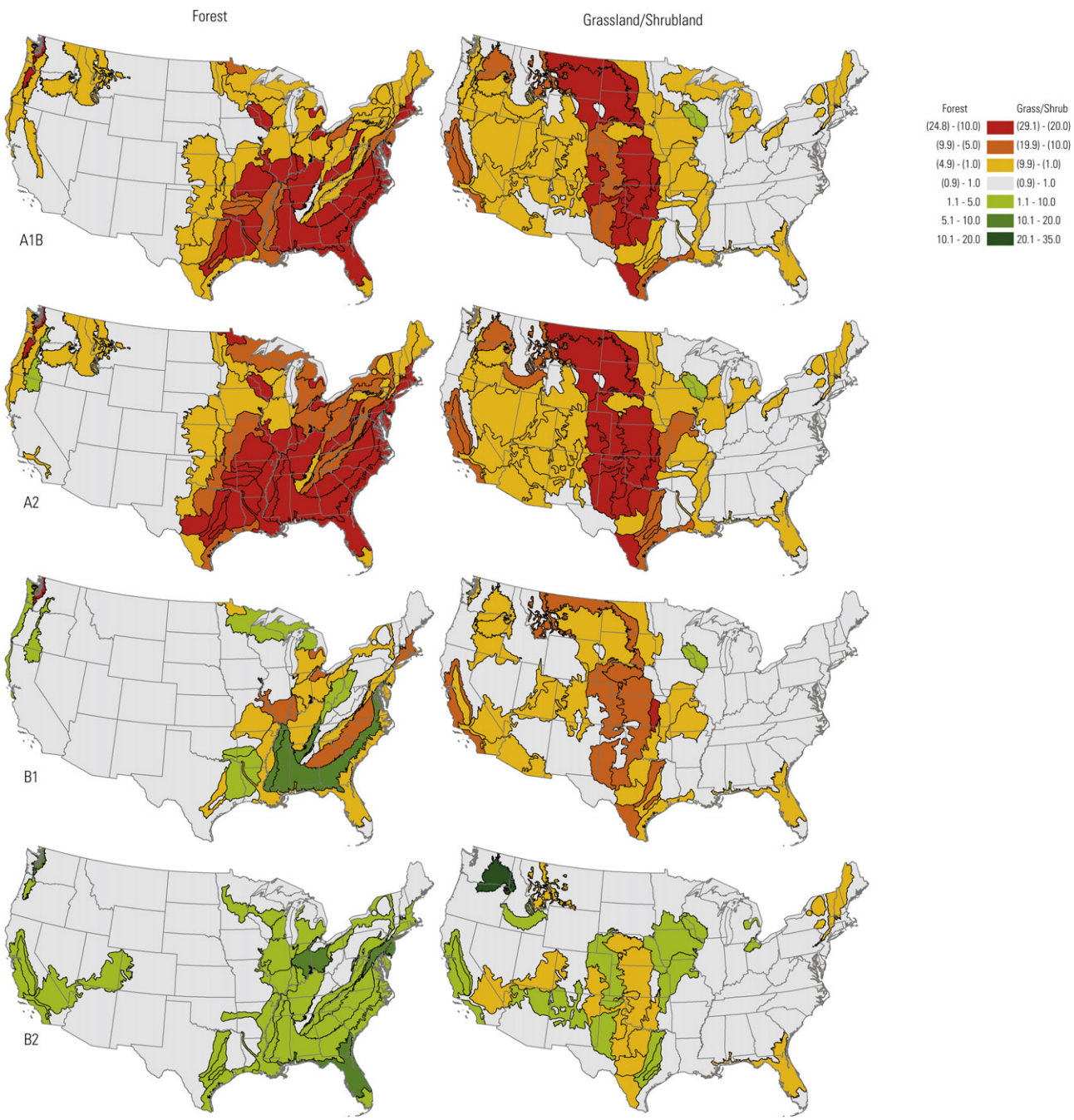

Fig. 11. Distribution of change in forest and grassland/shrubland land covers (2000–2100) by Level III ecoregion. Units are percent of ecoregion area changed.

4. Conclusion

In this paper we have presented methods and results of an effort to downscale IPCC-SRES global emission scenarios to the ecoregional scale for the conterminous United States for use in ecoregion-based environmental assessments. This was accomplished by incorporating modeling results from an integrated assessment model, LULC histories, and expert knowledge, within an accounting model framework, functioning at multiple geographic scales. The scenario-downscaling approach described here, coupled with the use of a spatially explicit LULC modeling framework, offers the opportunity to provide rich, spatially detailed, LULC information consistent with global scenario assumptions and local-scale LULC histories. Results presented here maintain consistency with the original source scenario data (i.e. IMAGE, SRES) by following the general trajectories of major land use categories as well as reflect the recent historical local-scale observations based primarily on inventory data. We believe the approach presented here provides a framework from which a range of global change assessments can be downscaled to be used at the local to regional scale. Furthermore, downscaled projections of LULC change at the ecoregion scale, such as those presented here, are an important contribution to global change science in that they provide companion products to downscaled climate data originating from a common framework (i.e. SRES).

An entirely new set of global scenarios, Representative Concentration Pathways (RCPs), are being developed for the IPCC's Fifth Assessment Report (AR5) (Moss et al., 2010). While downscaled IPCC-SRES scenarios were the primary product of this paper, flexibility of the modeling tools presented here provide the necessary framework to downscale a wide range of global environmental change frameworks, including RCPs. Research is currently underway to: (1) downscale initial RCP LULC projections using harmonized LULC data from Hurtt et al. (2009), and (2) using the same gridded fractional data produce 'backcasted' simulations of LULC to 1850. These data, along with the sheer volume of SRES-based assessments including those presented here, provide a tremendous opportunity to investigate scenario-based effects of LULC change on processes including carbon and other GHG cycling, climate, biodiversity, water quality, and other ecosystem services.

To the authors knowledge the research presented here is the most thematically and spatially detailed effort to regionalize future changes in LULC consistent with a global environmental change assessments. As such it represents only a first step in the development of tools and models. A number of improvements are needed to address a more complete set of LULC changes, including incorporation of vegetation succession models used to simulate the response of vegetation to future changes in climate and ecosystem disturbance, tighter integration with a spatially explicit wildfire simulation model, and linkage with hydrologic models to simulate fluctuations and changes in water and wetland land covers.

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