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ORIGINAL ARTICLE

Evaluating climate impacts on carbon balance of the terrestrial ecosystems in the Midwest of the United States with a process-based ecosystem model

Xiaoliang Lu · Qianlai Zhuang

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Abstract The Midwest of the United States includes 12 states and accounts for about a quarter of the total United State land area. In recent years, there is an increasing interest in knowing the biomass potential and carbon balance over this region for the past and the future. In this study, we use the Terrestrial Ecosystem Model (TEM) to evaluate these quantities in the region from 1948 to 2099. We first parameterize the model with field data of major crops, including corn (*Zea mays*), soybean (*Glycine max*), and wheat *(Triticum spp*); then the model is applied to the region for the historical period (1948–2000). Next, we evaluate the simulated forestry biomass with forest inventory data, the agricultural net primary production (NPP) with agricultural statistics data, and the regional NPP with a satellite-based product at the regional scale. Our results show that the simulated annual NPP for the Midwest increased by 1.75% per year and the whole Midwest terrestrial ecosystem acted as a carbon sink during 1948–2005. During the 21st century, vegetation and soil carbon fluxes and pools show an increase trend with a great inter-annual variability. The ecosystems serve as a carbon sink under future climate scenarios. NPP in the Midwest will increase and net ecosystem production (NEP) will also increase and show an even larger interannual variability. This study provides the information of the biomass and NEP at a state- level in the Midwest, which will be valuable for the region stakeholders to better manage their land for the purpose of increasing carbon sequestration on the one hand and meeting the increasing demand of biomass on the other.

Keywords Carbon cycle · Midwest · Model simulation · Future scenarios · Satellite

X. Lu (✉) · Q. Zhuang
Department of Earth & Atmospheric Sciences and Department of Agronomy,
Purdue University, CIVIL 550 Stadium Mall Drive,
West Lafayette, IN 47907-2051, USA
e-mail: lxiaolia@purdue.edu

Q. Zhuang
Department of Earth & Atmospheric Sciences,
Purdue University, CIVIL 550 Stadium Mall Drive,
West Lafayette, IN 47907-2051, USA

Abbreviations

TEM	Terrestrial Ecosystem Model
NPP	Net primary production
NEP	Net ecosystem production
R_H	Heterotrophic respiration
VEGC	Carbon storage in vegetation
SOILORGC	Carbon storage in soil
MODIS	Moderate Resolution Imaging Spectroradiometer
GPP	Gross primary production
NCEP	National Center for Environmental Prediction
NCAR	National Center for Atmospheric Research
MRF	Median range forecast
SRES	Special Report on Emission Scenarios
NLCD	National Land Cover Dataset
SRTM	Shuttle Radar Topography Mission
DEM	Digital Elevation Model
FAO/CSRC	Food and Agriculture Organization/Civil Service Reform Committee
PsnNet	Net photosynthesis
FIA	Forest Inventory and Analysis
NASS	National Agricultural Statistics Service
MEI	Multivariate ENSO index
LAI	Leaf area index
FIADB	Forest Inventory and Analysis Database

1 Introduction

The Midwest of the United States (hereafter Midwest) accounts for about a quarter of the total United State land area and has a variety of ecosystems. The area spans 12 states covering 1.8 million square kilometers. The landscape is primarily agricultural land with forested regions in the northern, eastern, and southern areas. Grassland dominates large areas of the western part of the area in western South Dakota and Nebraska. Corn (*Zea mays*) and soybeans (*Glycine max*) are the dominant crops grown in the central part of the area and spring wheat (*Triticum spp*) in the northwest, winter wheat in the west and southwest (NASS 2002). Many factors such as climate changes, carbon dioxide (CO_2) concentration and land use cause the variations in the terrestrial carbon sink. The changes in climate and atmospheric composition are generally believed to enhance the vegetation growth and thus account for a large part of the terrestrial carbon sink (Friedlingstein et al. 1995; Thompson et al. 1996), but some studies suggested the contribution is not as much as expected (Caspersen et al. 2000; Schimel et al. 2000). Thus, the research on evaluating the effects of climatic change on carbon balance for the past and the future in this region is still needed. In particular, the large-scale data on biomass and carbon fluxes obtained through forest inventory, agricultural statistics, and remote sensing are now available to help the evaluation.

The Midwest agriculture has been under great pressure to have high productivity and the arable land could be further exploited to intensify its agriculture and biofuel crops with the rising demand of biomass and corn and soybean. The reason is that, in recent years, the agricultural-based and cellulosic biofuels have been contemplated as a major substitute for fossil fuel energy in the U.S. However, to increase carbon sequestration is also a great effort in this region. Consequently, a better understanding to the biomass potential and carbon balance over this unique region are fundamentally important. To help stakeholders of this region to better use their land resources and meet both challenges, we conduct a study to evaluate how biomass and carbon budgets respond to the climate changes in the past and future at a higher resolution (8 km × 8 km) with a process-based biogeochemistry model, the Terrestrial Ecosystem Model (TEM5.0; Zhuang et al. 2003) for the Midwest of the United States. Our study provides valuable information on biomass potential and carbon balance at a state-level in the region.

2 Method

2.1 Overview

To conduct a regional analysis, we first need to develop a set of parameters for the model TEM. In the past, we have parameterized TEM for various natural ecosystems (Zhuang et al. 2003). Here we parameterize the TEM to include major crops in the Midwest, namely, corn, soybean and wheat. Next, we apply TEM and parameters to the region to quantify the regional net primary production (NPP), net ecosystem production (NEP), heterotrophic respiration (R_H), carbon storage in vegetation (VEGC) and soils (SOILORGC) from 1948 to 2005. The responses of these variables to historical climate variability are analyzed on a regional scale. Before applying the model to project the regional biomass and carbon balance during the 21st century, we evaluate the model with Moderate Resolution Imaging Spectroradiometer (MODIS) NPP product (Heinsch et al. 2003), forest inventory data (Birdsey 1992) and agricultural statistical data (Stephen et al. 2001). Finally, we examine the responses of regional carbon fluxes and storage to the plausible climate scenarios simulated with the Hadley Centre Coupled Model (HadCM3), a general circulation model (IPCC 2007).

2.2 Model description and parameterization

The Terrestrial Ecosystem Model (TEM) is a process-based ecosystem model that describes carbon (C) and nitrogen (N) dynamics of plant and soils for non-wetland ecosystems of the globe (Raich et al. 1991; McGuire et al. 1992; Zhuang et al. 2003). It uses spatially information on climate, elevation, soils, vegetation and water availability as well as soil- and vegetation-specific parameters to make monthly estimates of important carbon and nitrogen fluxes and pool sizes. The TEM operates on a monthly time step and any defined spatial resolution. TEM consists of five pools (C in vegetation, N in vegetation, C in soil, organic N in soil, inorganic N in soil) and nine fluxes (gross primary productivity, plant respiration, C in litter production, soil respiration, N input to the ecosystem, N uptake by vegetation, N in litter production, net N mineralization, N lost from the ecosystem). In TEM, annual primary production is the difference between carbon captured from the atmosphere as gross primary production (GPP) and carbon respired to the atmosphere by the vegetation. GPP is calculated as a function of light availability, air temperature, atmospheric CO_2 concentration, moisture availability and nitrogen supply. Plant respiration is a function of vegetation carbon (i.e. biomass) and air temperature.

Many parameters in the model are defined from published information (e.g., Raich et al. 1991; McGuire et al. 1992; Zhuang et al. 2003) and some are determined by calibrating the model to fluxes and pool sizes of the intensively studied vegetation types.

To apply TEM to the Midwest, which has large cropland areas, we create vegetation-specific parameterizations for corn, soybean and wheat. The observed pools and fluxes are used to calibrate the rate limiting parameters in the flux equations for gross primary production, autotrophic respiration, heterotrophic respiration, litterfall carbon, litterfall nitrogen, plant nitrogen uptake, and soil nitrogen immobilization (Table 1). The long-term averaged monthly climate data over the period from 1990 to 2000 obtained from the Climate Research Unit (CRU; Mitchell and Jones 2005) are used to drive model calibration. For model calibration, we follow the technique and protocol used in Raich et al. (1991) and McGuire et al. (1992).

2.3 Development of spatially-explicit forcing data

The primary driving variables for TEM are monthly meteorological data, including precipitation, solar radiation and average air temperature. The datasets for the Midwest during the period 1948–2005 are obtained from the median range forecast (MRF) Global Flux Archive from the National Center for Environmental Prediction (NCEP), distributed by the National Center for Atmospheric Research (NCAR) (Kistler et al. 2001). All meteorology data are re-sampled to a spatial resolution of 8 km×8 km using the bilinear interpolation scheme.

For simulations of future scenarios, the climate data are from the IPCC Special Report on Emission Scenarios (SRES-storylines: A1b, A2, B1; Nakicenovic et al. 2000). Specifically, the scenarios data of transient CO_2 concentration and climate change between 2000 and 2099 are from the United Kingdom Meteorological Office Hadley Centre's HadCM3 model simulations (Gordon et al. 2000). Monthly climate data from the GCM simulations are spatially interpolated to a resolution of 8 km.

The land cover data are derived from the National Land Cover Dataset (NLCD 1992, Vogelmann et al. 2001), which is the first land-cover mapping project with a national (conterminous) scope. NLCD 1992 provides 21 different land cover classes at the native 30-meter resolution of Landsat TM for every state. NLCD 1992 was completed in December 2000 (Vogelmann et al. 2001). Because of the difference in land cover type system between the NLCD and the TEM, we collapse the NLCD land cover types into the

Table 1 Pools and fluxes used to calibrate TEM for corn, soybean and wheat ecosystems

	Corn	Soybean	Wheat	Sources and comments
Cs	3071	1916	1625	Evrendilek and Wali 2004
GPP	650	211	233	Evrendilek and Wali 2004
NPP=Cv (harvested biomass)	297	93.7	104	Evrendilek and Wali 2004
Ns	307	192	162	Evrendilek and Wali 2004
NPPn=Nv (harvested Biomass)	5	5	4	Evrendilek and Wali 2004
N_{uptake}	4	4	3.2	Estimated
				Estimated
NPPsat	445	141	157	Estimated
Nav	4	4	4	Risser and Parton 1982

Units for vegetation carbon (*Cv*) and soil carbon (*Cs*) are g C m^{-2}. Units for vegetation nitrogen (*Nv*), soil N (*Ns*), and available inorganic N (*Nav*) are g N m^{-2}. Units for annual gross primary production (*GPP*), net primary production (*NPP*), and NPP_{sat} are g C m^{-2} yr^{-1}. Units for annual N uptake by vegetation (N_{uptake}) are g N m^{-2} yr^{-1}

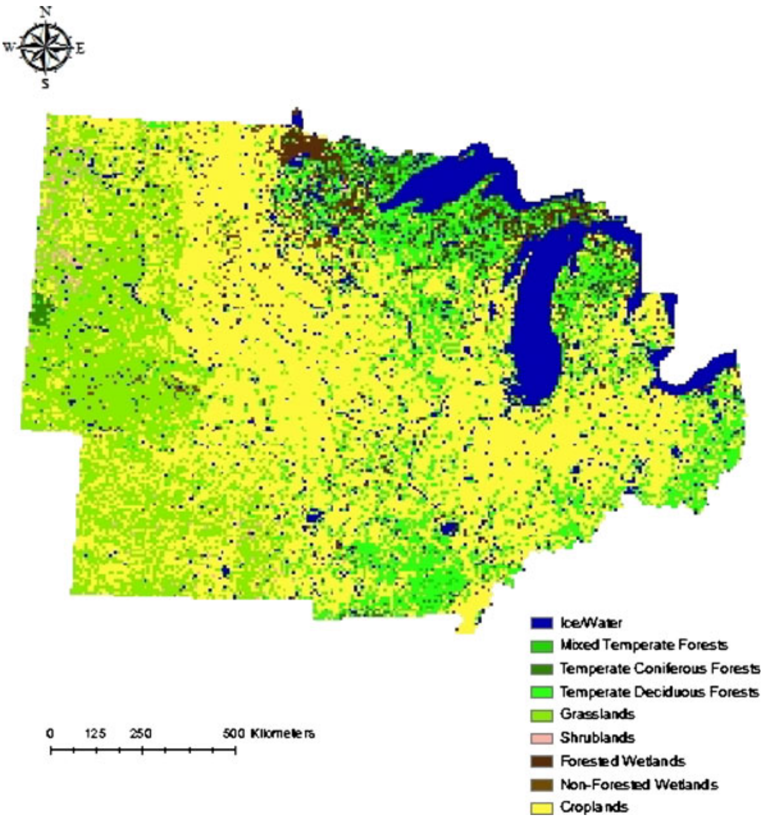


Fig. 1 Land cover in the Midwest derived from NLCD database. Open water, perennial ice/snow, low intensity residential, high intensity residential, commercial/industrial/transportation, quarries/strip, mines/gravel pits and bare rock/sand/clay in NLCD are defined as Ice in TEM. Pasture/hay, row crops and small grains, the three agricultural related types in NLCD, are calculated as croplands in TEM. Meanwhile, deciduous forest, evergreen forest, mixed Forest, shrublands, grasslands/herbaceous, woody wetlands and emergent herbaceous wetlands are reclassified as temperate deciduous forests, temperate coniferous forests, mixed temperate forest, shrublands, grasslands, forested wetlands and non-forested wetlands, respectively

TEM types (Fig. 1) and resample the dataset into a resolution of 8 km×8 km (Fig. 1). About 16% of the Midwest land is covered mainly by temperate coniferous forests and temperate deciduous forests. Dominant forest type in the north is conifer forests diminishing gradually southward. Most of deciduous forests are in the southern part. Another large land component is grasslands in the west, which account for 18.1% of the total land area. About half of the Midwest are croplands, which spread over the middle and east parts. Water bodies also occupy about 10% and the remaining cover types occupy relatively small portions of the total area.

The elevation data is used in the model to determine high-elevation snow cover. Digital Elevation Model (DEM) from the Space Shuttle Endeavor in the Shuttle Radar Topography Mission (SRTM) is used as the elevation dataset (Rabus et al. 2003). SRTM data are at 1 km and 90 m resolutions for the world and a 30 m resolution for the US. We produce an 8 km×8 km elevation map by re-sampling the 1 km×1 km dataset. The states in the Midwest are generally perceived as being relatively flat, but there is a measure of geographical variation. In particular, the eastern Midwest lies near the foothills of the

Appalachians, and northern parts of Wisconsin, Minnesota, and Iowa demonstrate a high degree of topographical variety.

Soil texture data including sand/silt/clay percentages are based on the soil map from the Food and Agriculture Organization/Civil Service Reform Committee (FAO/CSRC) digitization. The data is on a 0.5×0.5° spatial resolution. To get a soil texture layer with the same projection and resolution with the other data layers, the original data are resampled into an 8-km resolution with ArcGIS 9.1.

Corn, soybean and wheat, the three main crops in the Midwest, occupy a major fraction of croplands. We parameterize TEM for each of these crops. To conduct the simulation, we use the crop distribution data of the Midwest (www.sage.wisc.edu/download/majorcrops/; Leff et al. 2004). The synthesized satellite-derived land cover data and agricultural census data classify crops into 18 major crops. The resulting data are representative of the early 1990s and describe the fraction of a grid cell occupied by each of the 18 crops.

2.4 Development of regional verification data

Grasslands, forestlands and croplands cover most area in the Midwest (Fig. 1). We verify the performance of TEM for the three main vegetation types with satellite data, forest inventory data and agricultural statistical data, respectively.

MODIS is a key instrument aboard the Terra and Aqua satellites. The MOD17 algorithm provides the first operational, near-real-time calculation of global GPP and NPP products from EOS MODIS sensor (Running and Hunt 1993). It has two sub-products: (1) MOD17A2, storing 8-day composite GPP, net photosynthesis (PsnNet) and corresponding QC, and (2) MOD17A3, which contains annual NPP and QC. These products are released as formatted HDF EOS files (http://hdfeos.gsfc.nasa.gov) in a two-dimensional array with 1,200 columns and 1,200 rows in a Sinusoidal projection.

We obtain MOD17A3 NPP dataset in 2004 (http://www.ntsg.umt.edu) and compare the data with the TEM simulation for the same year. Before making comparison, we re-projected the original MODIS Sinusoidal projection into the NAD1983 projection system. In the MOD17A3, annual NPP is expressed as:

$$NPP = \sum_{i=1}^{365} \left[PsnNet - \left(R_{mo} + R_g\right)\right] \tag{1}$$

where R_{mo}(kg C day^{-1}) is maintenance respiration by all other living parts except leaves and fine roots (e.g., livewood), R_g (kg C day^{-1})is growth respiration and PsnNet (kg C day^{-1}) is defined as:

$$PsnNet = GPP - R_{ml} - R_{mr} \tag{2}$$

where (kg C day^{-1}) and (kg C day^{-1}) are the maintenance respiration of leaf and fine root mass, respectively.

For annual MOD17A3 products, however, there is not enough data to define annual QC at launch and a constant value (33) is used across all vegetated pixels. For the MOD17, an annual QC for GPP or NPP is expressed as:

$$QC = \left(\frac{Nu_g}{Total_g}\right)*100 \tag{3}$$

where NU_g is the number of days during the growing season with unreliable or missing MODIS leaf area index (LAI) inputs, and $TOTAL_g$ is total number of days in the growing season. The growing season is defined as all days with a minimum air temperature above −8°C. To select good NPP pixels for our verification, we exclude the low-quality pixels by selecting QC>45. Most excluded pixels are located in forest areas. The poor quality in LAI retrieved by the backup algorithm may be the reasons for this situation (Turner et al. 2006).

Because MODIS NPP datasets have low quality on forestlands, we use well-designed and statistically-sound national forest inventories over the long term from local sample plots to verify our simulated forest NPP. The Forest Inventory and Analysis (FIA) program has been conducting periodic surveys of the nation's forested land since 1928 (Birdsey and Schreuder 1992; Birdsey and Lewis 2003). While an annual sampling scheme is currently being implemented nationwide, recent inventories have typically been conducted every 5 to 7 years in the southeastern states and every 10 to 15 year in the northeastern states. The database provides forest type, biomass, stand-size, stand age, stand volume, total basal area and stand density. We use the forest biomass information from Forest Inventory and Analysis Database (FIADB) to test the performance of TEM on forestlands. Biomass data include live biomass on forestland and live merchantable biomass on forestland. The biomass means total biomass which includes contributions from roots, trunks and leaves. All the data are provided on the oven-dry and green basis. The oven-dry live biomass data on forestlands for the Midwest from 2004 to 2005 are obtained (http://www.fia.fs.fed.us) and we convert the biomass into a carbon weight by multiplying a factor of 0.45.

The National Agricultural Statistics Service (NASS) publishes U.S., state, and county level agricultural statistics for many commodities and data series. These data allow us to test NPP estimation on croplands (Stephen et al. 2001). The yields for some crops are reported in volume (e.g., bushels) rather than mass. For these crops, the reported yield of the economic product was multiplied by volume to mass conversion factors. To make a comparison with model simulated results, we calculate biomass of above-ground yield from the harvested yield statistics using harvest indices and then get total biomass based on root: shoot biomass ratios. Since our NPP simulations are expressed with the weight of carbon, we convert the total biomass into dry matter based on the conversion factor from fresh to dry mass and then to carbon weight based on the conversion factor from dry mass to carbon. The statistics-based NPP is computed by the following formula:

$$NPP = \frac{\sum_{i=1}^{N} Y_i*(1 - MC_i)*0.45/(HI_i*0.8)}{\sum_{i=1}^{N} A_i} \quad (4)$$

where Y_i is the reported yield, MC_i is the typical harvest moisture content (mass water/harvested mass, g g^{-1}), HI_i is the harvest index (ratio of yield mass to aboveground biomass) and A_i is the harvested area. Subscript i stands for different crops. Nine major crops are considered (N=9). It is assumed that 45% of crop biomass is C and 80% of NPP is allocated to aboveground parts. Potential variability within species for each of the factors used to convert yield to NPP is not considered in this study. Values for MC_i and HI_i are taken and adapted from Hicke and Lobell (2004) (Table 2). We obtain production

Table 2 Parameters used for converting statistical yields data to net primary production (*NPP*)

Commodity	Mass per reporting unit (kg)	Conversion to proportion dry matter	Harvest index	Root: shoot ratio
Corn (Zea mays) grain	25.4	0.871	0.53	0.18
Corn silage	907	0.262	1.00	0.18
Soybean (Glycine max)	27.2	0.920	0.42	0.15
Oats (Avena sativa)	14.5	0.923	0.52	0.40
Barley (Hordeum vulgare)	21.8	0.904	0.50	0.50
Wheat (Triticum spp)	27.2	0.894	0.39	0.20
Sunflower (Helianthus annuus)	0.453	0.931	0.27	0.06
Hay, alfalfa	907	0.850	1.00	0.87
Hay, others	907	0.850	1.00	0.87

and harvested acreage datasets for the reported commodities from 1995 to 2005 for every state in the Midwest.

3 Results and discussion

3.1 Model evaluation

Simulated spatial distribution of NPP is compared well with satellite-based MODIS NPP in 2004 (Table 3). The differences are relatively low in grasslands in comparison to forests and some croplands. MODIS NPP of grassland pixels has good quality and is compared well with TEM simulations. The large difference for forests might be due to MODIS NPP of forests having a poor-quality. About half of NPP data are excluded by the QC threshold and the remainders have higher values than the simulated NPP. For croplands, the MODIS algorithm uses one constant light use efficiency coefficient for

Table 3 The quality of MODIS net primary production (*NPP*) dataset for the Midwest in 2004 and its mean differences between TEM and MODIS NPP for different land cover types

Land cover types	Total pixel number	Pixel number with good quality	Mean NPP difference (TEM minus MODIS, g c m^{-2} yr^{-1})
Mixed Temperate Forests	465	150	171
Temperate Coniferous Forests	537	220	−89
Temperate Deciduous Forests	4273	2144	110
Grasslands	5959	5592	−86
Shrublands	239	217	−117
Forested wetland	1152	488	−338
No-Forested wetland	570	395	−144
Croplands	16483	12927	−186

Table 4 Comparison between forest inventory data and TEM simulations in each State of the Midwest

States	Forest carbon in 2004 from the forest inventory data (Tg C)	Simulated forest carbon in 2004 (Tg C)	Forest carbon in 2005 from the forest inventory data (Tg C)	Simulated forest carbon in 2005 (Tg C)
Illinois	87.1	455.0	89.5	457.8
Indiana	99.6	441.0	103.5	442.5
Iowa	44.9	236.1	46.6	238.2
Kansas	29.6	89.5	29.5	90.2
Michigan	324.0	754.4	327.3	755.5
Minnesota	191.2	708.2	191.2	713.1
Missouri	238.6	1639.3	240.4	1654.9
Nebraska	16.9	63.5	16.3	64.2
North Dakota	8.3	27.7	8.1	27.8
Ohio	204.5	743.3	200.2	745.3
South Dakota	13.0	49.9	13.5	51.2
Wisconsin	246.0	796.1	247.1	799.0
Total	1503.7	6004	1513	6039

different croplands to convert light energy into biomass. This may be the reason for the large differences between our modeled data and satellite-based cropland NPP.

The simulated forest vegetation carbon on the state level (Table 4) is generally larger than that estimated from the inventory data (Forest $VEGC_{simulated}$ = 3.49* (Forests

Table 5 Comparison of agricultural statistical average net primary production (*NPP*) and the simulated cropland average NPP in each State of the Midwest

States	Agricultural statistical average NPP from 1996 to 2005 (Tg C)	Simulated cropland average NPP from 1996 to 2005 (Tg C)
Illinois	72.1	42.1
Indiana	43.1	26.5
Iowa	82.2	41.6
Kansas	42.6	28.9
Michigan	26.2	14.5
Minnesota	65.0	33.0
Missouri	43.4	31.9
Nebraska	53.7	25.5
North Dakota	27.9	14.6
Ohio	33.6	21.1
South Dakota	36.9	23.2
Wisconsin	37.1	20.1
Total	563.7	322.9

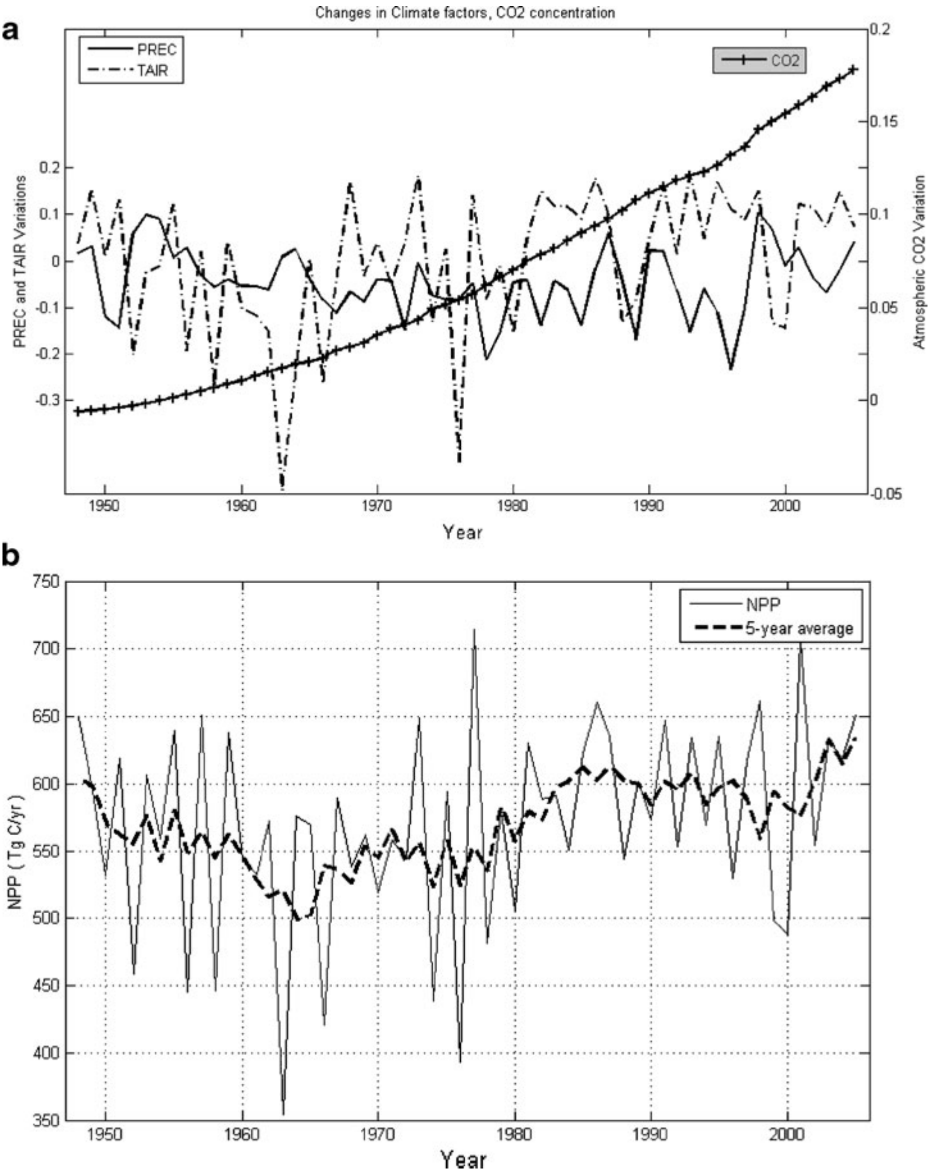


Fig. 2 **a** Interannual variations in atmospheric CO_2 (ppmv), annual average air temperature (Tair, °C) and annual average precipitation (Prec, mm yr^{-1}) from 1948 to 2005. All values represent the proportional changes of the variables relative to the averages from 1948 to 1960. Interannual changes in **b** net primary production (NPP, Tg C yr^{-1}), **c** net ecosystem production (NEP, Tg C yr^{-1}) and **d** heterotrophic respiration (R_H, Tg C yr^{-1}) in the Midwest from 1948 to 2005. For NEP, Positive values indicates carbon uptake and negative values indicate carbon release

$VEGC_{inventory}$) + 62.1, units: Tg C), while their correlation is good (r^2=0.67, P<0.05). This discrepancy is primarily because we have not considered the stand age effects, which may lead to this overestimation as forests accumulate carbon in young and middle age, but the rates decline as stands mature (Sierra et al. 2009). In addition, decreased nutrient

Table 6 Simulated mean annual net primary production (NPP) (1948–2005) for different ecosystems. Model results represent the potential climate impacts on ecosystem carbon fluxes

Land cover	Mean NPP (g C m^{-2} yr^{-1})	Total (Tg C yr^{-1})
Mixed temperate forest	586	17.4
Temperate coniferous forests	447	15.4
Temperate deciduous forests	790	216
Grasslands	212	80.9
Shrublands	163	2.5
Forested wetlands	158	11.6
Non-forested wetlands	230	8.4
Croplands	207	218.4

availability and increased stomatal limitation cause a decline in NPP as stands age (Gower et al. 1996).

At a state-level during 1996–2005 (Table 5), TEM underestimates cropland NPP (Croplands $NPP_{simulated}$ = 0.47* (Croplands $NPP_{statistics}$) + 4.5, units: Tg C yr^{-1}), but the correlation is good (r^2=0.8, p<0.05). The reason for underestimation may be because the effects of irrigation, fertilization and technology improvement on crop yields have not been considered in our simulations.

3.2 Carbon dynamics from 1948 to 2005

3.2.1 Net primary production

The simulated regional NPP varies between 354 and 714 Tg C yr^{-1}, the annual mean NPP for the period 1948–2005 is 570 Tg C yr^{-1} (Fig. 2(b)). Annual total NPP in the Midwest shows a slight increasing trend by 0.12% yr^{-1} during the period. The interannual variation of NPP is highly correlated with precipitation (R^2=0.57, P<0.01), while the correlation of NPP with temperature is much lower. Precipitation tends to be the dominant factor for NPP in the region. However, temperatures affect the responses of NPP to precipitation, an

Table 7 Decadal average net primary production (NPP) (g C m^{-2} yr^{-1}) variations in different ecosystems in the last 50 years of the 20th century. Model results represent the potential climate impacts on ecosystem carbon fluxes

Vegetation land cover	1950s	1960s	1970s	1980s	1990s
Mixed forest	601	552	563	594	610.6
coniferous forests	443	427	437	452	462.1
deciduous forests	803	722	746	811	817
Grasslands	188	196	210	231	224
Shrublands	156	154	163	176	167
Forested wetlands	159	150	155	159	160
Non-forested wetlands	231	218	221	250	247
Croplands	201	190	198	215	213

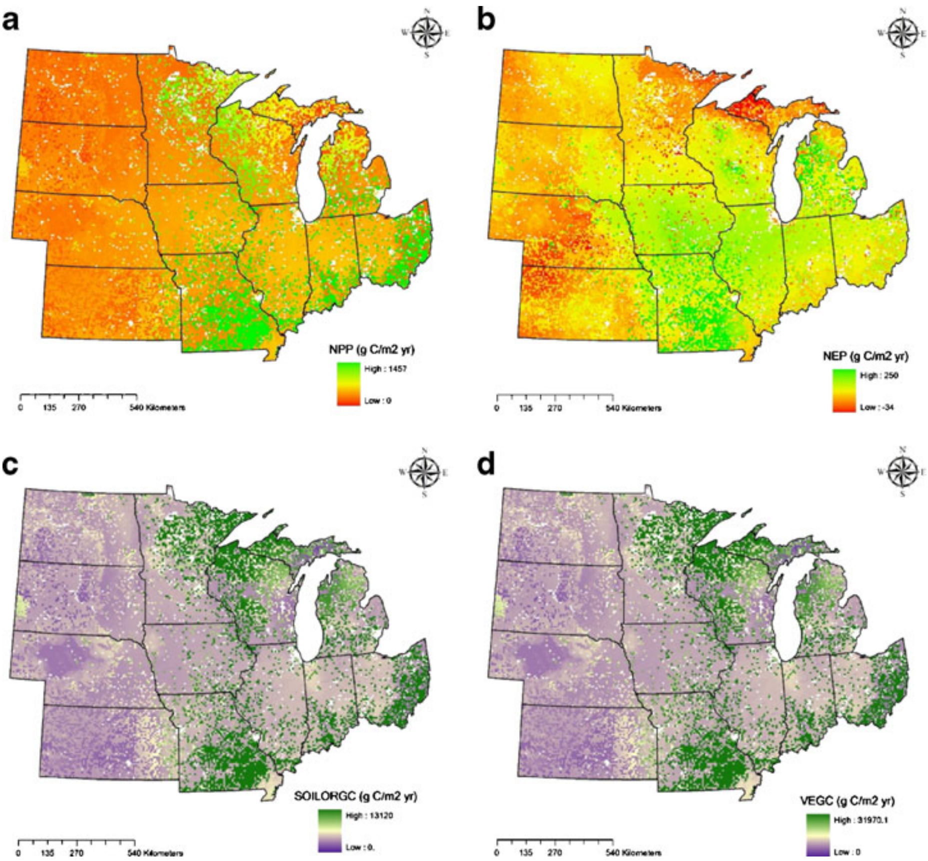


Fig. 3 Mean annual carbon fluxes and pools during 2000–2005: **a** NPP, **b** NEP, **c** SOILORGC and **d** VEGC

increase in temperature will enhance NPP in wet years (e.g. in 1986, 1987) and a decrease in dry years (e.g., in 1952, 1963). Meanwhile decreases in temperature appear to slightly decrease NPP in dry years (e.g. in 1977, Fig. 2(b)).

During some extreme climate years, NPP responds differently compared to the responses in normal climate years. For example, NPP decreases markedly in 1963 because of a combined warming and drought (Fig. 2(a)). In this year, the regional mean NPP is lower than the average level by 38%, which is associated with an increase of 5% in temperature and a decrease of precipitation by 34% in comparison with the average. NPP increases substantially in 1978 when precipitation reaches a high level on the record and temperature is slightly lower than the average.

The simulated NPP depends greatly on vegetation type and density (Table 6). Deciduous and mixed forests have the highest capability of absorbing carbon on per unit surface area, followed by coniferous forest, grasslands and croplands. During the study period, the average annual NPP for forested areas is 698 g C m^{-2} yr^{-1} while the regional mean NPP is only 301 g C m^{-2} yr^{-1}. Although croplands are only about half as productive as deciduous forests on per unit area, croplands, as a whole, contribute the greatest portion, i.e. 38%, to the regional annual NPP because of their large coverage (Fig. 1).

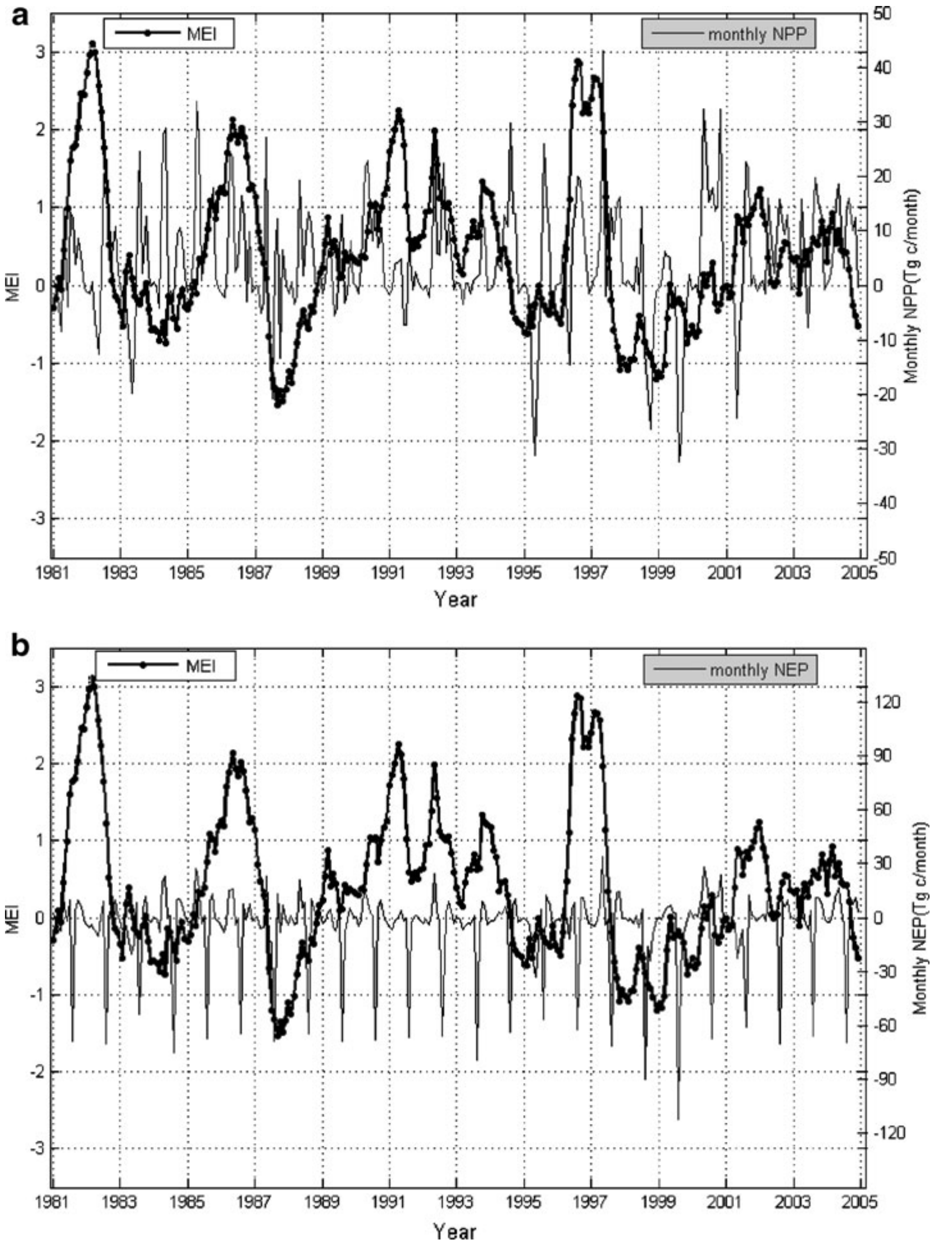


Fig. 4 Temporal changes in the Midwest NPP (**a**) and NEP (**b**) anomalies. The anomalies are the deviations from the mean values between 1981 and 2005. The multivariate ENSO index (MEI) represents the intensity of El Niño or La Niña events that normally have a MEI above 0.5 and under −0.5, respectively (24)

We investigate the decadal average NPP changes from the 1950s to the 1990s for all vegetation types used in TEM. Except for forested wetlands, NPP for all vegetation types show a decrease in the 1960s and an increase in the 1980s (Table 7). No significant increasing trends are observed for forested wetlands in the Midwest, which is probably due

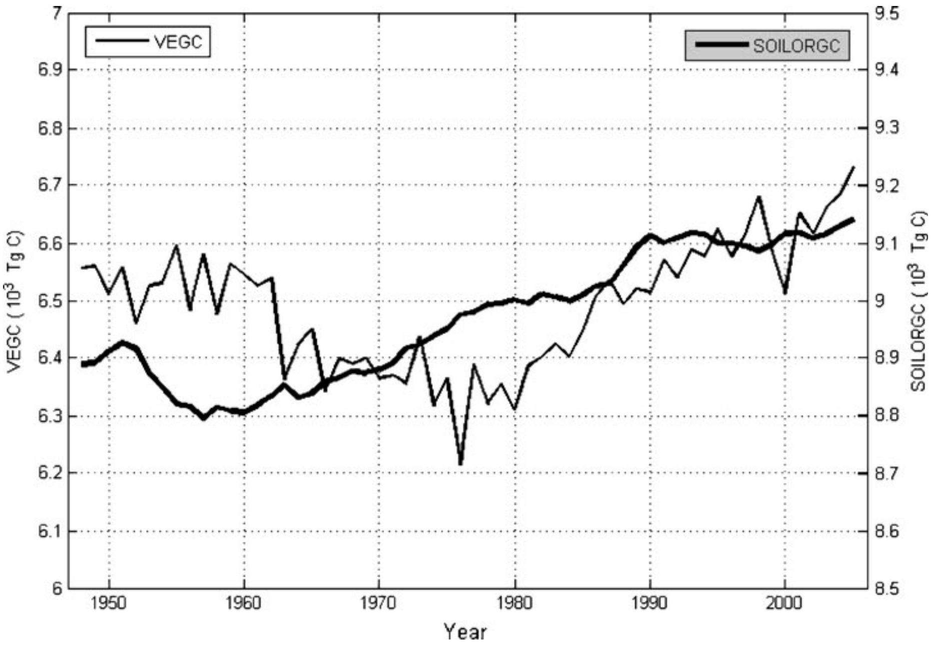


Fig. 5 Changes in vegetation carbon (*VEGC*) and soil organic carbon (*SOILORGC*) in the Midwest during 1948–2005

to a small of numbers of grid cells. During that period, the largest increase in NPP occurred in grasslands with an annual mean 0.7 g C m^{-2} yr^{-1}, while other vegetation types only have a slight increase in NPP (Table 7). The mean increase rate of NPP for most vegetation types is close to 0.15% per year, which is similar to the annual mean increase rate of 0.12% over the whole region.

Spatially, forests, mainly in the northern and southern Midwest, have higher NPP which are normally between 500 and 800 g C m^{-2} yr^{-1}; croplands and grasslands are major types in the middle and west parts and have NPP ranging from 200 to 400 g C m^{-2} yr^{-1} (Fig. 3a).

3.2.2 Net ecosystem production

`Annual NEP varies considerably from year to year, ranging from 91.7 to 82.5 g C m^{-2} yr^{-1} from 1948 to 2005, and from −156 to 174 Tg C per year in the region (Fig. 2(c)). During the same time period, the mean annual NEP in the Midwest is 26.8 Tg C yr^{-1}, indicating that Midwest's terrestrial ecosystem as a whole is a carbon sink under the change of climatic conditions and the increase of atmosphere CO_2. NEP shows a small increasing trend of 0.62 Tg C yr^{-1}, suggesting that the capacity of carbon uptake of Midwest's ecosystems is increasing during 1948–2005. NEP generally responds to climatic factors in the same way to that of NPP. Specifically, an increase in temperature and decrease in precipitation leads to a decrease in NEP, while both increases will make a great increase in NEP. At the regional

Fig. 6 5-year average time series of regional annual **a** NPP, **b** vegetation carbon (*VEGC*) and **c** soil organic carbon (*SOILORGC*) simulated with TEM under the future climate scenarios A1B, A2 and B1 scenarios ▶

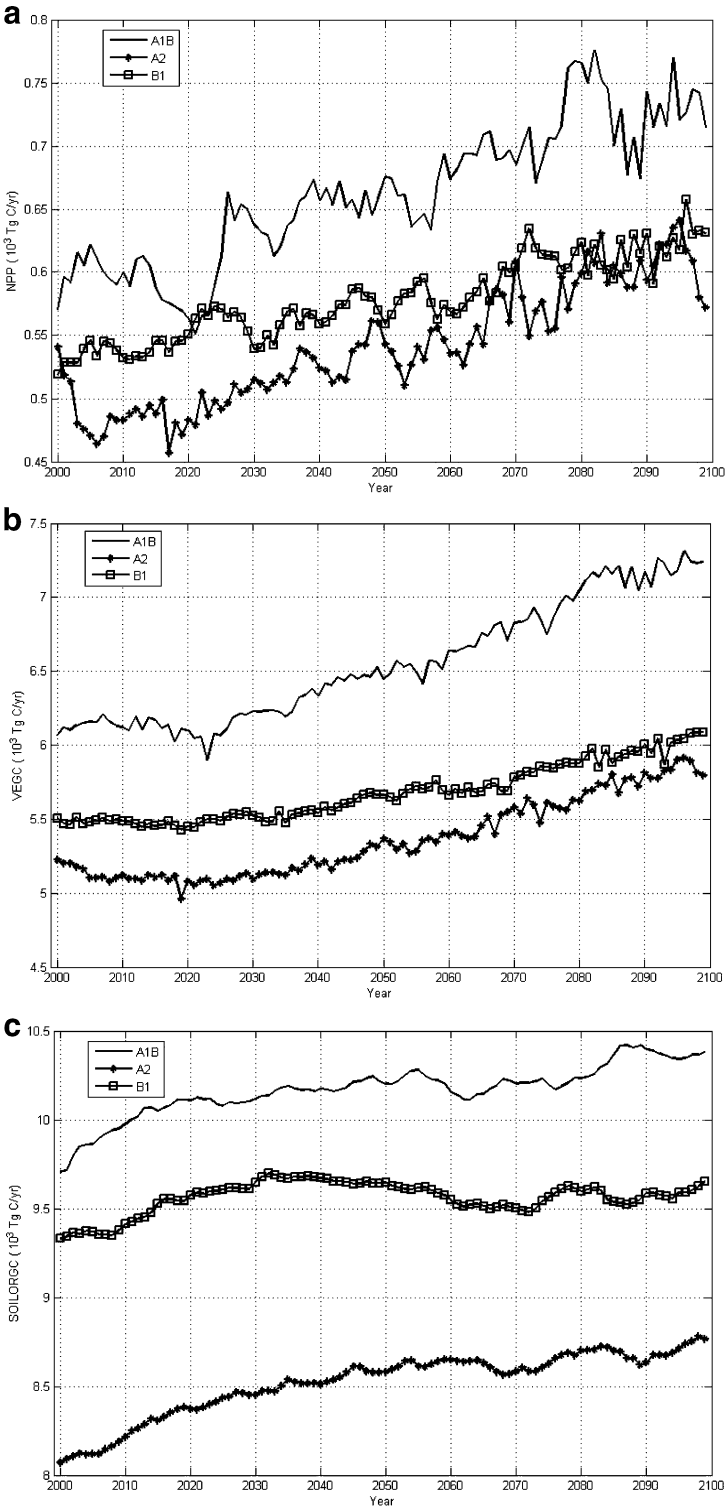

a
A1B
A2
B1
NPP (10³ Tg C/yr)
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year
b
A1B
A2
B1
VEGC (10³ Tg C/yr)
7.5
7
6.5
6
5.5
5
4.5
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year
c
A1B
A2
B1
SOILORGC (10³ Tg C/yr)
10.5
10
9.5
9
8.5
8
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year

Table 8 Changes in carbon pools (Tg C) and annual fluxes (Tg C yr^{-1}), presented as average differences between the periods 2000–2029 and 2070–2099. Model results represent the potential climate impacts on ecosystem carbon fluxes and pools. NPP, NEP, RH, SOILORGC, and VEGC represents net primary production, net ecosystem production, heterotrophic respiration, soil organic carbon, and vegetation carbon, respectively

Variables	2000–2029, A1b	2070–2099, A1b	Δ	Δ(%)	2000–2029, A2	2070–2099, A2	Δ	Δ(%)	2000–2029, B1	2070–2099, B1	Δ	Δ(%)
NPP	596.3	727.1	130.8	21.9	490.4	595.5	105.1	21.4	546.3	618.9	72.6	13.3
NEP	31.27	45.325	14.1	44.9	25.8	34.2	8.4	32.6	25.9	35.7	9.8	37.8
R_H	565.06	681.8	116.7	20.7	464.6	561.2	96.6	20.8	520.3	583.2	62.9	12.1
SOILORGC	9999.2	10303	303.8	3.0	8278.2	8675.6	397.4	4.8	9479.6	9570.2	90.6	1.0
VEGC	6117.6	7076.1	958.5	15.7	5108	5712.5	604.5	11.8	5482.3	5929.3	447.0	8.2
Total carbon	16117	17379	1262.0	7.8	13386	14388	1002.0	7.5	14962	15500	538.0	3.6

scale, annual NEP is positively correlated with precipitation (R^2=0.61, P<0.05), while its correlations with temperature is not significant. NEP reaches the highest in 1977 with a great increase in NPP and a slight rise in R_H (Fig. 2(d)). NEP is the lowest in 1963 when NPP reaches the lowest level because of the severe drought across the whole Midwest (Fig. 2(a)).

While the obvious seasonal fluctuations dominate the temporal variations in ecosystem carbon fluxes, the deseasonalized anomalies (the difference between the value in a given month and the mean value for that month from 1981 to 2005) of carbon fluxes in the Midwest ecosystems show a clear correlation with ENSO cycles (Fig. 4(a)). The Midwest mean monthly NPP for El Niño seasons, defined as the period when the multivariate ENSO index (MEI) is above 0.5 (Wolter and Timlin 1998), is 4.14% lower than that for La Niña seasons when the MEI is under −0.5 (Fig. 4(a)). On the whole region scale, northern forests and most grasslands are carbon sources under the current climate, whereas the southern forests and almost all croplands are functioning as a carbon sink (Fig. 3(b)).

During the period of 1981–2005, terrestrial ecosystems release 4.7 Tg C month^{-1} in El Niño years but sequester 10.0 Tg C month^{-1} in La Niña years. NEP decreases greatly, by up to 10–20%, in the strong El Niño periods of 1982/1983, 1986/1987, and 1997/1998. In the 1991/1992 El Niño period, NPP decreases, but NEP increases due to the decreases in R_H (Fig. 4(b)) associated with a cooling caused by the Mount Pinatubo eruption (Hansen et al. 1996). In normal or La Niña years such as 1984/1985, 1988/1989, 1995/1996 and 1998/1999, temperatures are lower and precipitation is higher than that in El Niño years, so the estimated higher NPP and lower R_H led to increases in NEP.

3.2.3 *Vegetation and soil carbon*

The average vegetation and soil carbon during 2000–2005 are presented in the Fig. 3(c) and (d). The deciduous forests in the south have larger vegetation carbon than coniferous forests in the north. There is a little difference in soil organic carbon in these two kinds of forests.

Total carbon storage in terrestrial ecosystems in the Midwest is 15460 Tg C averaged over 1948–2005, with 6490 Tg C in vegetation and 8970 Tg C in soils (Fig. 5). Our soil organic carbon estimation is similar to the results reported by Peter et al. (2006). Both vegetation carbon and soil organ carbon increase slightly from 1948 to 2005. TEM simulates a small decline in soil organic carbon during the late of the 1950s followed by a sharper increase from the 1970s. Vegetation carbon changes similarly in comparison to soil carbon, but with more pronounced patterns. There is a decrease from the middle of the 1960s to the early of the 1980s with the minimum in 1978. In the 58-year period, NPP increases from 175 to 250.6 Tg C yr^{-1}, resulting in an increase of 425.7 Tg C for total vegetation carbon pools. Our analysis indicates that the increase rate of R_H due to increasing temperature cannot catch up with the increase of NPP as increasing precipitation stimulates photosynthesis, leading to an increasing of vegetation carbon, soil carbon, and total carbon at 3.1, 4.3 and 7.4 Tg C yr^{-1}, respectively.

3.3 Carbon dynamics during 2000–2099

By the end of the 21st century, the thirty-year average NPP increases under all the scenarios to 102.8 Tg C yr^{-1}, a 19% increase relative to the first 30-year average. Increases in NPP range between 22% and 21% for the A1b and A2 scenarios (Fig. 6(a), Table 8), from 596.3 to 727.1 and from 490.4 to 595.5 Tg C yr^{-1}, respectively. The lowest NPP increase of 13%, from 546.3 to 618.2 Tg C yr^{-1}, under the B1 scenario. B1 is the most ecologically friendly scenario with its modest increase in CO_2 concentrations and temperature. The other two scenarios give almost the same increase magnitude in NPP. Our analysis suggests that the photosynthetic capacity of vegetation in the Midwest will be stimulated moderately under the sharp increase in the temperature and CO_2 concentrations.

In the first half of the 21st century, the magnitude of the changes in NEP keeps a steady increasing trend under all the scenarios except in some extreme years (Fig. 7). Interannual fluctuations in NEP will increase after the 2060s. There are strong fluctuations between source and sink behavior during the second half of the century. However, under all the three scenarios, on average the region will be a carbon sink during the 21st century. Compared to the first 30-year average NEP, the annual NEP will increase in the order of 33–45%, resulting in net carbon storage from 34.2 to 45.3 Tg C per year by the end of the 21st century (Table 8). Benefiting from low R_H, NEP under the B1 scenario markedly increases by 38%. The large increase in NPP under the A1B and A2 scenarios, on the other hand, are counteracted to some extent by their associated increase in R_H, leading to increases in their NEP from 31.3 to 45.3 Tg C yr^{-1} and 25.8 to 34.2 Tg C yr^{-1}, respectively.

The size of the soil carbon pool is a function of the litter input, and hence indirectly of NPP, and the heterotrophic respiration rate. By 2099, the three climate scenarios show changes in the soil carbon pool that range between an increase of 90.6 Tg C or 1% (B1, Fig. 6(c)) and an increase of 397.4 Tg C or 4.8% (A2, Fig. 6(c)), on average a minor increase of 264 Tg C or 2.8% (Table 8). The magnitude of increases in R_H is approximately equal to that in NPP (Table 8).

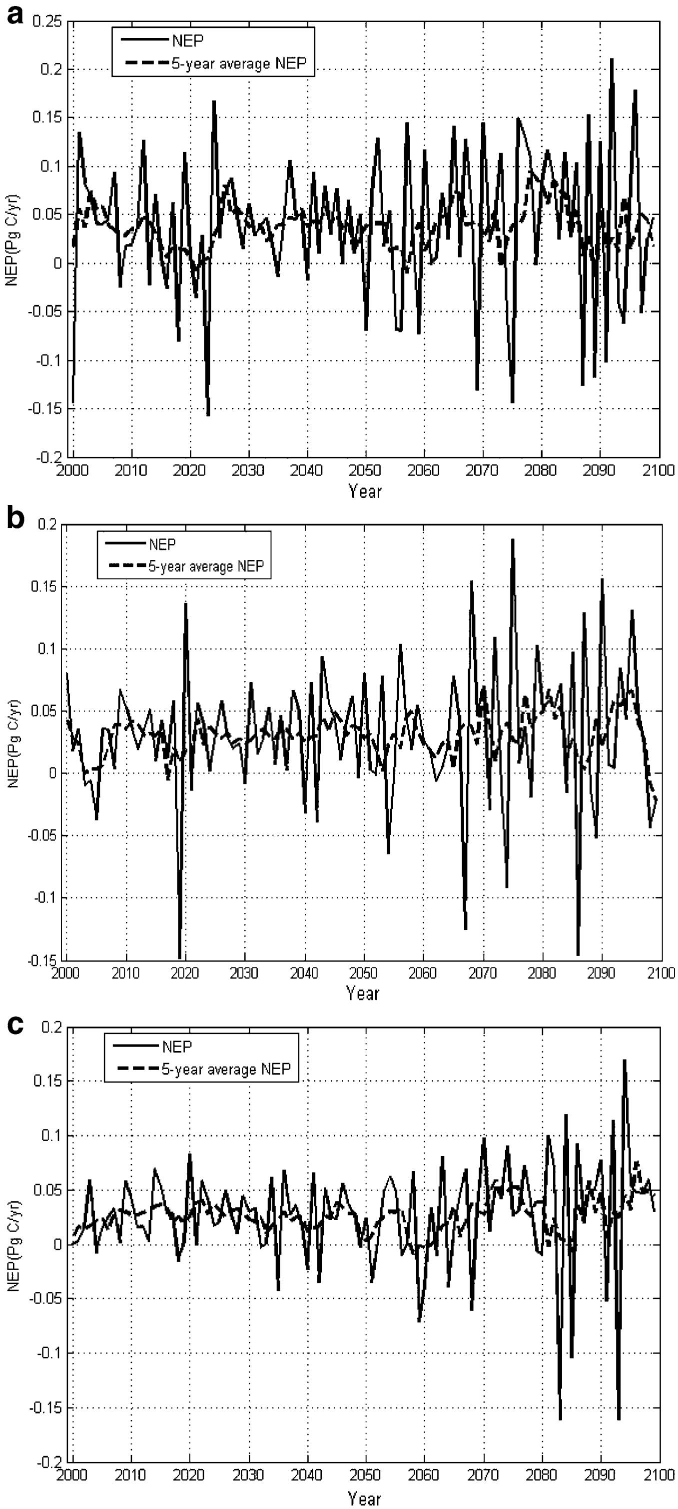
The size of the vegetation carbon pool is a function of NPP and plant mortality. Despite increases in NPP for all scenarios, the B1 scenario (Fig. 6(a)) has the lowest increases in NPP, suggesting only minor changes in biomass (less than 447 Tg C or 8%). The other two results show increases of 958.5 and 604.5 Tg C of vegetation carbon in the Midwest under the A1B and A2scenarios, respectively (Fig. 6(b), Table 8). The higher CO_2 concentrations exert the fertilization effect under the latter two scenarios on plants, leading to a larger vegetation carbon pool size.

Total average carbon storage in 2070–2099 under the A1B is estimated to be 17,397 Tg C, a small increase of 1262 Tg C or 7.8% relative to the data in 2000–2029 (Table 8). A similar response under the A2 scenario shows a 1002 Tg C or 7.5% increase. Under the cooler and less dry B1 scenario, the regional ecosystem carbon only increases 538 Tg C or 3.6% from the level in the first 30-years period by the end of the 21st century.

4 Conclusion

In this study, we quantify carbon fluxes and pools in vegetation and soil for the Midwest United States under the contemporary and future climate conditions with a process-based ecosystem model at a high resolution (8 km×8 km). The simulated annual NPP increases by 2% during 1948–2005. The variations of NPP and NEP are correlated with ENSO cycles with decreases in El Niño and increases in La Niña seasons. Most ecosystems gain a similar enhancement of C uptake. Precipitation is the dominant factor for the increasing in NPP. Precipitation exerts stronger effects on R_H than air temperature does. As a result, NEP is increased. The regional total NEP ranges from a source of 156 Tg C per year to a sink of 174 Tg C per year with a mean value of

Fig. 7 Time series of regional NEP simulated with TEM under the future climate scenarios **a** A1B, **b** A2 and **c** B1 scenarios ▶


a
NEP
5-year average NEP
NEP(Pg C/yr)
Year
b
NEP
5-year average NEP
NEP(Pg C/yr)
Year
c
NEP
5-year average NEP
NEP(Pg C/yr)
Year

26.8 Tg C yr^{-1}, resulting in carbon accumulation in the Midwest terrestrial ecosystem of 1554 Tg C during 1948–2005. Under the three future climate scenarios, the Midwest will act as a carbon sink with higher fluctuations in the second 50 years of the 21st century.

This evaluation and analysis focuses on the potential impacts of climate change on changes of vegetation and soil carbon of the terrestrial ecosystem in the Midwest of the United States. In this study, we have used the best available data of forestry inventory, agricultural statistics, and satellite remote sensing data to evaluate our simulations and then used the model to evaluate the potential responses of carbon dynamics in the region during the 21st century. While the ecosystem model used here has not explicitly modeled crop ecosystems, the vegetation and soil carbon and nitrogen data of pools and fluxes of major crops in the region were used to parameterize our model. We recognize that this analysis has not considered the effects of land-use and land-cover change and the effects of fertilization, irrigation and management on agricultural ecosystems. Thus, our future analysis should take these effects into account.

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