ENVIRONMENTAL SCIENCE & POLICY 21 (2012) 94–105

Available online at www.sciencedirect.com

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Forest cover, carbon sequestration, and wildlife habitat: policy review and modeling of tradeoffs among land-use change scenarios

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ARTICLE INFO

Keywords:
Climate mitigation
Carbon sequestration
Land-cover change
Environmental policy

ABSTRACT

Local and regional governments have developed climate action plans with significant implications for forests and wildlife. The effectiveness of climate mitigation through forest carbon sequestration depends on understanding the spatial and temporal dynamics of land-cover and land-use change (LCLUC). Few studies project future LCLUC effects on forest carbon sequestration, and even fewer examine the resulting consequences for forest connectivity and wildlife habitat. First, we asked what forest-relevant climate mitigation strategies have been identified in US state climate mitigation plans, and do they consider implications for wildlife habitat and forest connectivity? Second, for Wisconsin, a partially forested state, what are the effects of three future LCLUC scenarios on afforestation, forest loss, carbon sequestration and storage, forest connectivity, and wildlife habitat? The 35 US states with climate mitigation plans recommended woody biomass for biofuels or energy production (27 states), forest loss prevention (24 states), and afforestation (17 states). Most plans (24 states) anticipated positive wildlife impacts while 7 plans indicated potential negative wildlife impacts from biomass energy; only 3 plans anticipated tradeoffs among afforestation and energy production. A LCLUC model for Wisconsin revealed substantial local variation in potential afforestation and forest loss, carbon sequestration, and wildlife habitat across LCLUC scenarios that range from no change in current conditions (Static Forest) to maximum afforestation potential (All Forest). Projected increases in forest cover under the Dynamic Forest scenario equated to 0.41 TgC sequestered per year, or 1.3% of Wisconsin's emissions of 33 TgC per year. Potential increases in core forest area and connectivity would increase habitat for 60 forest-associated species of greatest conservation need, but may decrease habitat for 48 grassland-associated species of greatest conservation need. These results indicate the importance of synergistic evaluation of multiple policy goals and LCLUC scenarios to examine tradeoffs and spatial dynamics of climate change mitigation strategies.

1. Introduction

Forests provide diverse ecological, economic, and social benefits and services, including timber production, carbon sequestration and storage, scenic amenities, and wildlife habitat. International efforts to mitigate climate change through forest carbon sequestration and greenhouse gas emission reduction have captured scientific attention (Canadell and Raupach, 2008). Local and regional governments are

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http://dx.doi.org/10.1016/j.envsci.2012.04.006

increasingly moving forward with climate mitigation plans that may have important implications for forests. The effectiveness of proposed climate mitigation strategies for reducing atmospheric CO_2 concentrations depends on other land-cover and land-use change (LCLUC) drivers such as fragmentation, development, and agricultural conversion. However these relationships and the resulting patterns of forest loss and afforestation, carbon sequestration and storage, and wildlife habitat are not well understood (McKinley et al., 2011). We examined these issues through two approaches: a national policy review of US state climate mitigation plans, and a model of land-use change scenarios through 2051 for one state with forested and unforested landscapes.

The majority of US states have developed climate action plans that propose mitigation strategies with relevance for forest conservation and management. Climate change is a global issue, but forest-relevant mitigation strategies are often pursued at local to regional scales, with place-based implications for forest resources (Millar et al., 2007; Charnley et al., 2010). Simultaneous with trends toward globalization, trends toward devolution in environmental governance emphasize the role of state governments in environmental policy (Lester and Lombard, 1990). State governments have primary responsibility for private forest management and wildlife conservation (Dana and Fairfax, 1980). States may work independently to address state needs or react to opportunities created at federal or international levels.

Assessing the effectiveness of climate mitigation strategies that seek to avoid forest loss, reduce greenhouse gas emissions, and enhance carbon sequestration depends on understanding spatial and temporal dynamics of LCLUC, such as forest loss to agriculture or urban development as well as forest regeneration (Watson et al., 2000). Studies have estimated carbon sequestration potential based on historic land cover and current land use (Rhemtulla et al., 2009; Fissore et al., 2010), land ownership (Zheng et al., 2010; Failey and Dilling, 2010), or carbon tax or carbon credit price thresholds that reduce greenhouse gas emissions (Lippke and Perez-Garcia, 2008). These studies concluded that while there is substantial carbon sequestration potential for forests in the United States, that potential is unlikely to be achieved fully where the high value of row-crop agriculture and low price of carbon limit forest retention or gain. However relatively few studies consider how projections of future LCLUC may alter forest cover.

Estimating the impact of new mitigation strategies requires an analysis of additionality, or comparison with the counterfactual scenario in the absence of the intervention (Alig et al., 1997). Forest carbon is often analyzed as an aspatial resource, meaning that carbon sequestration is accounted for in total, independent of its spatial configuration. However LCLUC is driven by spatial processes with important implications for carbon sequestration patterns (de Jong, 2001). Analyses of additionality conducted for protected areas reveals that protecting forests with a low threat of forest loss results in minimal additional conservation gains (Andam et al., 2008; Byrd et al., 2009). Similarly, analysis of carbon mitigation policies must rely on future spatial projections of LCLUC, both to demonstrate additionality and to understand spatial and temporal dynamics of forest cover.

Forest loss, fragmentation, and gain have important implications for forest connectivity and wildlife habitat. Forest loss and fragmentation decrease the amount of habitat available for forest-associated species and can negatively impact area or edge sensitive species (Andren, 1994). Increases in core forest area and connectivity, and decreases in forest edge, can improve habitat conditions for many forest-associated wildlife species (Litvaitis, 1993). However, these changes may negatively impact habitat conditions for grassland-associated wildlife species, many of which have experienced marked population declines from 1960s to present concurrent with the loss of grassland in the eastern and central United States (Sauer et al., 2011).

We investigated potential synergies and tradeoffs among carbon sequestration, forest connectivity, and wildlife habitat among LCLUC scenarios. First, we asked what forest-relevant climate mitigation strategies have been identified in US state climate mitigation plans, and do they consider implications for wildlife habitat and forest connectivity? Second, what are the effects of three future LCLUC scenarios on afforestation, forest loss, carbon sequestration, forest connectivity, and wildlife habitat? We focus the scenario modeling on Wisconsin, a state with diverse ecological landscapes that span a gradient from forested to non-forested. We considered three LCLUC scenarios from no change in current conditions to maximum afforestation potential, and examined the resulting effects on carbon sequestration via afforestation and greenhouse gas emissions via forest loss. Finally, we examined the impacts of LCLUC scenarios on forest connectivity and wildlife habitat.

To answer these questions, we first review state government policies on forest-relevant climate change mitigation strategies and their consideration of wildlife habitat and spatial landscape dynamics (Section 2). We then model scenarios of land-use change to identify synergies and tradeoffs among land-cover change, carbon sequestration, and wildlife habitat across a diversity of ecological landscapes in Wisconsin (Section 3). Based on the policy review and land-use change model, we conclude with recommendations for developing and evaluating forest mitigation strategies (Section 4).

2. Review of forest-relevant state mitigation strategies

2.1. Methodology

We identified state Climate Action Plans or government reports (hereafter; plans) from an online database maintained by the Pew Center on Global Climate Change.[1] Based on these plans, we developed a list of mitigation strategies identified by state governments. We classified strategies according to their primary goal (carbon sequestration, emission reduction, combination of carbon sequestration and emission reduction, or program administration), and summarized forest-relevant strategies and recommendations. We also noted their consideration of wildlife impacts and spatial landscape dynamics such as forest connectivity and competition with alternate land uses.

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[1] http://www.pewclimate.org/what_s_being_done/in_the_states/action_plan_map.cfm (accessed 03/31/11).

2.2. Results

At least 70% of states (35 of 50) within the US have developed a climate mitigation plan (Table 1). Mitigation strategies and recommendations in these plans tended to be clearly defined with substantial overlap among states. For example, 77% of plans (27 of 35 plans) recommended woody biomass for biofuel or energy production and 69% of plans (24) recommended forest loss prevention. Half of plans (17) recommended afforestation and reforestation, sustainable management of forests, and urban forestry programs. One-quarter of plans (9) indicated that their recommended actions may positively impact forests (i.e., increase forest connectivity, reduce fragmentation, or restore function to forests). Only 3 plans expressed concern regarding potential incompatibility among mitigation strategies, specifically between afforestation and bioenergy production. Specific statements regarding potential wildlife impacts and spatial landscape dynamics varied by state. While 69% of plans (24) noted that the recommended actions may positively impact wildlife habitat (i.e., provide, improve, increase or protect habitat), only 20% of plans (7) indicated the potential for a negative impact on wildlife habitat from a mitigation strategy. Concerns for negative impacts on wildlife habitat pertained to woody biomass for biofuel or bioenergy production.

3. Implications of land-cover change for forest-relevant climate mitigation strategies

3.1. Land-cover change scenarios

We developed land-cover change scenarios for Wisconsin, a midwestern state with diverse ecological landscapes. Land cover includes a mix of agriculture, grasslands, and woodlands in southern Wisconsin and forests in northern Wisconsin. Land cover has been shaped by agrarian Native American settlement (Lentz, 2000) followed by Euro-American settlement, with large-scale forest clearing and conversion of grassland to agriculture from 1870 to 1940. Some former agricultural lands have since reverted to forest cover (Rhemtulla et al., 2007) or urban development (Rittenhouse et al., in press-b).

We considered three land-cover change scenarios that spanned a gradient from no change in existing forest cover (Static Forest) to maximum afforestation potential (All Forest), with projected land-cover change (Dynamic Forest) representing an intermediate position.

1. Static Forest – All land-cover types, including forest, held constant from 2001 to 2051 on public and private lands.
2. Dynamic Forest – All agriculture, grassland, forest, and shrubland land-cover types on private lands had a probability of transitioning to another land-cover type by 2051. We used the 2005 USGS Wisconsin GAP Stewardship Data[2] and 2009 Managed Forest Law[3] data to classify land ownership

Table 1 – Forest-relevant US state-level climate change mitigation strategies from state action plans (35 of 50 states) and their consideration of wildlife impacts and spatial landscape dynamics.

Mitigation goal	Mitigation strategy	Recommendations	Wildlife impacts	Spatial landscape dynamics
Carbon sequestration	Afforestation and reforestation	Facilitate conversion of non-forest land to forest [AZ, AR, CO, FL, HI, IA, KY, MD, MA, MI, MO, NC, OR, PA, RI, SC, WI][a] = 17	Provides, improves, or increases wildlife habitat [DE, IA, MD, MN, MO, MT, NM, NC, OR, PA, SC, WI] = 12	Increases connectivity, reduces fragmentation, or restores function to forests [DE, MD] = 2 Competes with or negatively impacts other strategies (e.g., biomass) [ME, NY, WI] = 3
	Sustainable forest management	Improve management of existing forests to sequester carbon [AK, AR, CA, CT, DE, IL, MD, MI, MN, MO, NH, NJ, NY, PA, VT, WA, WI] = 17	Provides, improves, or increases wildlife habitat [AR, HI, MD, MO, PA, WA, WI] = 7	Increases connectivity, reduces fragmentation, or restores function to forests [MD] = 1 Directs development or optimizes spatial location of resources [AR, PA] = 2
	Urban tree or urban forestry program	Increase funding and provide incentives to plant trees in urban areas [AL, AR, CT, DE, IA, MD, MA, MI, MO, MT, NC, OR, PA, RI, UT, WA, WI] = 17	Provides, improves, or increases wildlife habitat [NC, OR, PA, WA, WI] = 5	
	Forest recovery or restoration	Reforest following fire, insect, or disease mortality, or from degradation [AK, AZ, AR, MT] = 4		

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[2] USGS Wisconsin GAP Stewardship Data is a geographic information system (GIS) dataset of conservation ownership data (http://dnr.wi.gov/maps/gis/documents/USGS_GAP_WI_Stewardship.pdf).

Table 1 (*Continued*)

Mitigation goal	Mitigation strategy	Recommendations	Wildlife impacts	Spatial landscape dynamics
Emission reduction	Forest loss prevention	Protect, reduce or limit forest loss, fragmentation, parcelization or conversion to non-forest land-cover types, or tree loss in urban setting [AZ, CA, CT, DE, FL, IL, ME, MD, MA, MI, MN, NH, NJ, NM, NY, OR, PA, RI, SC, UT, VT, VA, WA, WI] = 24	Protects, provides, or maintains wildlife habitat [AZ, CT, ME, MD, MN, MT, NY, OR, SC, UT, VT, WA, WI] = 13	Increases connectivity, reduces fragmentation, or restores function to forests [AZ, CT, MO, NY, PA, WA] = 6 Considers future land-use change [PA, WA] = 2 Directs development or optimizes spatial location of resources [ME] = 1
	Catastrophic emission reduction	Thinning, prescribed fire, or biomass harvesting to reduce wildfire risk, e.g., following insect or disease outbreaks, or to improve forest health [AK, AZ, CA, CO, ME, MT, NM, OR, UT, WA] = 10	Protects wildlife habitat [CO, NM, OR, UT, WA] = 5	
	Buy local	Promote use of locally produced forest products [AR, MD, MT, VT] = 4		
Carbon sequestration and emission reduction	Woody biomass for biofuel or energy production	Promote and increase production of woody biomass for biofuel or energy production [AL, AK, AZ, AR, CA, CO, FL, IA, KY, ME, MD, MA, MI, MN, MT, NH, NM, NY, NC, OR, PA, RI, SC, UT, VT, WA, WI] = 27	Provides or improves wildlife habitat [AK, IA, NH] = 3 Reduces or impacts wildlife habitat [FL, MD, MN, SC, VT, VA, WI] = 7	Directs development or optimizes spatial location of resources [AK, NH, UT] = 3 Competes with or negatively impacts other strategies (e.g., afforestation) [NY, WI] = 2
	Wood product substitution	Require use of wood or wood products in construction and maintenance of state buildings and/or promote use of wood or wood products in private sector [CT, ME, MO, MT, NH, PA, VT, WA] = 8		
	Working lands or working forests	Protect or perpetuate working forest lands for carbon sequestration and biomass utilization [MA, MT, NM, NC, WA] = 5	Improves wildlife habitat [NC] = 1	Increases connectivity, reduces fragmentation and parcelization, or restores function to forests [NC] = 1
Program administration	Carbon accounting	Establish standards and protocols for carbon monitoring and measurement [CA, MN, OR, VA, WA, WI] = 6		
	Carbon or emissions registry	Establish registry of carbon sequestration or GHG emission projects [MA, PA, SC] = 3		

[a] *State codes*: AL = Alabama, AK = Alaska, AZ = Arizona, AR = Arkansas, CA = California, CO = Colorado, CT = Connecticut, DE = Delaware, FL = Florida, HI = Hawaii, IL = Illinois, IA = Iowa, KY = Kentucky, ME = Maine, MD = Maryland, MA = Massachusetts, MI = Michigan, MN = Minnesota, MO = Missouri, MT = Montana, NH = New Hampshire, NJ = New Jersey, NM = New Mexico, NY = New York, NC = North Carolina, ND = North Dakota, OR = Oregon, PA = Pennsylvania, RI = Rhode Island, SC = South Carolina, UT = Utah, VT = Vermont, VA = Virginia, WA = Washington, WI = Wisconsin.‘

and assign protected area status. Protected lands included all federal, state, county and tribal lands, and forestlands enrolled in Wisconsin's Managed Forest Law. Protected lands had no land-cover transition probability under this scenario.

3. All Forest – All agriculture, grassland, and shrubland land-cover types on public and private lands transition to forest by 2051.

We used the 2001 National Land Cover Dataset to establish initial conditions for all three scenarios. We grouped 2001 NLCD classes into forest (NLCD classes 41, 42, 43), agriculture (82), grassland (81), shrubland (52, 71), urban (21–24), and water (11, 12, 31, 90, 95). For the Static Forest scenario, we held current land cover constant from 2001 to 2051. Under the All Forest scenario, all agriculture, grassland, and shrubland land-cover types on private lands transitioned to forest by 2051. The resulting LCLUC maps constituted the 2051 Static Forest and the 2051 All Forest maps, respectively.

The 2051 Dynamic Forest map was based on the ''business as usual'' scenario in an econometric model of land-cover transition that permitted transitions among all non-urban and non-water land-cover classes on private lands (Radeloff et al., 2012). The econometric model explained observed land-use change trends from 1992 to 1997 as a function of current land use (agriculture, grassland, forest, urban, and shrubland), county-level net economic returns to various land uses (Lubowski et al., 2006), the economic costs of converting from one land use to another, and soil quality and agricultural potential (USDA, 1973).[4] Land-use change under the business-as-usual scenario was substantial and included a 79% increase in urban land, a 7% increase in forest cover, and declines in cropland (−16%) and grassland (−13%). This modeled increase in forest cover is consistent with the net gain of forest cover in Wisconsin from 1992 to 2001 (Rittenhouse et al., in press-a, in press-b).

We used the results of the Radeloff et al. (2012) econometric model to populate a probabilistic map for each land-cover type (i.e., a land-cover probability map). The cell values within each land-cover probability map represented the probability of a given cell being a particular land-cover type, and thus ranged from 0 to 1. We used ArcGIS to determine on a cell-by-cell basis the highest probability across all land-cover probability maps and assigned the corresponding land-cover type to a given cell, producing a 2051 land-use and land-cover map for the Dynamic Forest scenario. With the exception of existing urban areas, which had a probability of urban equal to 1 to ensure that existing urban land did not transition to a different land-cover type, the probability of transition to urban was very low. To allow for some urban growth, we tested thresholds of urban growth by assigning a value of 1 to all cells with probability of urban ≥ 0.10, ≥ 0.20, or ≥ 0.25 within the urban land-cover probability map. We chose ≥ 0.20 as the threshold for urban, which translated to a 3.31% increase in urban land cover, from 6.67% of Wisconsin in 2001 to 9.98% of Wisconsin in 2051. We used the revised 2051 Dynamic Forest, the 2051 Static Forest, and the 2051 All Forest maps for all subsequent analyses.

To assess potential changes in land cover, we tracked all transitions in a ''from–to'' fashion for each scenario. We grouped land-cover types as persistent non-forest (cropland, grassland, urban, and shrubland), non-forest change (any ''from–to'' transition among non-forest land-cover types), forest loss (any ''from forest–to non-forest''), afforestation (any ''from non-forest–to forest''), and persistent forest.

We developed the land-cover change scenarios for illustrative purposes with a goal of understanding policy implications. In so doing we also made several simplifying assumptions that downplay the interrelated roles of driving forces such as historical land cover and land use, climate variability and change, economics, technology, and government policy. First, under all three scenarios we assumed no loss of live trees to tree harvest or other sources of mortality (e.g., natural events, disease, and insects). This assumption provided a ''theoretical maximum'' scenario of carbon sequestration potential and facilitated comparison among scenarios, but overestimated the potential amount of carbon sequestered and stored by forests. Second, the basis for land-cover change under the Dynamic Forest scenario was optimal land use given economic values, based on past trends. However, additional factors such as changes in land markets and commodity prices may alter land-use trajectories inconsistent with past trends. Third, under the All Forest scenario we assumed that all agriculture, grassland, and shrubland land-cover types transitioned to forest irrespective of their potential forest productivity. Fourth, under the All Forest scenario we assumed that no other land uses would compete with forest land. In reality, and as modeled in the Dynamic Forest scenario, agriculture has a higher economic return than forest, and urban has a higher economic return than agriculture.

3.2. *Carbon sequestration potential*

We used a multi-step process to estimate aboveground carbon sequestration potential of live trees by 2051 under the Static Forest, Dynamic Forest, and All Forest scenarios. First, we used LANDFIRE Existing Vegetation Type information[5] to map existing vegetation type and forest cover for Wisconsin. The Existing Vegetation Type (EVT) layer used a predictive modeling approach based on field reference data, Landsat imagery, and spatially explicit biophysical gradient data to map EVTs at 30 m resolution. Of the 46 EVTs in Wisconsin, we grouped 14 forest EVTs into 7 forest types based on dominant tree associations: northern hardwoods, aspen-birch, elm-ash, maple-beech-birch, oak-hickory, spruce-fir, and white-red-jack pine.

Second, we used U.S. Forest Service Forest Inventory and Analysis (FIA) data to obtain initial biomass and forest type-

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[3] Wisconsin Managed Forest Law is a landowner property tax incentive program that encourages sustainable forestry (http://dnr.wi.gov/forestry/publications/pdf/FR-295.pdf).

[4] Additional details of the processes driving land-cover change in the Dynamic Forest scenario are provided in Radeloff et al. (2012).

[5] http://www.landfire.gov/NationalProductDescriptions21.php (accessed 04/21/10).

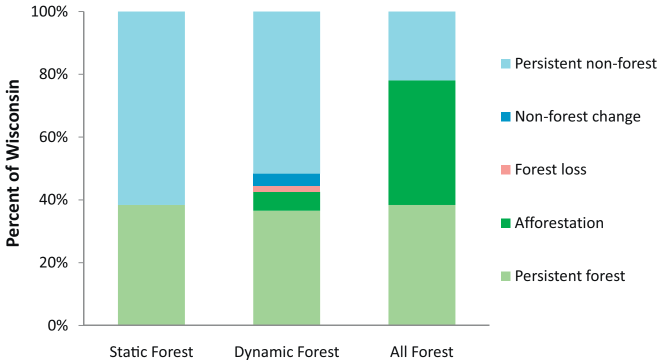

Fig. 1 – Potential land-cover composition in Wisconsin by 2051 for three land-cover change scenarios.

specific age information for Wisconsin (Blackard et al., 2008). The area-weighted mean age by forest type ranged from 36.9 yrs for aspen-birch to 64.8 yrs for maple-beech-birch and averaged 53.8 yrs across all forest types and ecoregions (i.e., statewide mean age).

Third, we used forest type-specific carbon sequestration equations to calculate aboveground carbon sequestration potential for live trees based on the proportion of each forest type within each ecological landscape (Smith et al., 2006). We distinguished existing forests from new forests that resulted from afforestation as follows. For existing forests in 2001, we estimated ecoregion-specific carbon sequestration potential to 2051 as the difference of growth from the statewide mean age of 55 yrs to 105 yrs, representing the 50-yr interval. For new forests resulting from afforestation, we approximated carbon sequestration potential as the growth of non-forest from age of 0 yrs to 25 yrs, the midpoint of the 50-yr interval, to account for uncertainty associated with when afforestation may begin during the interval. By using year 25 as the mid-point, as opposed to the mid-point of the carbon accumulation curve to year 50, we underestimated carbon accumulation by 6% (elm-ash) to 26% (pine). We assumed natural regeneration of tree species in the same proportion as the current composition of tree species within each ecological landscape. We expressed carbon in TgC/ha.

3.3. *Co-benefits and tradeoffs with forest connectivity and wildlife habitat*

Our review of mitigation plans indicated that 20% of plans (7 of 35 plans) considered the potential negative impacts to wildlife habitat or landscape planning that may result from implementing the recommended actions. We used findings of our review to refine our spatial modeling project to explicitly incorporate LCLUC impacts on carbon sequestration capacity and spatial attributes of forest cover. Retaining the spatial context allowed for quantification of changes in forest attributes that contribute to wildlife habitat.

We used morphological spatial pattern analysis to classify spatial patterns of forest cover and quantify forest core, connector (or bridge), and patch area (Soille and Vogt, 2009) from the Static Forest, Dynamic Forest, and All Forest maps. Morphological spatial pattern analysis consisted of a sequence of logical operations conducted within a moving window of specified size. We used a 3 by 3 cell window size, equivalent to an 8-cell neighborhood surrounding the center (focal) cell. We used a cell size of 100 m and specified a size parameter of 1 cell, meaning that core forest was at least 100 m (1 cell) from the forest–non-forest boundary. Core forest was assigned to the center cell provided all cells within the window contained forest. Connector forest was defined as forest that connected at least two different core forest areas, but did not itself contain core forest (i.e. consisted of forest edge only). Patch forest was defined as isolated forest that was too small to contain core forest.

We quantified potential impacts of land-cover change (i.e., gain or loss of habitat) for species of greatest conservation need in Wisconsin using the Wisconsin Department of Natural Resources' online database.[6] We included 58 bird species, 16 reptile species, 5 amphibian species, and 14 mammal species that were moderately or significantly associated with grassland, northern forest, and southern forest natural communities, as designated in the online database. We obtained population trend information for bird species of greatest conservation need from the North American Breeding Bird Survey (Sauer et al., 2011).

3.4. *Results*

3.4.1. *Land-cover change*

Potential land-cover change under the Static Forest, Dynamic Forest, and All Forest scenarios reflected a gradient from no change to maximum possible afforestation. The Static Forest Scenario, which maintained current land-cover types from 2001 to 2051, resulted in 38.4% persistent forest in Wisconsin (Fig. 1). Under the Dynamic Forest scenario, afforestation was only 6.0% and forest loss was 1.8% based on land-cover change trends, for a total of 42.6% forest cover in Wisconsin. The majority (55.6%) of Wisconsin remained in non-forested land-cover types under the Dynamic Forest scenario. The All Forest scenario, which allowed all agriculture, pasture, and shrubland to afforest, resulted in afforestation of 39.7% of Wisconsin's lands, for a total of 78.1% forest cover in Wisconsin.

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[6] http://dnr.wi.gov/org/land/er/biodiversity/ (accessed 04/05/11).

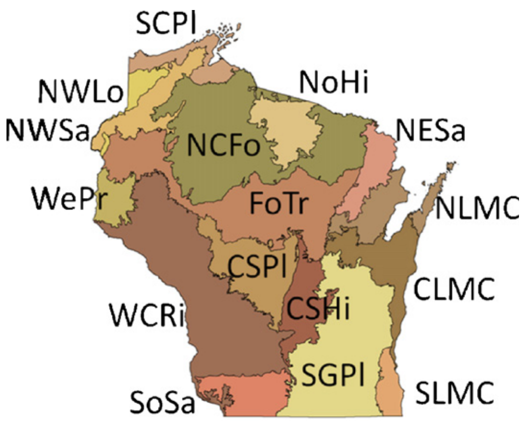

Fig. 2 – Ecological landscapes of Wisconsin. CLMC: Central Lake Michigan Coastal; CSHi: Central Sand Hills; CSPl: Central Sand Plains; FoTr: Forest Transition; NCFo: North Central Forest; NESa: Northeast Sands; NLMC: Northern Lake Michigan Coastal; NoHi: Northern Highland; NWLo: Northwest Lowlands; NWSa: Northwest Sands; SCPl: Superior Coastal Plain; SGPl: Southeast Glacial Plains; SLMC: Southern Lake Michigan Coastal; SoSa: Southwest Savanna; WCRi: Western Coulee & Ridges; WePr: Western Prairie.

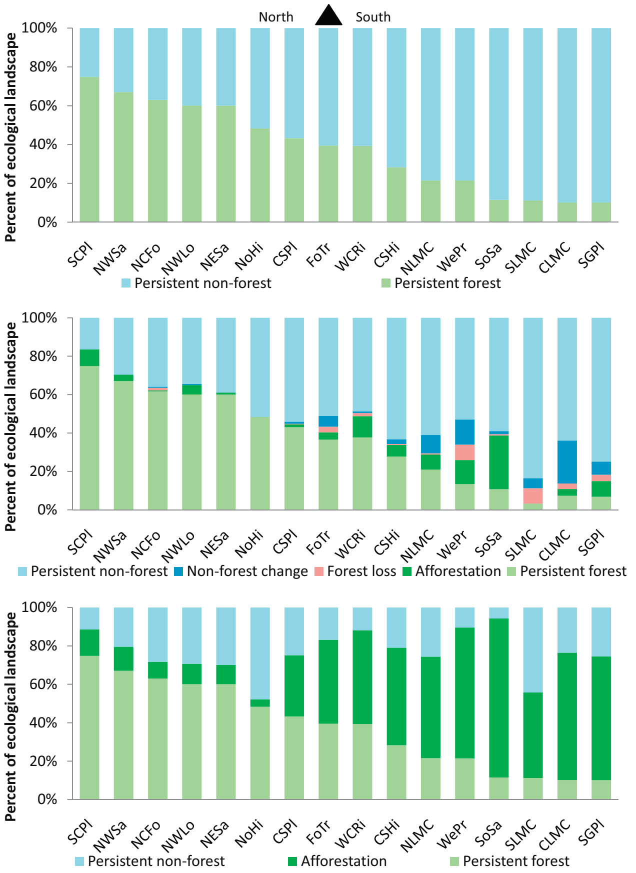

Fig. 3 – Potential land cover in 2051 by ecological landscape of Wisconsin for the Static Forest (upper), Dynamic Forest (middle), and All Forest (lower) scenarios of land-cover change.

Among ecological landscapes[7] (Fig. 2), afforestation potential under the All Forest scenario varied with the proportion of persistent non-forest land cover, which consisted of urban and water (Fig. 3). Ecological landscapes with a high proportion of persistent non-forest land cover also had high potential for afforestation. Among all ecological landscapes, the Western Coulee and Ridges and the Southeast Glacial Plains had the greatest area of afforestation, while the predominantly forested ecological landscapes had the least area of afforestation (Fig. 4). These results were expected given the initial proportion of persistent non-forest land cover within these two large ecological landscapes.

In contrast to the All Forest scenario, the Dynamic Forest scenario had a limited potential for afforestation due to retention of existing agriculture, pasture, and shrubland within many ecological landscapes, as well as land-cover transitions among non-forest land-cover types instead of conversion to forest (Fig. 3). Forest loss to urban expansion occurred in 11 of 16 ecological landscapes, with the greatest losses by area occurring in the Southeast Glacial Plains and the Forest Transition ecological landscapes (Fig. 4). A net loss of forest cover (i.e., forest loss exceeded afforestation) occurred in the North Central Forest and the Southern Lake Michigan Coastal ecological landscapes. The greatest net gain in forest area occurred in the Western Coulee and Ridges, Southwest Savanna, and Southeast Glacial Plain ecological landscapes.

3.4.2. *Carbon sequestration potential*

Carbon sequestration and storage from 2001 to 2051 varied among land-cover change scenarios and ecological landscapes in a pattern that mirrored modeled changes in forest cover. Compared to the 121 TgC stored in forests in 2001, carbon sequestration and storage potential was 267 TgC under the Static Forest Scenario (221% increase from 2001), 288 TgC under the Dynamic Forest scenario (238% increase), and 440 TgC under the All Forest scenario (363% increase). Note that these figures represent the theoretical maximum carbon sequestration and storage under each scenario assuming no tree harvest or mortality besides LCLUC. Compared to the Static Forest scenario, the greatest potential changes in carbon sequestration and storage under the All Forest scenario was in the Southeast Glacial Plains and Western Coulee and Ridges ecological landscapes (Fig. 5). The Northwest Lowlands and the Northern Highland ecological landscapes had the lowest potential change in carbon sequestration and storage. Under the Dynamic Forest scenario, the North Central Forest, Forest Transition, and Southern Lake Michigan Coastal ecological landscapes had net loss of carbon due to forest loss.

3.4.3. *Co-benefits and tradeoffs with forest connectivity and wildlife habitat*

Our analysis provided insights into potential benefits and tradeoffs for wildlife due to land-cover change. Under the All Forest scenario, a general pattern of increased core forest area is evident for all

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[7] http://dnr.wi.gov/landscapes/ (accessed 04/28/11).

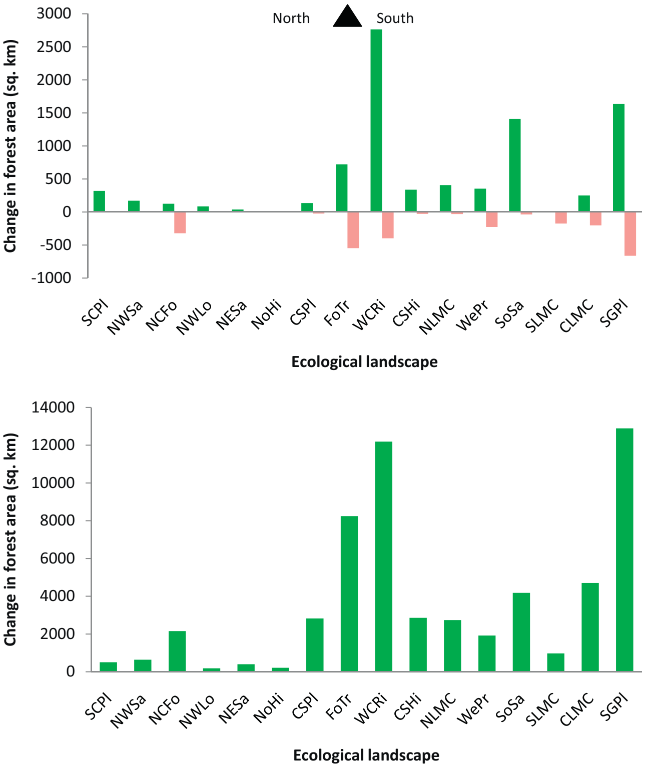

Fig. 4 – Change in forest area from Static Forest scenario via afforestation (dark green) or forest loss (pink) by ecological landscape, under the Dynamic Forest (upper) and All Forest (lower) scenarios of land-cover change in Wisconsin by 2051. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

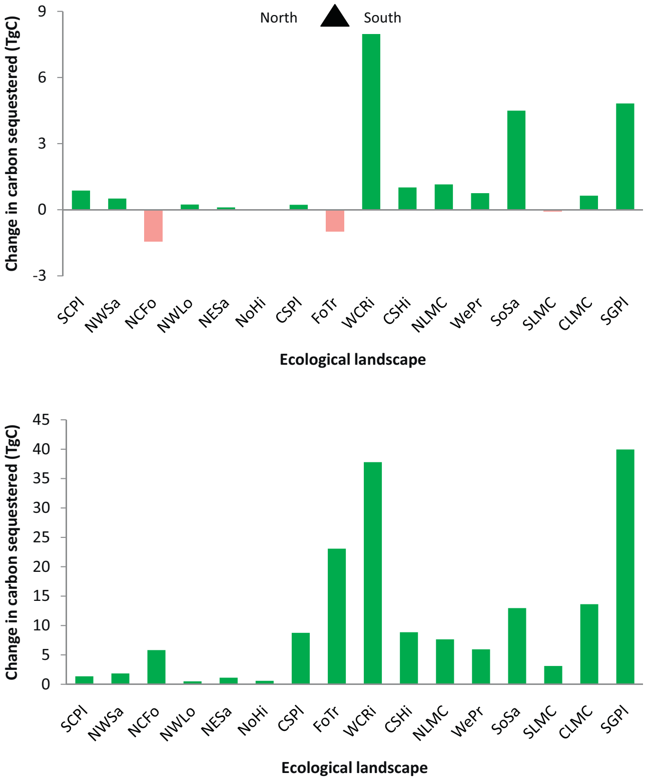

Fig. 5 – Change in carbon sequestered from Static Forest scenario for Dynamic Forest (upper) and All Forest (lower) scenarios of land-cover change in Wisconsin by 2051.

ecological landscapes (Fig. 6). In predominantly non-forest ecological landscapes, afforestation decreased the area of connector forests and forest patches. This result was expected as those forest types were assimilated into core forest. Under the Dynamic Forest scenario, the impacts of forest loss and change among non-forest land-cover types affected the magnitude and direction of changes in forest attributes. In the predominantly non-forested ecological landscapes of central and southern Wisconsin, increases in connector forest exceeded increases in core forest area (Fig. 6). Among ecological landscapes, the Western Coulee and Ridges, Superior Coastal Plain, and Southwest Savanna ecological landscapes had the greatest increases in core forest area.

The changes in core forest area and connectivity among core forests present clear tradeoffs for biodiversity and population trends of forest-associated versus grassland-associated wildlife species. While the increases in core forest area and connectivity among core forests would increase habitat for some forest-associated species of greatest conservation need in Wisconsin, which include 34 bird, 12 reptile, 3 amphibian, and 11 mammal species, the increases in forest area would come at the expense of loss of pasture land (grassland) to afforestation. Thus, afforestation could negatively impact habitat for grassland-associated species of greatest conservation need, including 25 bird, 16 reptile, 3 amphibian, and 4 mammal species in Wisconsin. Based on known population trend information for bird species of greatest conservation need (Sauer et al., 2011), nearly twice as many grassland (80%, 12 of 15 species) as forest bird species (39%, 7 of 18 species) had significant negative population trends from 1968 to 2009.

4. Moving forward: challenges and opportunities for forest-relevant climate change mitigation

State governments are increasingly developing and implementing climate change mitigation strategies in the United States and elsewhere. Our review of US state government climate change mitigation plans identified 12 mitigation strategies with important implications for forests. The majority of plans encouraged woody biomass for biofuel or bioenergy production and avoided forest loss, while half recommended afforestation, modification of forest management practices to sequester additional carbon, and enhancement of urban forests. Few state government reports considered how mitigation strategies might impact wildlife, forest connectivity, or other societal goals for forests.

4.1. *Incorporating spatial and temporal dynamics of land-cover change*

Our analysis of land-cover change scenarios revealed that even in the absence of additional incentives, land-cover

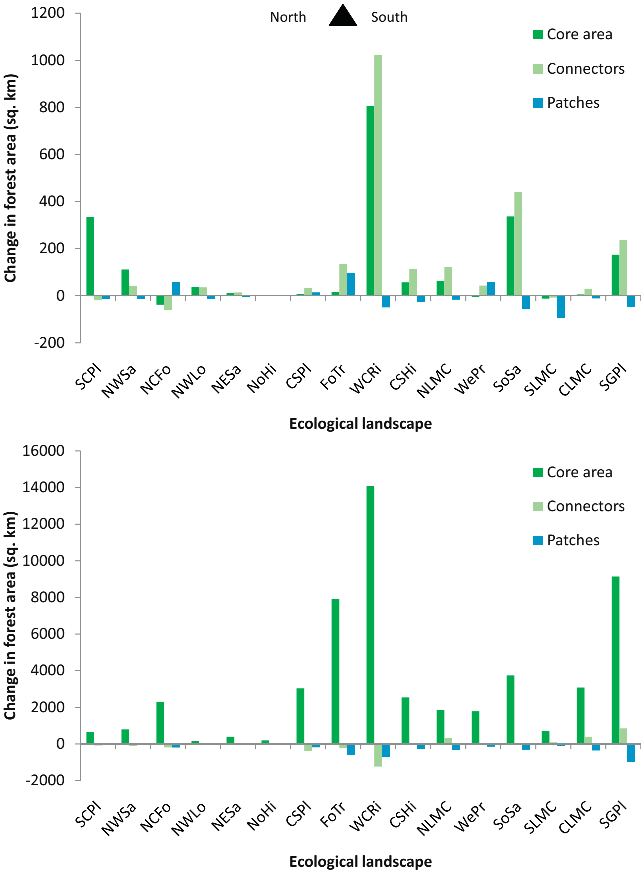

Fig. 6 – Change in forest attributes from Static Forest scenario for Dynamic Forest (upper) and All Forest (lower) scenarios of land-cover change in Wisconsin by 2051.

change will have a substantial impact on the potential for afforestation and forest loss in Wisconsin. The scenarios were designed to indicate an extreme range of policy-relevant conditions, rather than a prediction for the future. The Dynamic Forest scenario modeled likely future land-use change based on current land use, net returns to various land uses, the costs of converting from one land use to another, soil quality, and agricultural potential. This scenario provided the most realistic estimate of future land use, and therefore a potential counterfactual or baseline for the evaluation of climate mitigation policy interventions. The Dynamic Forest scenario revealed ecological landscapes where avoided deforestation efforts could achieve the greatest gains by preventing high probability forest loss to urban development. It also revealed where afforestation is likely to occur without any additional incentives. Analysts may be tempted to use the Static Forest scenario, equivalent to current land-cover maps, for policy development and evaluation. We caution that the use of the Static Forest scenario would underestimate potential carbon sequestration from afforestation by 7.6% statewide and 1–1430% depending on ecological landscape, as well as underestimate potential carbon loss from forest loss by 1–85% depending on ecological landscape, compared to the Dynamic Forest scenario.

While afforestation was projected to exceed forest loss statewide under the Dynamic Forest scenario, resulting in a net gain of carbon sequestered, ecological landscapes within the state spanned a gradient with respect to land-cover change and carbon sequestered. Ecological landscapes in northern Wisconsin were relatively static with respect to land-cover change, carbon sequestration, and forest attributes compared to southern Wisconsin. For example, only 8% of the additional 22.8 TgC sequestered by 2051 under the Dynamic Forest scenario, compared to the Static Forest scenario, came from northern Wisconsin. Even within southern Wisconsin, 76% of the carbon sequestered came from only three ecological landscapes: Western Coulee and Ridges (35%), Southeast Glacial Plains (21%), and Southwest Savanna (20%). We view this north–south distinction as an indicator of where opportunities to promote afforestation exist. Most climate change mitigation and adaptation planning efforts have focused on public forest lands in northern Wisconsin (Swanston and Janowiak, 2012). Our results indicate that southern Wisconsin may also play an important role in climate change mitigation, warranting greater consideration of private forestland and currently non-forested lands.

For the most part, afforestation and forest loss to urbanization were spatially disjunct within ecological landscapes. Only within a few ecological landscapes was there potential for both afforestation and forest loss to occur in proximity, which would impact carbon sequestration policies. A concern with the proximity of afforestation strategies and efforts to protect existing forests in an urbanizing area is the high potential for leakage, or an unanticipated change in greenhouse gas emissions outside of an area (Schwarze et al., 2002). This could arise, for example, from efforts to protect forests from development or agriculture that ultimately shift those activities to other forests. However, it may be difficult to predict or regulate development pressure due to heterogeneity in initial forest conditions and development, land owner decision processes, and zoning regulations (Butsic et al., 2010). A step toward identifying and preventing leakage is to consider the project within a broad socio-economic and geographic scope (Chomitz, 2002). At present there are several national (Alig, 2003; Alig and Butler, 2004; Radeloff et al., 2010; Theobald, 2010) and regional (Tyrrell et al., 2004; Sohl and Sayler, 2008) projections of land-cover change that could be utilized for policy development and evaluation in the United States.

4.2. *Adapting existing programs for mitigation*

Nearly 90% of states with climate action plans (31 of 35) proposed greater carbon sequestration, including afforestation and reforestation, sustainable forest management, urban forestry, and forest recovery or restoration programs. The All Forest scenario demonstrated that even in the unlikely future in which afforestation occurs on all agriculture, pasture, and shrubland, afforestation alone will not offset Wisconsin's annual emissions. The projected increases in forest cover under the All Forest scenario equated to 3.46 TgC sequestered per year, or 10.5% of Wisconsin's emissions of 33 TgC per year (Governor's Task Force on Global Warming, 2008). Achieving additional carbon sequestration and storage from forests will require identifying not only where but also when and what types of policies to enact.

Existing policies, including the federal Conservation Reserve Program (CRP)[8] and state forest property tax programs, could be adapted to provide mechanisms for additional forest-based carbon sequestration. CRP successfully used financial incentives to compensate land owners for limiting agricultural activities on marginal lands, and approximately 9% of CRP lands afforested from 1986 to 1995 (Barker et al., 1995), with demonstrable improvements in wildlife habitat (Johnson and Schwartz, 1993; Ryan et al., 1998) and soil organic carbon sequestered (Johnson et al., 2005). Based on past trends, the Dynamic Forest scenario projected that existing CRP lands (as of 2007) will comprise 11% of afforestation occurring in Wisconsin by 2051. However, this trend may not hold in the face of high corn prices that are shifting expiring CRP lands into agricultural production. Further, expiring CRP contracts have been considered for potential biomass-based energy production. For example, an Energy-Crop Reserve Program (E-CRP), identified in our policy review and described in Wisconsin's plan (Governor's Task Force on Global Warming, 2008), would provide financial incentives to grow biomass for energy production. E-CRP proposals primarily considered perennial grasses such as switchgrass, not woody biomass, for energy production. Should E-CRP or similar programs be enacted, afforestation rates on pasture lands and marginal agricultural lands would likely decline.

Forest property tax laws exist in all 50 states and provide incentives via payments or a reduction in property taxes for sustainable forest management (Hibbard et al., 2001). These programs require a minimum acreage of forest land for enrollment, which could be reduced to promote afforestation, provided enrolled properties commit to expansion of forest area and a long-term contract (e.g., 50 yrs; Governor's Task Force on Global Warming, 2008). Forest property tax laws typically require a forest management plan, which could be amended to incorporate carbon sequestration as a component of sustainable forest management. Modifications such as extending rotation age, maintaining site productivity, or retaining greater residual basal area at harvest could enhance carbon sequestration or retain carbon sequestered (Foley et al., 2009; Ray et al., 2009; Nunery and Keeton, 2010).

4.3. *Identifying tradeoffs between climate mitigation, wildlife habitat, and forest connectivity*

Our land-cover change analysis revealed likely tradeoffs among mitigation strategies, specifically that afforestation will conflict with existing land uses of agriculture and pasture, as well as with biomass for energy production. Yet our policy review found that few states considered these inherent tradeoffs when managing for energy production versus carbon sequestration (Righelato and Spracklen, 2007). Further, tradeoffs among afforestation, energy production, and carbon sequestration extended to wildlife habitat and presented important policy and management decisions regarding forest-associated and grassland-associated species of greatest conservation need. In Wisconsin, efforts to manage grassland birds will require habitat restoration among multiple sites due to loss of native grasslands and grass-based agriculture, whereas efforts to manage forest birds have focused on maintenance of forested landscapes and improving forest structure (A. Paulios, Wisconsin Department of Natural Resources, pers. comm.). Biomass for energy production that reduces grassland habitat will likely impact biodiversity and wildlife populations. Similar tradeoffs exist for predominantly forested states that historically contained grasslands or vice versa. Based on our findings, we offer two suggestions to improve the evaluation and decision-making process regarding climate mitigation, wildlife habitat, and forest connectivity.

First, analyze carbon within a spatial and temporal context to facilitate identification of links between land-cover change, wildlife habitat, and mitigation strategies. Many US states have determined the cost-effectiveness of mitigation strategies without explicit consideration of future LCLUC dynamics, the local and regional contexts that contribute to additionality and leakage, and other policy goals in the decision process. Cost-effectiveness determination is useful for ranking and prioritizing mitigation strategies based on cost per unit carbon, but may be insufficient for accommodating other policy goals with unspecified market value such as wildlife habitat and forest connectivity. In the absence of valuation, spatial models provide important information on current and future landscape composition and structure that complements cost-effectiveness studies.

Second, recognize potential tensions between global governance and local implementation. Global to national policy can set goals, develop standards and protocols, and model system change. Yet many policies will be implemented in specific local contexts. State-level policy review and modeling bridges these scales by examining regional variability in land-use trends, carbon sequestration capability, and wildlife habitat. We encourage efforts that integrate state agencies, local stakeholders, and policy makers in the policy evaluation and decision process.'

Acknowledgements

We thank V.C. Radeloff for the projections of land-cover change, E.A. Padley and K.J. Martin for their contributions to study design and manuscript review, undergraduate research assistant L. Straka, and two anonymous reviewers.

REFERENCES

Alig, R.J., 2003. U.S. landowner behavior, land use and land cover changes, and climate change mitigation. Silva Fennica 37, 511–527.

Alig, R.J., Adams, D., McCarl, B., Callaway, J., Winnett, S., 1997. Assessing effects of carbon mitigation strategies for global climate change with an intertemporal model of the U.S. forest and agriculture sectors. Environmental & Resource Economics 9, 259–274.

Alig, R.J., Butler, B.J., 2004. Projecting large-scale area changes in land use and land cover for terrestrial carbon analyses. Environmental Management 33, 443–456.

Andam, K.S., Ferraro, P.J., Pfaff, A., Sanchez-Azofeifa, G.A., Robalino, J.A., 2008. Measuring the effectiveness of protected area networks in reducing deforestation. Proceedings of the

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[8] www.nrcs.usda.gov/programs/crp/ (accessed 03/31/11).

National Academy of Sciences of the United States of America 105, 16089–16094.

Andren, H., 1994. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. Oikos 71, 355–366.

Barker, J.R., Baumgardner, G.A., Turner, D.P., Lee, J.J., 1995. Potential carbon benefits of the Conservation Reserve Program in the United States. Journal of Biogeography 22, 743–751.

Blackard, J.A., Finco, M.V., Helmer, E.H., Holden, G.R., Hoppus, M.L., Jacobs, D.M., Lister, A.J., Moisen, G., Nelson, M.D., Riemann, R., Ruefenacht, B., Salajanu, D., Weyermann, D.L., Winterberger, K.C., Bradeis, T.J., Czaplewski, R.L., McRoberts, R.E., Patterson, P.L., Tymcio, R.P., 2008. Mapping U.S. forest biomass using nationwide forest inventory data and moderate resolution information. Remote Sensing of Environment 112, 1658–1677.

Butsic, V., Lewis, D.J., Radeloff, V.C., 2010. Lakeshore zoning has heterogeneous ecological effects: an application of a coupled economic-ecological model. Ecological Applications 20, 867–879.

Byrd, K.B., Rissman, A.R., Merenlender, A.M., 2009. Impacts of conservation easements for threat abatement and fire management in a rural oak woodland landscape. Landscape and Urban Planning 92, 106–116.

Canadell, J.G., Raupach, M.R., 2008. Managing forests for climate change mitigation. Science 320, 1456–1457.

Charnley, S., Diaz, D., Gosnell, H., 2010. Mitigating climate change through small-scale forestry in the USA: opportunities and challenges. Small-scale Forestry 9, 445–462.

Chomitz, K.M., 2002. Baseline, leakage and measurement issues: how do forestry and energy projects compare? Climate Policy 2, 35–49.

Dana, S.T., Fairfax, S.K., 1980. Forest Range and Policy: Its Development in the United States. McGraw-Hill Book Company, New York, NY, 458 pp.

de Jong, B.H.J., 2001. Uncertainties in estimating the potential for carbon mitigation of forest management. Forest Ecology and Management 154, 85–104.

Failey, E.L., Dilling, L., 2010. Carbon stewardship: land management decisions and the potential for carbon sequestration in Colorado, USA. Environmental Research Letters 5, 24005, http://dx.doi.org/10.1088/1748-9326/5/2/024005.

Fissore, C., Espeleta, J., Nater, E.A., Hobbie, S.E., Reich, P.B., 2010. Limited potential for terrestrial carbon sequestration to offset fossil-fuel emissions in the upper midwestern US. Frontiers in Ecology and the Environment 8, 409–413.

Foley, T.G., Richter, D. de B., Galik, C.S., 2009. Extending rotation age for carbon sequestration: a cross-protocol comparison of North American forest offsets. Forest Ecology and Management 259, 201–209.

Governor's Task Force on Global Warming, 2008. Wisconsin's Strategy for Reducing Global Warming. , 232 pp.

Hibbard, C.M., Kilgore, M.A., Ellefson, P.V., 2001. Property tax programs focused on forest resources: a review and analysis. Staff Paper Series No. 150. Department of Forest Resources, University of Minnesota, St. Paul, MN.

Johnson, D.H., Schwartz, M.D., 1993. The Conservation Reserve Program and grassland birds. Conservation Biology 7, 934–937.

Johnson, J.M.F., Reicosky, D.C., Allmaras, R.R., Sauer, T.J., Venterea, R.T., Dell, C.J., 2005. Greenhouse gas contributions and mitigation potential of agriculture in the central USA. Soil & Tillage Research 83, 73–94.

Lentz, D.L. (Ed.), 2000. Imperfect Balance: Landscape Transformations in the Precolumbian Americas. Columbia University Press, New York, NY.

Lester, J.P., Lombard, E.N., 1990. The comparative analysis of state environmental policy. Natural Resources Journal 30, 301–319.

Lippke, B., Perez-Garcia, J., 2008. Will either cap and trade or a carbon emissions tax be effective in monetizing carbon as an ecosystem service. Forest Ecology and Management 256, 2160–2165.

Litvaitis, J.A., 1993. Response of early successional vertebrates to historic changes in land use. Conservation Biology 7, 866–873.

Lubowski, R.N., Plantiga, A.J., Stavins, R.N., 2006. Land-use change and carbon sinks: econometric estimation of the carbon sequestration supply function. Journal of Environmental Economics and Management 51, 135–152.

McKinley, D.C., Michael, G.R., Birdsey, R.A., Giardina, C.P., Harmon, M.E., Heath, L.S., Houghton, R.A., Jackson, R.B., Morrison, J.F., Murray, B.C., Pataki, D.E., Skog, K.E., 2011. A synthesis of current knowledge on forests and carbon storage in the United States. Ecological Applications 21, 1902–1924.

Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications 17, 2145–2151.

Nunery, J.S., Keeton, W.S., 2010. Forest carbon storage in the northeastern United States: net effects of harvesting frequency, post-harvest retention, and wood products. Forest Ecology and Management 259, 1363–1375.

Radeloff, V.C., Nelson, E., Plantinga, A.J., Lewis, D.J., Helmers, D., Lawler, J.J., Withey, J.C., Beaudry, F., Martinuzzi, S., Butsic, V., Lonsdorf, E., White, D., Polasky, S., 2012. Economic-based projections of future land use in the conterminous United States under alternative policy scenarios. Ecological Applications 22, 1036–1049.

Radeloff, V.C., Stewart, S.I., Hawbaker, T.J., Gimmi, U., Pidgeon, A.M., Flather, C.H., Hammer, R.B., Helmers, D.P., 2010. Housing growth in and near United States protected areas limits their conservation value. Proceedings of the National Academy of Sciences of the United States of America 107, 940–945.

Ray, D.G., Seymour, R.S., Scott, N.A., Keeton, W.S., 2009. Mitigating climate change with managed forests: balancing expectations, opportunity, and risk. Journal of Forestry 107, 50–51.

Rhemtulla, J.M., Mladenoff, D.J., Clayton, M.K., 2007. Regional land-cover conversion in the U.S. upper Midwest: magnitude of change and limited recovery in Wisconsin (1850–1935–1993). Landscape Ecology 22, 57–75.

Rhemtulla, J.M., Mladenoff, D.J., Clayton, M.K., 2009. Historical forest baselines reveal potential for continued carbon sequestration. Proceedings of the National Academy of Sciences of the United States of America 106, 6082–6087.

Righelato, R., Spracklen, D.V., 2007. Carbon mitigation by biofuels or by saving and restoring forests? Science 317, 902.

Rittenhouse, C.D., Padley, E.A., Martin, K.J., Rissman, A.R. Past and potential future land cover change around Wisconsin's State Forests. Research Report. Wisconsin Department of Natural Resources, Madison, WI, in press.

Rittenhouse, C.D., Pidgeon, A.M., Albright, T.P., Culbert, P.D., Clayton, M.K., Flather, C.H., Radeloff, V.C. Land-cover change and avian diversity in the conterminous United States. Conservation Biology, in press.

Ryan, M.R., Burger, L.W., Kurzejeski, E.W., 1998. The impact of CRP on avian wildlife: a review. Journal of Production Agriculture 11, 61–66.

Sauer, J.R., Hines, J.E., Fallon, J.E., Pardieck, K.L., Ziolowski Jr., D.J., Link, W.A., 2011. The North American Breeding Bird Survey, Results and Analysis 1966–2009. Version 3.23.2011. USGS Patuxent Wildlife Research Center, Laurel, MD, USA.

Schwarze, R., Niles, J.O., Olander, J., 2002. Understanding and managing leakage in forest-based greenhouse-gas-mitigation projects. Philosophical Transactions of the Royal Society of London, Series A 360, 1685–1703.

Smith, J.E., Heath, L.S., Skog, K.E., Birdsey, R.A., 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. General Technical Report NE-343. USDA Forest Service, Northeastern Research Station, Newton Square, PA, USA, 216 pp.

Sohl, T., Sayler, K., 2008. Using the FORE-SCE model to project land-cover change in the southeastern United States. Ecological Modelling 9, 49–65.

Soille, P., Vogt, P., 2009. Morphological segmentation of binary patterns. Pattern Recognition Letters 30, 456–459.

Swanston, C.W., Janowiak, M.K. (Eds.), 2012. Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers. General Technical Report NRS-87. USDA Forest Service, Northern Research Station, Newtown Square, PA, USA, 121 p.

Theobald, D.M., 2010. Estimating natural landscape changes from 1992 to 2030 in the conterminous US. Landscape Ecology 25, 999–1011.

Tyrrell, M.L., Hall, M.H.P., Samlpon, R.N., 2004. Dynamic models of land use change in northeastern USA-developing tools, techniques, and talents for effective conservation action. GISF Research Paper 003. Program on Private Forests, Yale University, 84 pp.

U.S. Department of Agriculture, Natural Resources Conservation Service, 1973. National Soil Survey Handbook, Title 430-VI. Available from: http://soils.usda.gov/technical/handbook/.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J., Dokken, D.J. (Eds.), 2000. Land Use, Land-Use Change and Forestry: A Special Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, p. 377.

Zheng, D., Heath, L.S., Ducey, M.J., Butler, B., 2010. Relationships between major ownerships, forest aboveground biomass distributions, and landscape dynamics in the New England region of USA. Environmental Management 45, 377–386.

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