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Vegetation and land carbon projections for Wisconsin, USA, in the 21st century

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ABSTRACT: In this sudy, a dynamic vegetation model is forced by statistically downscaled climate projections across Wisconsin for the 21st century, produced by the Wisconsin Initiative on Climate Change Impacts using climate output from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. The mean climate projection is substantial warming and an increase in cool-season precipitation. Drying soil leads to reduced tree cover across southern and western Wisconsin, establishing a more prairie-like environment. Along with a statewide reduction in evergreen tree cover and increase in deciduous tree cover, the tension zone shifts northward, potentially out of the state by the end of the century. Projected climate change produces a dramatic loss of terrestrial carbon, primarily from vegetation during the first half of the century and from both vegetation and soil in the second half. Carbon fertilization should partly offset this loss of carbon to the atmosphere. Projected transfers of carbon from terrestrial vegetation to the atmosphere are larger for higher-end climate-change scenarios. The land carbon projections for Wisconsin in this study have critical implications to the state's future plans to reduce atmospheric greenhouse gas concentrations through focused efforts to cut emissions.

KEY WORDS: Terrestrial carbon · Dynamic vegetation modeling · Climate change · Tension zone · Carbon fertilization · Wisconsin

1. INTRODUCTION

As atmospheric greenhouse gas concentrations continue to rise, the general climatic projections for the Midwest United States include higher temperatures, an increase in cool-season precipitation, a longer growing season, more heat waves, and an increased frequency of extreme precipitation events (Wuebbles & Hayhoe 2004, Diffenbaugh et al. 2005, Christensen et al. 2007). All of these changes, except an increase in heat waves, are already occurring in Wisconsin, according to observations from the previous 6 decades by Serbin & Kucharik (2009) and Kucharik et al. (2010). One of the products of the Wisconsin Initiative on Climate Change Impacts (WICCI; www.wicci.wisc.edu) has been a high-resolution, statistically downscaled dataset of climate projections across the state of Wisconsin for the mid- and late 21st century, based on the Climate Model Intercomparison Project Phase 3 (CMIP3) global climate models (GCMs) used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4). The numerous working groups of WICCI are applying this downscaled dataset to assess risks to the state's resources and to develop adaptation strategies (WICCI 2011). Based on these data for Wisconsin, Notaro et al. (2010a, 2011) projected a substantial reduction in snowfall and snow depth and a dramatic northward shift in plant hardiness zones (geographic areas where specific plant categories can grow, based on climatic conditions) during the 21st century.

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There are 2 primary means to counter anthropogenic climate change: mitigation and adaptation. Wisconsin has the goal of reducing greenhouse gas emission levels to 75% below the 2005 level by the year 2050 (DNR 2008). This would consist of an annual reduction of 94 million metric tons of equivalent carbon dioxide. The largest sources of greenhouse gas emissions in Wisconsin include utilities, transportation, and industry, comprising 71% of total 2003 emissions. Recognizing that Wisconsin's forests are a substantial sink of atmospheric carbon (~37 tC ha^{-1}; Brown et al. 2008) with opportunity for further carbon sequestration (Rhemtulla et al. 2009), the Governor's Task Force (DNR 2008) developed a series of forestry-related mitigation strategies for the state. They advocated voluntary mitigation programs with incentives to increase terrestrial sequestration, with the recommendation that the success of these voluntary programs be assessed in 2012 in consideration of mandatory measures. The task force encouraged afforestation and reforestation, the establishment of urban forests, prairie planting, and improved soil management practices to increase carbon storage in agricultural soils.

The Forestry Working Group of WICCI focuses on the risks to Wisconsin's forests imposed by climate change and adaptation strategies that may lessen those risks. In the WICCI report (WICCI 2011), the Forestry Working Group makes the following conclusions: (1) The rate of climate change may exceed species' maximum dispersal rates, increasing mortality rates for species with poor mobility. (2) Wisconsin's forests are vulnerable to changes in soil moisture, with young forests being particularly sensitive. (3) The projected warming should lead to increased abundances of the central hardwood trees, including hickory, black oak, and black walnut. (4) However, summer warming and late summer droughts should be harmful to boreal species, particularly species along the southern edge of their range such as aspen, white birch, white spruce, black spruce, balsam fir, and red pine. The suitable habitat for these species may shift into northern Minnesota and the upper peninsula of Michigan. The Forestry Working Group recommends monitoring sites for forest ecosystems (to track changes in wildlife species, trees, shrubs, and herbs), consideration of assisted migration, the establishment of corridors of contiguous habitat that aid in migration, and management techniques that increase biodiversity and landscape connectivity.

The Chequamegon-Nicolet National Forest Climate Change Response Framework, funded by the US Department of Agriculture, has focused more specifically on risk assessment and adaptation strategy development for Wisconsin's northern woods. Northern Wisconsin contains much of the infrastructure of the state's forest industry, including 63% of the state's sawmills, and is a recreational hub for camping, hunting, fishing, boating, and bird watching. The ecosystem vulnerability report for the Chequamegon-Nicolet National Forest (Swanston et al. 2011) combined analyses using a landscape model (Scheller et al. 2007) and species distribution models (Prasad et al. 2007) and concluded that the suitable habitat for many of Wisconsin's tree species will move northward, with the loss of boreal tree species.

Paleo-reconstructions involving the biological tension zone (Curtis 1959, 1971), which cuts through Wisconsin, reveal how climate change can dramatically alter the ecological landscapes of the state. The tension zone largely separates boreal forests, mixed conifer-hardwood forests, and pine savannas across northern Wisconsin from tallgrass prairies, oak savannas, and southern-hardwood forests across southern Wisconsin, while also representing a gradient in insect and bird species (Curtis 1959, Gromme 1963, Medler & Carney 1963). Soils are primarily loamy to the north and silty loam to the south of the tension zone (Kassulke & Mladenoff 2009). Pollen records indicate pronounced shifts in the tension zone during the Holocene (Webb & Bryson 1972, Webb 1974, Griffin 1997). The tension zone was positioned across southern Wisconsin around 10000 BP, as the glaciers retreated, and shifted north of its current location ~4000 BP, in response to mid-Holocene warming and drying (Griffin 1997). Jones et al. (1994) projected a northward shift of the tension zone across Michigan in response to future warming.

Given that Wisconsin's forests are a substantial carbon pool, which could be threatened by climate change, it is essential to develop 21st century ecological and terrestrial carbon pool projections based on statistical and dynamical models and the latest climate change scenarios. Here, we force a dynamic vegetation model with a range of statistically downscaled climate projections and a couple of atmospheric carbon dioxide projections to assess the response of Wisconsin's natural vegetation and terrestrial carbon budget. This study addresses the following questions: (1) How will climate change affect Wisconsin's ecosystems and the tension zone ecotone? (2) How will Wisconsin's terrestrial carbon pool respond to climate change in the 21st century? (3) How will carbon dioxide fertilization affect ecosystems' responses to climate change in Wisconsin?

Table 1. Summary of the 9 global climate models (GCMs) from CMIP3 used to force the Lund-Potsdam-Jena (LPJ) model, including the originating group and country, model name, and reference

Originating group	Country	Model ID	Source
Canadian Centre for Climate Modelling & Analysis	Canada	CGCM3.1 (T63)	Flato et al. (2000)
Météo-France / Centre National de Recherches Météorologiques	France	CNRM-CM3	Déqué et al. (1994)
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.0	Gordon & O'Farrell (1997)
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.5	Gordon et al. (2002)
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.0	Delworth et al. (2006)
Institut Pierre Simon Laplace	France	IPSL-CM4	Dufresne & Friedlingstein (2000)
Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan	MIROC3.2(medres)	Hasumi & Emori (2004)
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group	Germany, Korea	ECHO-G	Roeckner et al. (1996)
Meteorological Research Institute	Japan	MRI-CGCM2.3.2	Kitoh et al. (1995)

In Section 2, the methods are presented, including the statistical downscaling, vegetation model, and simulations. Results and discussion are provided in Sections 3 and 4, respectively.

2. METHODS

Output from 9 global climate models (Table 1) for the 21st century is statistically downscaled across Wisconsin and used to drive a dynamic vegetation model to predict how future climate change and atmospheric carbon dioxide levels might affect the state's ecology and land carbon pools.

2.1. Statistical downscaling

Output from 9 of the Climate Model Intercomparison Project Phase 3 (CMIP3) global climate models (GCMs) (Meehl et al. 2007) (Table 1) is statistically downscaled for WICCI, using a method that preserves the observed mean, variance, and extremes of daily temperature and precipitation (Notaro et al. 2011, WICCI 2011). The downscaling method includes debiasing, which is vital given the significant regional biases over Wisconsin, with most CMIP3 global models exhibiting a wet bias in winter and warm, dry bias in summer (Notaro et al. 2011). These global models are characterized by coarse spatial resolutions and rather simple representations of convection and atmospheric boundary layer processes, so their reliability on a regional scale is limited. Statistical downscaling enhances this regional reliability by establishing an observed relationship between the large-scale atmospheric circulation pattern and local meteorological conditions and then applying that relationship to the large-scale circulation as produced by the global climate models, which is generally well represented.

The WICCI downscaled data consist of daily maximum and minimum temperature and daily precipitation amount for the domain surrounding Wisconsin (42.1°–47.1° N, 93.4°–86.6° W) on a 0.1° × 0.1° grid. Based on CMIP3 data availability (particularly the availability of daily precipitation), statistical downscaling of 9 CMIP3 models is performed for the late 20th century (1961 to 2000) using historical 20th-Century Climate in Coupled Models (20C3M) simulations (forced by increased greenhouse gas levels as observed in the 20th century) and also the mid- (2046 to 2065) and late (2081 to 2100) 21st century for the A2 and B1 emission scenarios. In order to generate a continuous series of downscaled data for 2001 to 2100, the annual cumulative distribution functions are interpolated across the gap periods and the daily meteorology is supplied from other independent simulations.

According to the IPCC's Special Report on Emissions Scenarios (IPCC 2001), A2 and B1 represent high and low end emission scenarios, with atmospheric carbon dioxide levels rising from 374 ppmv in 2000 to either 820 or 550 ppmv by 2100, respectively. Under the A2 scenario, the global population continues to rise, countries are self-reliant, technology changes are slow and fragmented, and economic development is regionally-orientated. Under the B1 scenario, the population rises until 2050 and then declines, economic growth is rapid, clean and efficient technologies are introduced, and an emphasis is placed on global solutions to environmental, social, and economic stability.

The statistical downscaling methodology, as further described by Notaro et al. (2011), occurs in 2 stages. First, the statistical relationship between the large-scale atmospheric state and local temperature/precipitation at weather stations is determined for each calendar month from the observational record. Second, this established statistical relationship is applied to predict the local temperature and precipitation, given a GCM's large-scale atmospheric state. The relationship between the large-scale atmospheric state and the weather stations is cross validated for all variables and seasons by alternately leaving out 3 yr of data, fitting the remaining years and testing the fit on the left-out data. Based on this cross validation, all statistical relationships are found to be robust.

In order to both simulate the variability and extremes and to properly account for the effect of the large-scale pattern on the weather at a point, the large-scale atmospheric state is related to the probability density function (PDF) (not a single value) of temperature and precipitation at a point. The large-scale atmospheric state does not completely determine the evolution of the atmosphere at small scales. To create a specific downscaled time series of temperature and precipitation at a point, we draw random numbers from the particular PDF for each individual day in the record. There are an infinite number of possible time series given the large-scale atmospheric evolution, and we call these possible outcomes 'realizations'. The current study applies 3 random climate realizations, thereby allowing us to better quantify the spread in ecological projections.

2.2. Vegetation model and simulations

We apply the Lund-Potsdam-Jena dynamic global vegetation model (LPJ-DGVM) (Sitch et al. 2003, Gerten et al. 2004), which consists of a modular framework that combines eco-physiological and ecological treatments of terrestrial vegetation dynamics, carbon cycling, and water cycling. LPJ represents both fast processes, such as photosynthesis and canopy conductance, and slow processes, such as competition for resources, biomass allocation, growth, establishment, mortality, soil and litter biogeochemistry, natural fire disturbances, and successional vegetation changes. LPJ represents natural vegetation with 10 plant functional types (PFTs), including 8 woody plants, and C3 and C4 grasses, but does not consider anthropogenic land use. LPJ successfully simulates the mean global vegetation distribution (Sitch et al. 2003), interannual vegetation responses to climate variability (Lucht et al. 2002), global fire patterns (Thonicke et al. 2001), and key hydrologic variables, including runoff, evapotranspiration, and soil moisture (Sitch et al. 2003, Wagner et al. 2003, Gerten et al. 2004). The model contains a 0.5 m upper soil layer, with an embedded 20 cm surface evaporative layer, and a lower 1 m soil layer. LPJ applies the photosynthesis model of Farquhar & von Caemmerer (1982), as simplified by Collatz et al. (1991, 1992) and Haxeltine & Prentice (1996) for global modeling purposes.

A major focus of this study is on the effects of climate change on Wisconsin's terrestrial carbon pools. Carbon storage in the terrestrial biosphere is assessed as the balance between net primary productivity (NPP) through photosynthesis and carbon losses through decomposition, land use, and disturbances (e.g. fire) (Foley & Ramankutty 2004). NPP represents the net flux of carbon from the atmosphere into green plants in a specified time period. It is computed as the difference between the gross primary productivity (GPP; rate at which plants capture and store chemical energy through photosynthesis) and total autotrophic respiration (sum of maintenance respiration for leaves, roots, and sapwood and plant growth respiration). In LPJ, terrestrial (or land) carbon consists of carbon sequestered in vegetation (leaves, heartwood, and sapwood), litter, and soil. During decomposition, a portion of the litter known as the highly labile fraction is directly respired to the atmosphere as carbon dioxide, while the remaining litter enters the intermediate and slow soil organic matter (SOM) pools (Foley 1995, Sitch et al. 2003). The litter has a fast decomposition rate of 2.86 yr, while the intermediate and slow SOM pools have rates of 33.3 and 1000 yr, respectively (Meentemeyer 1978, Foley 1995, Sitch et al. 2003). This litter decomposition rate of 2.86 yr is the litter turnover rate at 10°C, computed by dividing the total litter by the total litterfall. The decomposition of above- and below-ground litter and SOM is enhanced by moist soils and high temperatures, the latter of which follows the modified Arrhenius relationship (Lloyd & Taylor 1994, Sitch et al. 2003). Fire consumes above-ground litter and puts carbon dioxide into the atmosphere.

The input data to LPJ include monthly-mean gridded surface air temperature, precipitation, cloud cover fraction, and number of wet days (≥1 mm) mo^{-1} from the WICCI downscaled data for 1961 to 2100. Each simulation begins with a 1000 yr spin-up from a bare-ground state for the carbon pools to reach equilibrium. Given that monthly cloud cover fraction was not available in the WICCI data, it is estimated using multiple linear regression from monthly-mean maximum and minimum temperature, and precipitation. For 7 select stations in the domain (in Wisconsin: Madison, Milwaukee, Greenbay, LaCrosse; in Minnesota: Rochester, Duluth; and in Iowa: Dubuque), monthly-mean maximum and minimum temperature, and precipitation are obtained from the National Oceanic and Atmospheric Administration (NOAA), and monthly cloud cover is retrieved from the Historical Sunshine and Cloud Dataset for the US (Karl & Steurer 1990). For each calendar month, regression formulas are developed between the predictors of monthly maximum and minimum temperature, and precipitation, and the predictant of monthly cloud cover using 21 to 40 yr of observational data among these 7 stations. The correlations between the actual and predicted monthly cloud cover for each calendar month were all statistically significant ($p < 0.01$), with a mean correlation of 0.61 ($N = 256$, based on 7 stations and 21 to 40 yr of data per station). The regression formulas are then applied to temperature and precipitation in the WICCI dataset to estimate monthly cloud cover.

Beyond climate inputs, LPJ also requires annual carbon dioxide concentrations and the distribution of soil categories. Annual concentrations of atmospheric carbon dioxide, another input to LPJ, are retrieved from the Carbon Dioxide Information Center (CDIAC) at Oak Ridge National Laboratory. An input soil dataset is developed using the State Soil Geographic (STATSGO) Soil Dataset, compiled by the Natural Resources Conservation Service of the Department of Agriculture and made available through the NOAA website. The STATSGO data indicate that southern Wisconsin is mostly silt loam and northern Wisconsin is mostly sandy loam. Based on these data, a $0.1° \times 0.1°$ map of the distribution of 7 LPJ soil types is produced, with fine-medium-coarse and medium soil types being most common in Wisconsin. In order to improve the simulation of the tension zone, the upper limit of the warmest month's temperature for boreal tree species in LPJ is changed from 23 to 22°C.

Four primary ensembles of LPJ experiments are created. In the A2fixCO2 and A2 ensemble sets, LPJ is forced by downscaled WICCI data of 3 realizations from 9 CMIP3 GCMs ($N = 27$ simulations) according to the A2 emission scenario during 1961 to 2100. The atmospheric carbon dioxide level is specified based on CDIAC observations during 1961 to 2000. Then, during 2001 to 2100, it either remains constant at 374 ppmv in the A2fixCO2 ensemble or rises to 820 ppmv by 2100 in the A2 ensemble. Similarly, the B1fixCO2 and B1 ensemble sets are created. Vegetation responds to climate change in A2fixCO2 and B1fixCO2 and to both climate change and carbon fertilization in A2 and B1. A2 and B1 are considered high-end and low-end carbon dioxide emission scenarios, but as of 2010, the observed atmospheric carbon dioxide concentration (390 ppm at Mauna Loa) most closely matches the A2 projection (390 ppm in A2 versus 388 ppm in B1), according to the ISAM carbon model (Kheshgi & Jain 2003). We consider uncertainty in climate projections, carbon dioxide emissions, and LPJ parameterization by considering projections from 9 different climate models, analyzing 2 contrasting emission scenarios, and either including or excluding the carbon dioxide fertilization effect on vegetation, respectively. An additional set of LPJ sensitivity experiments is performed (NoFire), similar to A2fixCO2 but with the fire module turned off. A comparison between A2fixCO2 and NoFire reveals the importance of trends in fire on projected changes in PFT distributions.

2.3. Additional datasets

The distribution of the 16 ecological landscapes of Wisconsin is obtained from the Wisconsin Department of Natural Resources. The percentage of crop cover across Wisconsin is retrieved from the Agricultural Lands in the Year 2000 dataset (Ramankutty et al. 2008), with the most common crops being hay, corn, alfalfa, and soybeans (USDA 1999). Fig. 1 serves as a reference for the distribution of the tension zone, 16 ecological landscapes, and agricultural lands of Wisconsin. For calculations that are specific to the natural regions of Wisconsin, the projected change in a variable within a grid cell is multiplied by the fraction of natural land within that grid cell (equal to: 1 – crop cover fraction). For the purpose of model validation, monthly remotely sensed NPP estimates from Moderate Resolution Imaging Spectroradiometer (MODIS 17A3), on a $1° \times 1°$ grid for 2000 to 2006, are retrieved from the University of Montana (Zhao & Running 2010).

We apply the Web-based, Water-Budget, Interactive, Modeling Program (WebWIMP; http://climate.geog.udel.edu/~wimp) to assess the climatically averaged, monthly water balance for Wisconsin, based on the modified Thornthwaite procedure (Willmott et al. 1985). In WebWIMP, we specify water holding capacity of soil to be 75 and 50 mm in southern (43° N, 89° W) and northern (45.5° N, 90° W) Wisconsin, respectively, based on data from the US Department of Agriculture (http://soils.usda.gov/use/worldsoils/mapindex/whc.html).

3. RESULTS

3.1. Climate of Wisconsin

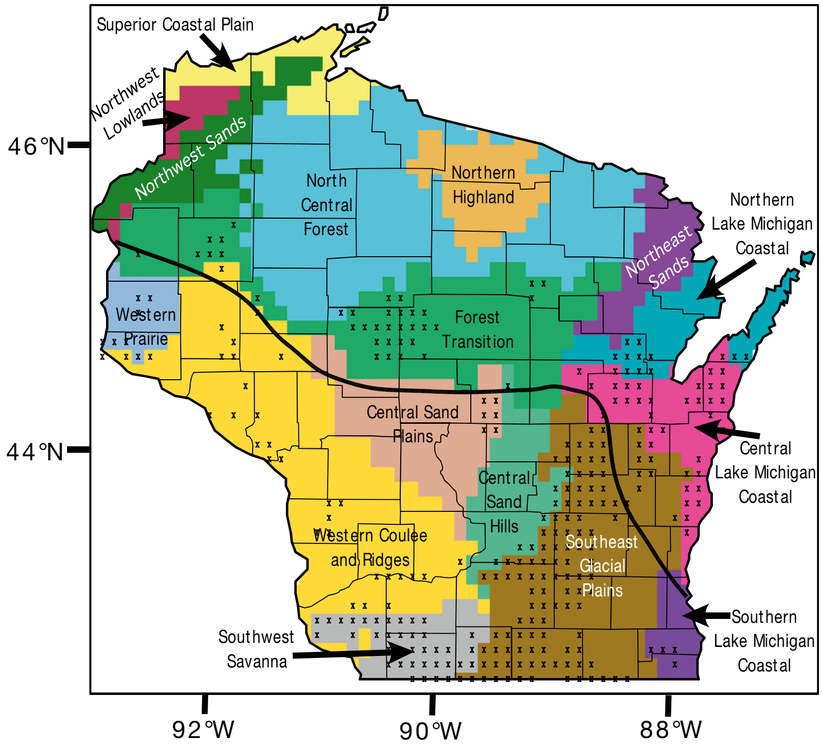

Fig. 1. Distribution of the 16 ecological landscapes of Wisconsin (Wisconsin Department of Natural Resources, http://dnr.wi.gov/topic/landscapes). X: regions with at least 50% crop cover (Ramankutty et al. 2008). Black curve: Curtis (1959, 1971) tension zone

Wisconsin is characterized by a fully humid, temperate continental climate, with cold winters and warm to hot summers (Moran & Hopkins 2002). Specifically, the Köppen climate classifications for southern and northern Wisconsin are Dfa (hot summer continental climate) and Dfb (warm summer continental climate), respectively (Fig. 2). During winter (DJF), the polar front and associated jet stream are typically located south of Wisconsin, so that winds across Wisconsin are primarily west-northwesterly and the most frequent air masses are polar and originate over the North Pacific (Bryson & Hare 1974, Moran & Hopkins 2002). As these polar air masses pass over the northern Rocky Mountains, they dry significantly before arriving in Wisconsin, so that winter is the driest season in the state. During summer (JJA), the polar front and mid-latitude jet stream are typically positioned north of Wisconsin. Humid Gulf and dry Pacific air masses reach Wisconsin at roughly equal frequencies during summer (Moran & Hopkins 2002). Based on the water balances computed by WebWIMP, there is a substantial soil moisture surplus during spring and autumn and a mild deficit during late summer across Wisconsin.

3.2. Climate projections

Statistically downscaled climate projections are examined for Wisconsin from 9 GCMs in CMIP3 (Table 1) for the A2 and B1 emission scenarios (Fig. 3). On average, the CMIP3 models project an increase in annual surface air temperature by the mid-21st century of 3.4 or 2.5°C for the A2 and B1

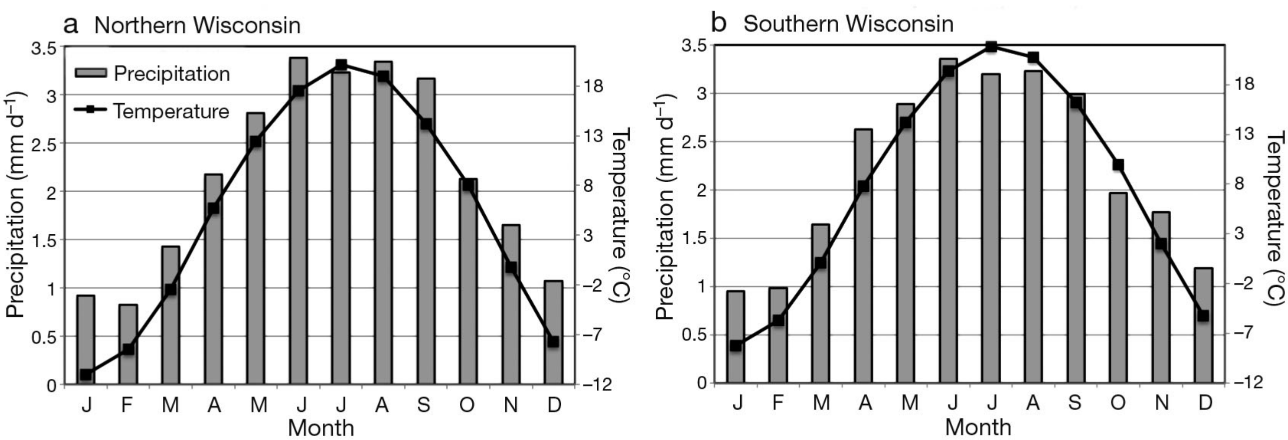

Fig. 2. Climographs for (a) northern and (b) southern Wisconsin, displaying monthly mean temperature (line: °C) and precipitation (bars: mm d^{-1}) for 1961–2000

scenarios, respectively (Fig. 3b,d). The magnitude of expected warming diverges greatly later in the century. The mean annual projected warming by the late 21st century is +6.1 or +3.6°C for the A2 and B1 scenarios, respectively (Fig. 3a,c). The amount of projected warming varies temporally and spatially across Wisconsin. Under the A2 (B1) scenario, the simulated warming by the late 21st century peaks during winter across the Northwest Sands at +7.5°C (+5.0°C) and dips during summer across the Central Lake Michigan Coastal landscape at +4.5°C (+2.5°C). All models robustly predict a warming trend in all 12 calendar months, although its magnitude varies among models. The projected annual warming by the late 21st century, under the A2 (B1) scenario, ranges from +4.3°C (+2.1°C) by CSIRO Mk3.0 to +8.8°C (+4.9°C) by MIROC3.2 (medres) (Fig. 3a).

The warming is projected to be strongest and most robust in DJF and weakest in JJA, thereby dampening the seasonal cycle of surface air temperature (Table 2). For example, according to the A2 (B1) emission scenario, by the end of the 21st century, Wisconsin's mean temperature will increase by 7.3°C (4.4°C) in DJF and 5.4°C (3.0°C) in JJA. Warming is predicted by all models for all seasons, time periods, and scenarios. The dramatic, projected warming in the cold season will substantially shorten the snow season in Wisconsin, despite a projected increase in cold-season precipitation (Notaro et al. 2011).

On average, Wisconsin's annual precipitation is projected to increase by 3.7 or 3.9 cm by the mid-21st century according to the A2 and B1 scenarios, respectively (Fig. 3f,h). The projected increase in annual precipitation diverges between the 2 scenarios by the late 21st century, with increases of 4.9 or 2.9 cm, for the A2 and B1 scenarios, respectively (Fig. 3e,g). The annual precipitation projections vary significantly among the 9 models, with 6 models simulating a positive trend by the late 21st century in A2fixCO2; the range is from −11.8 cm in MIROC3.2 (medres) to +16.1 cm (MRI CGCM2).

Among the CMIP3 models, the most robust change (based on signal-to-noise ratio) in precipitation during the 21st century is an increase during DJF, while the largest increase is projected

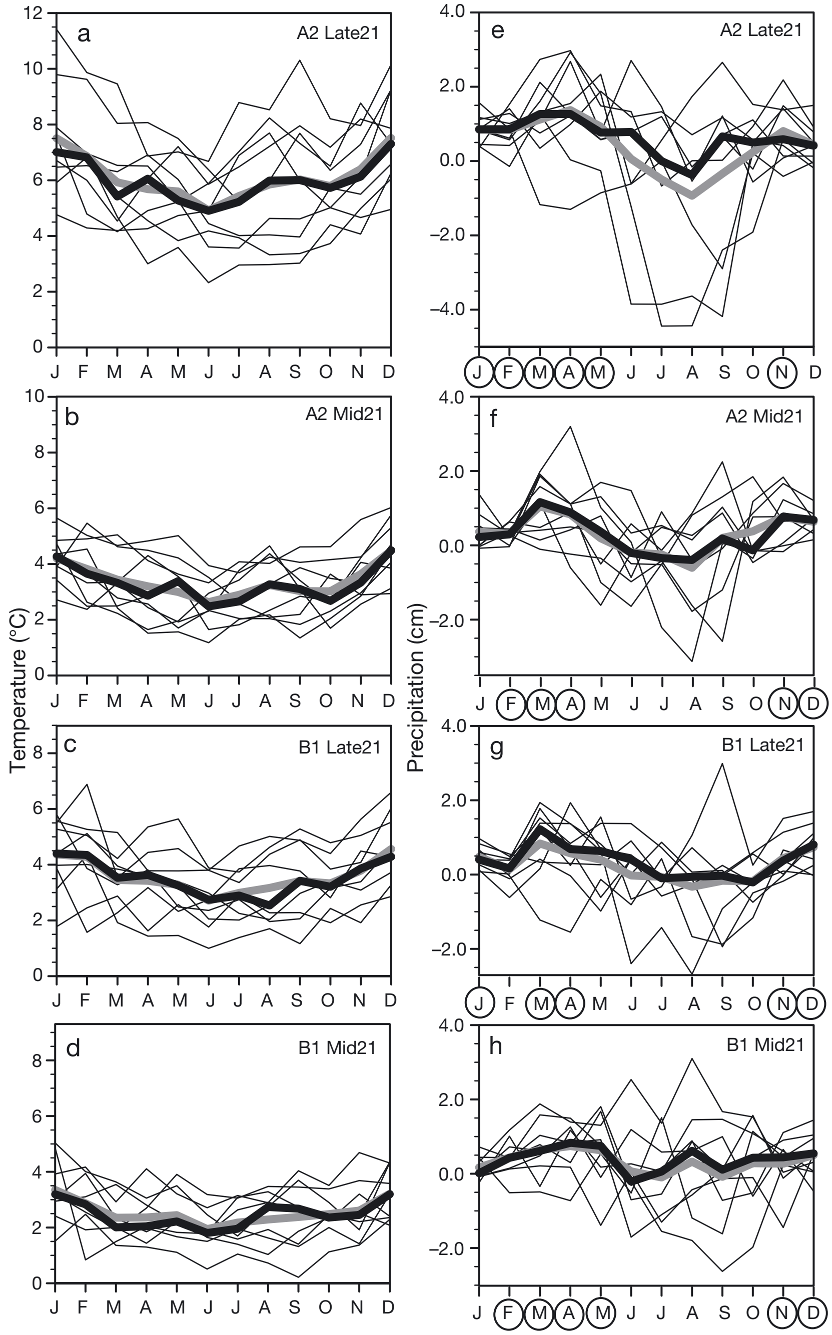

Fig. 3. Projected changes in monthly Wisconsin mean (a–d) temperatures and (e–h) precipitation by the mid- and late 21st century, under the A2 and B1 emission scenarios, respectively. Mid21: difference between the late 20th century (1961–2000) and mid-21st century (2046–2065); Late21: difference between th late 20th and late 21st centuries (2081–2100). Thin black lines: 9 global climate models; thick black (gray) line: mean (median) projections; (e–h) black circles: months in which at least 7 models produce a positive trend in precipitation

to occur during spring (MAM) (Table 2). For example, according to the A2 emission scenario, by the end of the 21st century, Wisconsin's mean precipitation will change by +2.1, +3.4, −1.4, and +0.7 cm for DJF, MAM, JJA, and fall (SON), respectively. All models project an increase in precipitation during DJF under the A2 scenario, both by the mid- and late 21st century. However, there is little consensus among the CMIP3 models on how summertime precipitation will change during the 21st century. Precipitation is expected to increase the most across northern Wisconsin, including a mean projected increase, by the late 21st century of +3.8 cm during MAM north of the tension zone under the A2 scenario. The response in Wisconsin's precipitation under the B1 emission scenario is roughly half that of the A2 scenario. According to the B1 emission scenario, Wisconsin's mean precipitation will change by +1.4, +1.8, −0.4, and +0.1 cm for DJF, MAM, JJA, and SON, respectively, by the end of the century, with all 9 models robustly increasing precipitation in winter (Table 2).

Projected changes in drought frequency in Wisconsin are assessed, based on total column fractional soil moisture. During 1980 to 1999, the mean simulated soil moisture fraction peaks in April at 0.58 (following snow melt) and reaches a minimum in August to September at 0.43 (due to high temperatures and large plant transpiration). After removing the mean seasonal cycle of soil moisture, 5% of months during 1980 to 1999 experienced an anomalous soil moisture fraction of −0.13 or less. The frequency of such extreme droughts is projected to increase substantially by 2081 to 2100, with percentage frequencies of 26, 22, 18, and 16% from the A2fixCO2, A2, B1fixCO2, and B1 simulations, respectively; the carbon fertilization effect only slight dampens the increasing frequency of droughts.

3.3. Vegetation projections

The general responses to climate change among the 4 ensemble sets are a decrease in tree cover, increase in grass cover, and minimal change in total vegetation cover fraction across Wisconsin (Table 3). The greatest mean reduction in tree cover fraction, −0.08, occurs in A2fixCO2 by the late 21st century in the absence of carbon fertilization (Fig. 4, Table 3); this represents a potential loss of 12.6% of the current Wisconsin forest area. Based on the NoFire and A2fixCO2 simulations, we found that the projected decline in Wisconsin's tree cover is not driven by enhanced fire occurrence or intensity. The forest die-off is partly diminished by carbon fertilization, consistent with Xu et al. (2007). The B1 simulations, with low-end carbon emissions and the inclusion of carbon fertilization, actually produce no notable change in Wisconsin's total forest cover fraction by the end of the century (Table 3).

Under the high emission scenario in A2fixCO2 and A2, the loss of tree cover in southern and western Wisconsin and eastern Iowa represents the development of a more prairie-like ecosystem (Fig. 4a,c), with grass cover expanding. This region experiences a substantial drying in the upper soil layer during summer and autumn of the 21st century, triggering the tree die-off; this drying will amplify the currently mild soil moisture deficit experienced in Wisconsin

Table 2. Projected change in seasonal surface air temperature (°C) and precipitation (cm season^{-1}) for the A2 and B1 emission scenarios by the mid- and late 21st century, based on 9 global climate models. Ratio: signal-to-noise ratio (mean change ÷ SD of changes among models); n: number of models that project an increase or decrease in temperature or precipitation. **Bold:** largest projected mean change and largest signal-to-noise ratio for each time period and scenario. DJF: winter, MAM: spring, JJA: summer, SON: fall

	DJF			MAM			JJA			SON		
	Change (mean ± SD)	Ratio	n	Change (mean ± SD)	Ratio	n	Change (mean ± SD)	Ratio	n	Change (mean ± SD)	Ratio	n
Temperature												
A2 Late 21st	**+7.30 ± 1.78**	**4.09**	9↑0↓	+5.74 ± 1.47	3.90	9↑0↓	+5.40 ± 1.78	3.04	9↑0↓	+6.07 ± 1.78	3.41	9↑0↓
A2 Mid-21st	**+4.17 ± 0.85**	**4.89**	9↑0↓	+3.21 ± 1.14	2.83	9↑0↓	+2.93 ± 0.86	3.40	9↑0↓	+3.23 ± 0.91	3.53	9↑0↓
B1 Late 21st	**+4.41 ± 1.24**	**3.55**	9↑0↓	+3.38 ± 1.07	3.15	9↑0↓	+2.96 ± 1.06	2.80	9↑0↓	+3.51 ± 1.12	3.14	9↑0↓
B1 Mid-21st	**+3.14 ± 0.83**	**3.77**	9↑0↓	+2.39 ± 0.76	3.12	9↑0↓	+2.14 ± 0.80	2.68	9↑0↓	+2.49 ± 0.96	2.59	9↑0↓
Precipitation												
A2 Late 21st	+2.13 ± 0.99	**2.15**	9↑0↓	**+3.42 ± 3.15**	1.08	8↑1↓	−1.37 ± 5.58	0.25	6↑3↓	+0.71 ± 3.11	0.23	6↑3↓
A2 Mid-21st	+1.31 ± 0.55	**2.39**	9↑0↓	**+2.07 ± 2.44**	0.85	7↑2↓	−1.04 ± 2.39	0.43	4↑5↓	+1.35 ± 1.16	1.16	9↑0↓
B1 Late 21st	+1.36 ± 0.90	**1.50**	9↑0↓	**+1.81 ± 2.31**	0.78	7↑2↓	−0.41 ± 2.55	0.16	6↑3↓	+0.09 ± 2.22	0.04	5↑4↓
B1 Mid-21st	+1.11 ± 0.79	**1.41**	8↑1↓	**+2.02 ± 1.93**	1.04	7↑2↓	+0.29 ± 3.25	0.09	4↑5↓	+0.47 ± 2.40	0.20	5↑4↓

Table 3. Projected changes in tree, grass, vegetation, evergreen tree, and deciduous tree cover fractions, total land carbon, vegetation carbon, litter carbon, and soil carbon (in gC m^{-2}), and upper and lower soil water fraction. Results are computed across the natural lands of Wisconsin. Changes are computed for mid- (2001–2050) and late (2001–2100) 21st century, based on linear regression, for A2fixCO2, B1fixCO2, A2, and B1. Mean change ± 1 SD (among the 9 Lund-Potsdam-Jena [LPJ] simulations) and mean percentage change are shown. Pink, yellow, white, green, and blue shading: 22–27 (robust decline), 16–21, 12–15 (minimal change), 6–11, or 0–5 (robust increase) of the 27 LPJ model simulations produce a negative trend in the specified variable. **Bold**: largest trend among the 4 scenarios for each variable

	A2fixCO2		B1fixCO2		A2		B1	
	Mean ± SD	%	Mean ± SD	%	Mean ± SD	%	Mean ± SD	%
Mid-21st century								
Tree cover fraction	**−0.05 ± 0.04**	**−7.6**	−0.04 ± 0.05	−5.6	−0.03 ± 0.03	−4.1	−0.02 ± 0.04	−3.1
Grass cover fraction	**+0.05 ± 0.03**	**+90.7**	+0.03 ± 0.05	+59.0	+0.03 ± 0.03	+50.3	+0.02 ± 0.04	+31.6
Vegetation cover fraction	−0.00 ± 0.01	−0.3	**−0.01 ± 0.01**	**−0.8**	−0.00 ± 0.01	−0.1	−0.00 ± 0.01	−0.5
Evergreen tree cover fraction	**−0.14 ± 0.07**	**−62.0**	−0.09 ± 0.07	−38.9	−0.14 ± 0.07	−60.8	−0.09 ± 0.07	−37.9
Deciduous tree cover fraction	+0.09 ± 0.04	+22.0	+0.05 ± 0.03	+12.5	**+0.11 ± 0.05**	**+26.7**	+0.07 ± 0.04	+15.9
Land carbon (gC m^{-2})	**−1975 ± 841**	**−10.4**	−1224 ± 841	−6.4	−834 ± 831	−4.4	−318 ± 814	−1.7
Vegetation carbon (gC m^{-2})	**−1848 ± 1092**	**−28.0**	−1127 ± 1252	−17.1	−1156 ± 1120	−17.5	−566 ± 1249	−8.6
Litter carbon (gC m^{-2})	+20 ± 154	+1.5	+32 ± 229	+2.4	**+185 ± 166**	**+14.0**	+162 ± 230	+12.2
Soil carbon (gC m^{-2})	**−147 ± 252**	**−1.3**	−129 ± 369	−1.2	+136 ± 262	+1.2	+85 ± 383	+0.8
Upper soil water fraction	−0.002 ± 0.018	−0.5	−0.006 ± 0.030	−1.4	**+0.006 ± 0.018**	**+1.4**	+0.001 ± 0.031	+0.3
Lower soil water fraction	**−0.052 ± 0.031**	**−10.5**	−0.041 ± 0.057	−8.3	−0.039 ± 0.033	−7.8	−0.030 ± 0.060	−6.1
Late 21st century								
Tree cover fraction	**−0.08 ± 0.10**	**−12.6**	−0.02 ± 0.03	−2.8	−0.01 ± 0.05	−2.1	+0.00 ± 0.03	+0.5
Grass cover fraction	**+0.06 ± 0.08**	**+121.8**	+0.01 ± 0.03	+27.1	+0.01 ± 0.04	+22.1	−0.00 ± 0.02	−5.1
Vegetation cover fraction	**−0.02 ± 0.03**	**−2.6**	−0.00 ± 0.01	−0.6	−0.00 ± 0.01	−0.3	+0.00 ± 0.01	+0.0
Evergreen tree cover fraction	−0.25 ± 0.06	−100	−0.21 ± 0.08	−91.5	**−0.25 ± 0.06**	**−100**	−0.21 ± 0.08	−91.6
Deciduous tree cover fraction	+0.17 ± 0.11	+39.4	+0.19 ± 0.09	+45.5	**+0.24 ± 0.07**	**+55.7**	+0.22 ± 0.09	+50.6
Land carbon (gC m^{-2})	**−5083 ± 1415**	**−26.7**	−3269 ± 1313	−17.1	−1804 ± 1340	−9.5	−1037 ± 1274	−5.4
Vegetation carbon (gC m^{-2})	**−2985 ± 1082**	**−45.2**	−2203 ± 1081	−33.4	−1113 ± 1112	−16.9	−944 ± 1086	−14.3
Litter carbon (gC m^{-2})	**−554 ± 228**	**−41.8**	−301 ± 188	−22.7	−205 ± 249	−15.5	−64 ± 185	−4.9
Soil carbon (gC m^{-2})	**−1543 ± 527**	**−13.8**	−765 ± 388	−6.9	−486 ± 525	−4.4	−28 ± 377	−0.3
Upper soil water fraction	+0.002 ± 0.044	+0.4	−0.001 ± 0.024	−0.3	**+0.019 ± 0.044**	**+4.4**	+0.007 ± 0.025	+1.7
Lower soil water fraction	**−0.101 ± 0.059**	**−20.5**	−0.085 ± 0.048	−17.3	−0.077 ± 0.078	−15.7	−0.070 ± 0.052	−14.2

during summer. Across northern Wisconsin, a weaker forest die-off is noted in all ensemble sets in response to summertime heat stress and drying of the deep soil, as evergreen forests abruptly collapse and are more gradually replaced by deciduous forests. Several of the CMIP3 models, when forcing LPJ, lead to dramatic statewide losses of tree cover after 2070 under A2fixCO2, with surges in grass cover, in response to soil drying. The establishment of a more prairie-like environment in western Wisconsin is modestly present in the B1fixCO2 simulations and absent in the B1 simulations (due to limited warming and enhanced water-use efficiency).

Climate change is expected to have a differential effect on evergreen and deciduous species in Wisconsin. The evergreen tree cover fraction of Wisconsin is projected to decline by −0.14 (−0.09) by the mid-21st century and −0.25 (−0.21) by the late 21st century in A2fixCO2 (B1fixCO2) (Table 3), with increases in deciduous tree cover fraction of +0.09 (+0.05) and +0.17 (+0.19), respectively. Given that the increase in deciduous tree cover fraction is less than the loss of evergreen tree cover, the net tree cover in Wisconsin declines. The response in evergreen and deciduous forests is much less pronounced in B1fixCO2 than A2fixCO2 by the mid-21st century but quite similar by the late 21st century. The inclusion of carbon fertilization in A2 and B1 has minimal effect on limiting the evergreen forest die-off in northern Wisconsin, attributed to summer heat stress, but enhances the rate of replacement by deciduous forest cover through strengthening the trees' resistance to drying soils (Table 3).

During the late 20th century, LPJ correctly simulates the east-west tension zone across central Wisconsin, with evergreen tree species to the north and deciduous tree species to the south (Fig. 5a,d,g,j). By the mid-21st century, in all ensembles, the tension zone shifts into northern Wisconsin (Fig. 5b,e,h,k), consistent with Jones et al. (1994). By the late 21st century, the tension zone either lies across northern Wisconsin under B1fixCO2 (or B1) or out of the state under A2fixCO2 (or A2) (Fig. 5c,f,i,l). The northward migration of the tension zone is projected to occur rapidly under A2fixCO2 at ~2 km yr^{-1}. In A2fixCO2 and A2, a robust decline in evergreen tree cover occurs among the models after 2030, particularly over the Chequamegon-Nicolet National Forest, in response to summer heat stress. The July mean temperature over the national forest is projected to increase from 19 to 22°C by 2035, triggering the bioclimatic limit for the upper limit of the warmest month's temperature for boreal tree species. The average deciduous tree cover fraction of Wisconsin in A2fixCO2 increases during 2001 to 2050, is steady until 2085, and then declines. Specifically, this consists of a gradual increase in deciduous tree cover across northern Wisconsin (replacing evergreen trees) and an abrupt reduction across southern Wisconsin in some models late in the century (due to soil drying and prairie establishment). The simulated response of boreal evergreen and temperate tree species across Wisconsin are consistent with projections of the Forestry Working Group (WICCI 2011), simulations by a forest landscape model, LANDIS (Scheller & Mladenoff 2008), and the US Department of Agriculture Climate Change Tree Atlas (Prasad et al. 2007), which include a decline in boreal species and expansion of central hardwoods.

3.4. Terrestrial carbon projections

Remotely sensed NPP from MODIS is compared to LPJ-simulated NPP across Wisconsin. The state-averaged NPP is 536 gC m^{-2} in LPJ and 472 gC m^{-2} in MODIS, with higher NPP values in the model across southern Wisconsin due to excessive tree cover and lack of land use in the model. Across the more natural forests of the Chequamegon-Nicolet National Forest, the mean NPP is 546 gC m^{-2} in LPJ and 587 gC m^{-2} in MODIS, indicating a close agreement in a natural area where we have more confidence in the model performance.

In all ensemble sets, the total land carbon pool is projected to decline during the 21st century across Wisconsin (Table 3). By the mid-21st century, the average loss in land carbon ranges from –318 gC m^{-2} (–1.7%) in B1 to –1975 gC m^{-2} (–10.4%) in A2fixCO2. The presence or absence of carbon fertilization has a more pronounced effect on future terrestrial carbon than the choice of emission scenarios, with carbon fertilization offsetting roughly two-thirds of the projected future loss of land carbon due to climate change. Carbon fertilization causes a reduction in transpiration, thereby limiting the soil drying trend and weakening the loss in land carbon. The average loss in land carbon by the late 21st century ranges from –1037 gC m^{-2} (–5.4%) in B1 to –5083 gC m^{-2} (–26.7%) in A2fixCO2, indicating that the loss in terrestrial carbon to the atmosphere will accelerate during the 21st century (Table 3, Fig. 6). Based on the mean projection for A2fixCO2, total land carbon will decrease by –25 gC m^{-2} yr^{-1} during 2001–2030 and by –58 gC m^{-2} yr^{-1} during 2031–2100 across Wisconsin, representing a 2.3 times increase in the slope of the decline after 2030 (Fig. 6a). The rapid loss in total land carbon after 2030 is related to vegetation carbon, while the land carbon decline further accelerates after 2050 due to soil and litter carbon. The decline in land carbon after 2030 is likewise present in the A2 simulations (hardly noticeable in the B1 simulations), but occurs at only 40% of the rate of decline as in the A2fixCO2 simulations.

While all 9 CMIP3 models suggest a decline in land carbon, the greatest loss is associated with those climate models with the most warming and secondarily with drying. Under A2fixCO2, CSIRO MK3.0 simulates a modest warming of +4.3°C and a substantial increase in precipitation of +9.5 cm yr^{-1} by the late 21st century, resulting in a terrestrial carbon loss of –2875 gC m^{-2} across the natural regions of Wisconsin. In contrast, MIROC 3.2 (medres) simulates a dramatic warming of +8.8°C and drying of –11.8 cm yr^{-1}, leading to a mean decline of –7350 gC m^{-2}. Among the 9 climate models, the correlation between the 21st century trends in annual temperature (precipitation) and land carbon is –0.86 (+0.66). The climate projections that favor the largest increase in drought frequency also support the most pronounced declines in terrestrial carbon.

By the mid-21st century, roughly 90% of the decline in terrestrial carbon in A2fixCO2 and B1fixCO2 is attributed to a reduction in vegetation carbon, with only a small decline in soil carbon and minor increase in litter carbon (Table 3). Likewise, the decline in terrestrial carbon by the mid-21st century is fully attributed to diminished vegetation carbon in the A2 and B1 simulations (Table 3) but substantially dampened by the carbon fertilization effect. The die-off of Wisconsin forests and ongoing conversion of the northern evergreen forests into deciduous forests, in response to rising summer temperatures and drying soil from enhanced evaporation, lead to the loss of vegetation carbon to the atmosphere. The greatest projected loss of vegetation carbon is north of the tension zone. This includes the Chequamegon-Nicolet National Forest, which is an abundant sink of

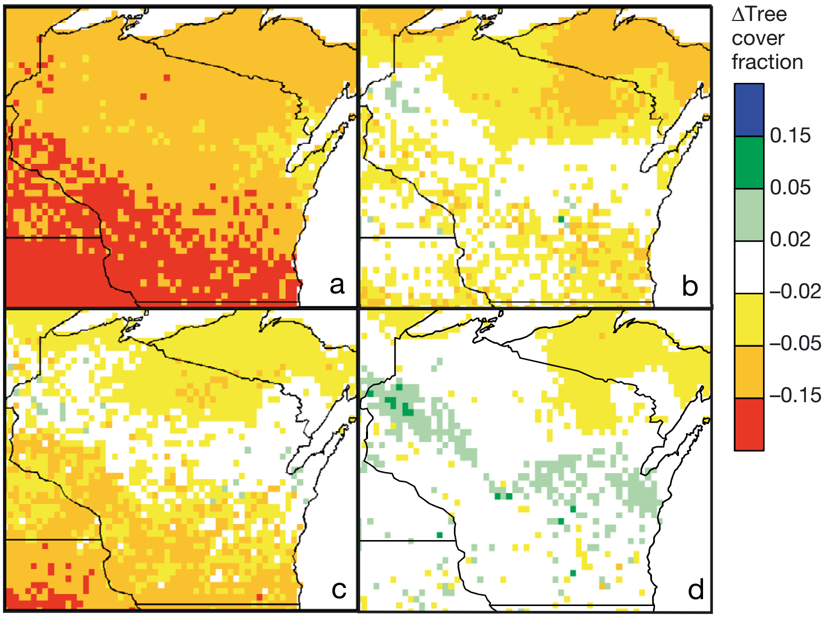

Fig. 4. Mean projected change in tree cover fraction during the 21st century (2081–2100 minus 1981–2000), based on 27 Lund-Potsdam-Jena model simulations forced by 9 global climate models with 3 realizations. Results are shown for (a) A2fixCO2, (b) B1fixCO2, (c) A2, and (d) B1

carbon, estimated as 100×10^6 gC ha^{-1} by LPJ versus 50–100 $\times 10^6$ gC ha^{-1} by Rhemtulla et al. (2009) for the mid-1800s prior to substantial land use. Carbon fertilization in A2 and B1 limits vegetation carbon loss (increased photosynthesis) and increases both litter and soil carbon (Table 3). Improved water use efficiency of plants decreases transpiration and increases soil moisture, thereby limiting drought stress and litter carbon losses.

By the late 21st century, the percent contribution of vegetation carbon to the loss in total land carbon in A2fixCO2 and B1fixCO2 drops to ~60%, as substantial declines in soil carbon emerge in additional to modest declines in litter carbon (Table 3). In A2fixCO2 (B1fixCO2), Wisconsin's terrestrial carbon pools are projected, on average, to decline substantially by −45.2 (−33.4), −41.8 (−22.7), and −13.8% (−6.9%) for vegetation, litter, and soil, respectively (Table 3). The inclusion of carbon fertilization in A2 (B1) reduces these percent losses to −16.9 (−14.3), −15.5 (−4.9), and −4.4% (−0.3%), respectively.

The sources of uncertainty in terrestrial carbon projections are explored. The standard deviations of these projections for the mid-21st century are 448, 724, and 845 gC m^{-2} between emission scenarios (A2 versus B1), between simulations with and without carbon dioxide fertilization, and among the 9 climate models, respectively. These standard deviations for the late 21st century are 913, 1949, and 1365 gC m^{-2}, respectively. The greatest source of uncertainty is the choice of climate model by the mid-21st century and the carbon dioxide fertilization effect by the late-21st century, with the difference between the emission scenarios contributing the least uncertainty in terrestrial carbon projections for Wisconsin.

Heterogeneous changes in terrestrial carbon are projected to occur across Wisconsin (Table 4). Mean projected changes in vegetation carbon (across the natural regions of Wisconsin) by the mid-21st century under A2fixCO2 range widely from −187 gC m^{-2} in the Western Prairie to −4258 gC m^{-2} in the Northern Highlands. By the late 21st century, these changes diverge even further by ecoregion, from −448 gC m^{-2} in Central Lake Michigan Coastal to −6580 gC m^{-2} in the Northern Highlands. The largest losses of vegetation carbon are expected across northern Wisconsin, related to the decline in boreal evergreen tree species. The magnitude of the mean projected loss in litter carbon by the late 21st century, in A2fixCO2, does not vary dramatically among the ecological landscapes, ranging from −215 gC m^{-2} in Central Lake Michigan Coastal to −616 gC m^{-2} in the Northeast Sands. Reductions in soil carbon by the late 21st century range significantly from −650 gC m^{-2} in the Superior Coastal Plain to −1875 gC m^{-2} in the Central Sand Plains. Overall, total land carbon losses to the atmosphere by the end of the century, under A2fixCO2, are projected to be smallest across the Central Lake Michigan Coastal (−1585 gC m^{-2}) and largest across the Northern Highlands (−8204 gC m^{-2}), with the rate being 3 times greater in the latter region than the former. This corresponds to the pattern of projected warming, with the greatest increase in temperature likely across northern Wisconsin and least along the coast of Lake Michigan.

4. DISCUSSION

The Wisconsin Governor's Mitigation Task Force has recommended a statewide reduction in greenhouse gas emissions to 75% below the 2005 level by the year 2050 (DNR 2008). If achieved by 2050,

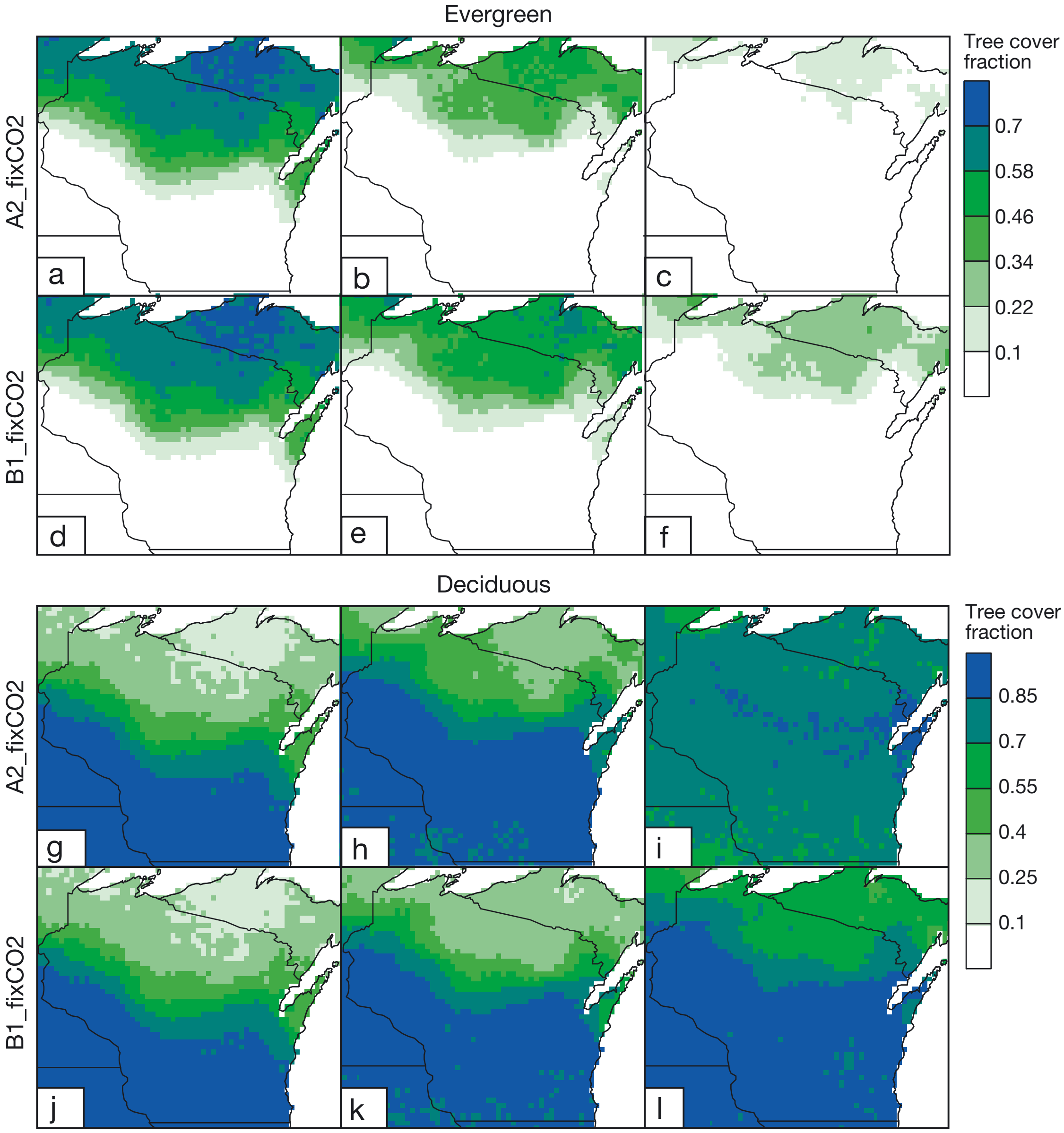

Fig. 5. Mean (a–f) evergreen and (g–l) deciduous tree cover fraction during the (a,d,g,j) late 20th century (1981–2000), (b,e,h,k) mid- (2041–2060), and (c,f,i,l) late 21st century (2081–2100), based on 27 Lund-Potsdam-Jena simulations forced by 9 GCMs with 3 realizations for A2fixCO2 and B1fixCO2

this policy would diminish anthropogenic emissions by 94 million metric tons of equivalent carbon dioxide per year (Mt CO_2e yr^{-1}). However, the gains from this ambitious effort may be significantly offset by the climate-driven vegetation changes projected here, particularly under the higher 21st-century emission scenarios. For A2fixCO2 (B1fixCO2), by the mid-21st century, LPJ simulates a mean terrestrial carbon loss of –1975 gC m^{-2} (–1224 gC m^{-2}) to the atmosphere across the natural regions of Wisconsin (130 768 km^2 in area), or –18.9 MMT CO_2e yr^{-1} (–11.7 MMT CO_2e yr^{-1}) during the first half of the century. This carbon loss is primarily caused by tree mortality and is only partially mitigated by natural forest regeneration. Such a loss of vegetation and soil carbon to the atmosphere would offset 20% of the benefit of the recommended anthropogenic emissions reduction. During the second half of the 21st century, under A2fixCO2 (B1fixCO2), the mean projected terrestrial carbon loss across the natural regions of Wisconsin is even more substantial, –29.7 Mt CO_2e yr^{-1} (–19.6 Mt CO_2e yr^{-1}), further offsetting the planned emissions reductions. If global emissions of greenhouse gases are reduced through national

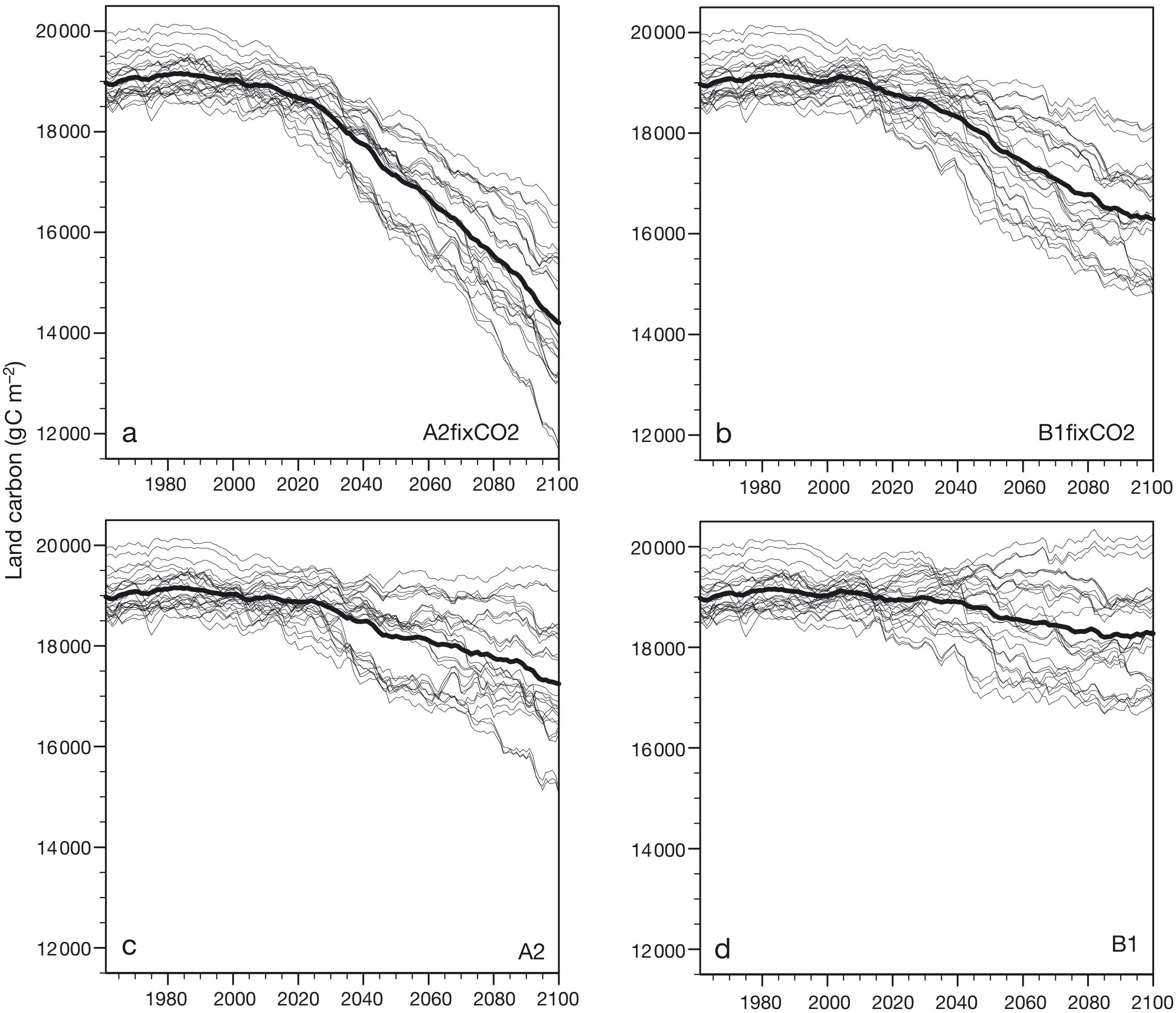

Fig. 6. Mean land carbon (gC m^{-2}), including vegetation, litter, and soil carbon pools, across the natural landscapes of Wisconsin during 1961–2100, from (a) A2fixCO2, (b) B1fixCO2, (c) A2, and (d) B1. Thin lines: 1 of 27 Lund-Potsdam-Jena model simulations; thick line: mean projection

and global mitigation efforts, then the vegetation changes discussed in this paper can be substantially diminished. For example, the projected reduction in Wisconsin's land carbon is ~40% less in the B1 emission scenario than A2 scenario throughout the 21st century. Thus, global-scale efforts to mitigate greenhouse gas emissions could aid Wisconsin's mitigation efforts by reducing the climate-driven loss of terrestrial carbon to the atmosphere. Nevertheless, under all global emission scenarios, there is a projected loss of terrestrial carbon from Wisconsin's natural ecosystems. If the effects of carbon fertilization in the A2 and B1 simulations are accurate, then the projected decline in terrestrial carbon in Wisconsin will be substantially reduced compared to the A2fixCO2 and B1fixCO2 simulations, about one-third in magnitude.

Under A2fixCO2 or A2 (B1fixCO2 or B1), LPJ simulates a northward shift of the tension zone in Wisconsin during the 21st century at 2 km yr^{-1} (1.5 km yr^{-1}); this northward shift is consistent with the study by Jones et al. (1994). Kucharik et al. (2010) found an observed northward shift of 15 to 20 km in climatically defined tension zone of Wisconsin during 1950 to 2006, which is consistent with future projections but more gradual in rate. LPJ does not consider seed dispersal or other limits to plant migration, so the projected northward shift in the tension zone likely occurs at an exaggerated rate. Plants will likely be unable to maintain pace with the projected warming trend, consistent with the study by Schwartz (1996). Most trees migrated at rates of 10 to 50 km century^{-1}, or 0.1 to 0.5 km yr^{-1}, during the late Quaternary (Davis 1981), which is slower than the projected northward shift of the tension zone by LPJ. Thus, it is likely that the replacement of northern Wisconsin evergreen trees by southern deciduous species will occur over a prolonged period of time, much slower than simulated by LPJ. A slower replacement presumably would enhance the projected carbon losses from the terrestrial vegetation. Assisted migration may be a viable strategy to aid southern Wisconsin species in their likely necessary migration into the northern state, although its effects should be carefully balanced against other possible risks and benefits (Hoegh-Guldberg et al. 2008). The LPJ simulations may be thought of as a management scenario with a limited form of assisted migration, i.e. one in which seeds were freely dispersed across the state, but there was no subsequent management for tree growth and survival.

Several limitations are noted regarding these LPJ simulations. LPJ represents vegetation with 10 PFT categories, not with specific species, and the bioclimatic limits of these PFTs were globally tuned in the development of the model, so their accuracy is limited on a regional scale. The PFT-type modeling of LPJ would not capture the potential shift towards more stress-tolerant species within individual PFTs, which might dampen the response in total forest cover fraction. Hellmann et al. (2010) projects an increase in the abundance of more heat- and drought-tolerant species (e.g. *Quercus macrocarpa* and *Q. stellata*) across the Midwest/Great Lakes Basin in response to 21st century climate change. Notaro et al. (2010b) previously noted that, by clumping diverse plant species into single PFTs with uniform characteristics, a DGVM fails to capture the drought resistance and deep roots of some plant species, leading to exaggerated vegetation die-offs and excessive loss of leaf cover simulated by LPJ during droughts. LPJ only simulates natural vegetation, so these projections do not include the effects of current or historic land use on the terrestrial carbon budget. Similarly, this paper has not considered the possible effects of mitigation efforts applied to Wisconsin's forests through silvicultural practice. LPJ neglects soil nitrogen limitation and does not model the effects of dispersal limitation on plant migration, so the establishment of PFTs in new regions occurs too rapidly.

In addition to widely varying precipitation projections among climate models and choice of emission scenario, another critical source of uncertainty in the current modeling study is parameterizations and processes representations in LPJ, especially carbon fer-

Table 4. Mean projected changes in carbon for vegetation, litter, soil, and total land, based on A2fixCO2, for mid- (2001–2050) and late (2001–2100) 21st century, using linear regression. Results are shown for the natural portions of the 16 ecological landscapes of Wisconsin, based on 27 Lund-Potsdam-Jena model simulations. Approximate area of each ecoregion is provided. *Italics* (**bold**): largest decline (largest increase or smallest decline) for each variable and time period

Ecoregion	Area (km^2)	Vegetation carbon ($gC\ m^{-2}$)		Litter carbon ($gC\ m^{-2}$)		Soil carbon ($gC\ m^{-2}$)		Total land carbon ($gC\ m^{-2}$)	
		Mid	Late	Mid	Late	Mid	Late	Mid	Late
Superior Coastal Plain	6160	−3042	−4688	+86	−394	+155	**−650**	−2801	−5732
Northwest Sands	5632	−2793	−3075	−149	−558	−16	−1600	−2958	−5233
Northwest Lowlands	2024	−3597	−4153	−91	−560	+150	−1437	−3538	−6151
North Central Forest	26 224	−4071	−5409	−3	−615	**+195**	−1276	−3879	−7301
Northern Highlands	5544	*−4258*	*−6580*	**+97**	−611	+193	−1013	*−3968*	*−8204*
Western Prairie	3256	**−187**	−1296	−100	−240	−528	−1314	−816	−2851
Central Sand Plains	8800	−219	−1190	*−166*	−406	*−678*	*−1875*	−1064	−3471
Central Lake Mich. Coastal	8008	−323	**−448**	−96	**−215**	−253	−922	**−672**	**−1585**
Southeast Glacial Plains	20 240	−250	−1052	−106	−248	−447	−1154	−803	−2453
Central Sand Hills	5720	−225	−1168	−135	−352	−622	−1622	−982	−3143
Western Coulee and Ridges	26 400	−527	−1745	−131	−326	−530	−1451	−1188	−3522
Southern Lake Mich. Coastal	2728	−409	−1378	−130	−292	−470	−1232	−1009	−2902
Southwest Savanna	5280	−607	−1381	−93	−248	−320	−991	−1019	−2620
Northern Lake Mich. Coastal	6952	−1001	−859	−98	−267	−71	−875	−1171	−2000
Northeast Sands	4488	−3233	−3040	−139	*−616*	+166	−1584	−3207	−5240
Forest Transition	18 832	−1593	−1712	−145	−425	−179	−1436	−1916	−3572

tilization (Zaehle et al. 2005, Koca et al. 2006, Lucht et al. 2006). Zaehle et al. (2005) assessed the effects of parameter uncertainties on the modeling of terrestrial biosphere dynamics in LPJ and concluded that the primary contributors to uncertainty in future carbon balance estimates are the rate of carbon accumulation in vegetation and the turnover time of soil organic matter.

Despite the knowledge gained through the Free-Air CO_2 Enrichment experiments (Ainsworth & Long 2005). The long-term effects of carbon enrichment remain uncertain. It is generally believed that elevated levels of atmospheric carbon dioxide should increase photosynthesis, water-use efficiency (due to reduced stomatal conductance), and productivity of plants (Field et al. 1995, Gerber et al. 2004). Norby et al. (2005) and Prentice et al. (2007) concluded that LPJ's carbon fertilization effect likely lies within the range of recent observational estimates. Nonetheless, the significance of carbon enrichment varies among ecosystem models and should be considered with caution. Based on an analysis of the global record of annual radial tree growth from the International Tree Ring Data Bank, Gedalof & Berg (2010) concluded that the influence of carbon fertilization on forest growth is only detectable at 20% of sites globally, with the observed growth increases primarily attributed to stimulation in photosynthesis rather than enhanced water use efficiency. They did not detect any change over time in the drought sensitivity of trees and found no difference in the proportion of sites that experienced increased growth between drought-limited and drought-insensitive sites. The continued controversy of carbon fertilization is a source of uncertainty in ecological forecasts for the 21st century.

5. SUMMARY AND CONCLUSIONS

The LPJ-DGVM is forced across Wisconsin by an array of high-resolution, statistically downscaled climate projections for the 21st century. The climate projections generally include an annual warming trend, increase in cold season precipitation, and potential summertime drying, although the summer precipitation projections vary dramatically among climate models. In response to these climate change projections for the 21st century, LPJ simulates a contraction of the northern Wisconsin evergreen forests, with replacement by deciduous forests, and the establishment of more prairie-like environments in the southwest state. These projected vegetation changes are accompanied by large losses of carbon from the biosphere and soil to the atmosphere, with greater risk under high emission scenarios. While these ecological trends are mostly consistent among the range of simulations, there is substantial uncertainty in the vegetation and terrestrial carbon projections related to differences among individual climate models and the role of carbon fertilization. Global climate models struggle to represent summer precipitation due to crude convective parameterizations, leading to vast uncertainty on how summer rainfall will change across Wisconsin this century. Further research should explore climate projections through dynamical downscaling, such as through the North American Regional Climate Change Assessment Program (Mearns et al. 2009), given the relative strength of regional climate models at simulating convection, heavy precipitation events, and lake–atmosphere interactions.

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