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Effects of Land Use Change for Crops on Water and Carbon Budgets in the Midwest USA

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Abstract: Increasing demand for food and bioenergy has altered the global landscape dramatically in recent years. Land use and land cover change affects the environmental system in many ways through biophysical and biogeochemical mechanisms. In this study, we evaluate the impacts of land use and land cover change driven by recent crop expansion and conversion on the water budget, carbon exchange, and carbon storage in the Midwest USA. A dynamic global vegetation model was used to simulate and examine the impacts of landscape change in a historical case based on crop distribution data from the United States Department of Agriculture National Agricultural Statistics Services. The simulation results indicate that recent crop expansion not only decreased soil carbon sequestration (60 Tg less of soil organic carbon) and net carbon flux into ecosystems (3.7 Tg·year^{-1} less of net biome productivity), but also lessened water consumption through evapotranspiration (1.04×10^{10} m^3·year^{-1} less) over 12 states in the Midwest. More water yield at the land surface does not necessarily make more water available for vegetation. Crop residue removal might also exacerbate the soil carbon loss.

Keywords: land use and land cover change; agriculture; evapotranspiration; soil organic carbon; net biome productivity; Agro-IBIS

1. Introduction

The Midwest USA is dominated by croplands. Historical land use and land cover change (LULCC) in the Midwest included expansion of annual crops [1,2]. In the past few decades, biofuels have attracted attention due to the demand for renewable energy and the issue of global warming. Accordingly, the increased demand for biofuel production has altered the landscape dramatically, with corn production increasing greatly and corn expansion being the dominant LULCC in the Midwest USA in recent years [2,3]. The trend of LULCC for bioenergy is likely to continue in the near future, and it might be altered when perennial grasses such as switchgrass and miscanthus become fully commercialized.

LULCC related to croplands affects water and energy cycles [2,4], soil properties [5], and ecosystem carbon storage [6], which are important in the environmental aspect of sustainable development. The impacts of LULCC are unlikely to be distributed evenly due to the heterogeneity of land surface characteristics. Instead, the specific effect is a combination of local weather, soil type, prior land use, and management strategies in agricultural lands. Recently, some studies have explored the effects of LULCC associated with bioenergy production and biofuel feedstock expansion in Europe [7] and in the USA [8–11]; however, none of these studies focused on the spatial distribution of the effects in the Midwest USA with explicit land cover scenarios. Vanloocke et al. (2010) and Vanloocke et al. (2012) used the same model that we use here over nearly the same spatial domain to quantify the potential hydrologic impacts of land use change for perennial grass bioenergy feedstock production (i.e., miscanthus and switchgrass) [12,13]. Here, we represent actual land use change over two recent time periods to estimate the impacts of land use change for corn ethanol production on corn grain yield, evapotranspiration, soil organic carbon, and net ecosystem productivity.

In this study, we used the process-based Integrated Biosphere Simulator, agriculture version (Agro-IBIS) [14], to estimate the changes in water budget, carbon exchange, and carbon storage associated with LULCC in the Midwest USA. We used data collected by the United States Department of Agriculture (USDA) National Agricultural Statistics Services (NASS) in 2007–2008 and 2011–2012 as an historical case. The paper is organized as follows: in Section 2 we describe the study domain, land cover distribution, and model simulations; in Section 3 we present the results of the model simulations; and in Section 4 we discuss our results.

2. Methods

2.1. Study Domain and Land Cover Scenarios

We focused on 12 states in the Midwest USA; Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin (Figure 1). The study domain provides a contiguous landscape encompassing large portions of the Midwestern plains, temperate forest, and croplands. The 12 states also include about 80% of operational U.S. bioethanol production facilities (total of 210) as of November 2013, making them the primary location of corn expansion to meet the ethanol production demand [10,15].

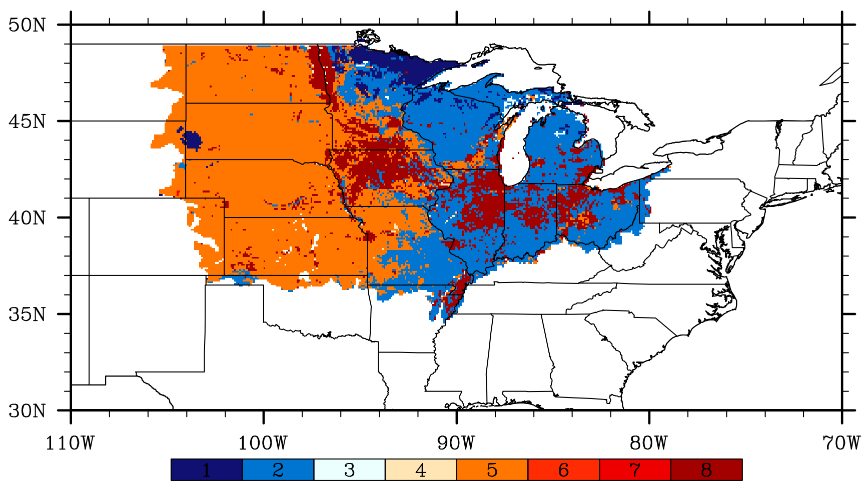

Figure 1. Natural vegetation distribution in the study domain in the baseline scenario 1: temperate evergreen conifer forest; 2: temperate deciduous forest; 3: mixed forest; 4: savanna; 5: grassland/steppe; 6: dense shrubland; 7: open shrubland; 8: unclassified, urban, barren.

To evaluate the impacts of recent LULCC, we built two crop distribution maps based on the USDA NASS Cropland Data Layer (CDL) database [16], one valid for 2007–2008 and one for 2011–2012. The resolution of the original CDL was 56 m for 2007–2008, and 30 m for 2011–2012. We reclassified the vegetation categories to fit those of Agro-IBIS (Table 1), and then aggregated the data to a 5-min spatial resolution to match that of the atmospheric forcing. Because Agro-IBIS currently only simulates natural vegetation along with the major annual crops of this region, corn, soybean, and wheat, all other crop types were replaced with the dominant natural vegetation in each corresponding grid cell. These crops usually grew in much smaller areas compared with corn, soybean, and wheat. The crop rotations were also considered in the model simulations (i.e., corn/soybean, corn/wheat, and soybean/wheat). The urban and barren land covers were considered unvegetated in Agro-IBIS and were masked out. The two dominant types of natural vegetation are grassland, which is mainly found in the western side of the domain, and temperate deciduous forest, which is in the eastern side of the domain (Figure 1).

Table 1. Classes of natural vegetation and annual crops in Agro-IBIS.

Natural vegetation	tropical evergreen forest/woodland
	tropical deciduous forest/woodland
	temperate evergreen broadleaf forest/woodland
	temperate evergreen conifer forest/woodland
	temperate deciduous forest/woodland
	boreal evergreen forest/woodland
	boreal deciduous forest/woodland
	mixed forest/woodland
	savanna
	grassland/steppe
	dense shrubland
	open shrubland
	tundra
	desert
Crops	corn
	soybean
	wheat

We calculate the fraction of the areas of natural vegetation and each crop type in every grid cell over the study domain. Figure 2 shows the area fractions of natural vegetation during the two time periods of the USDA scenario. Between 2007–2008 and 2011–2012, the crops expanded at the expense of natural vegetation from the center of the study domain in all directions. Corn and corn/soybean rotation increased dramatically between the two time periods (Figure 3). The other four crop types increased as well, but with relatively smaller magnitudes (Figure 4).

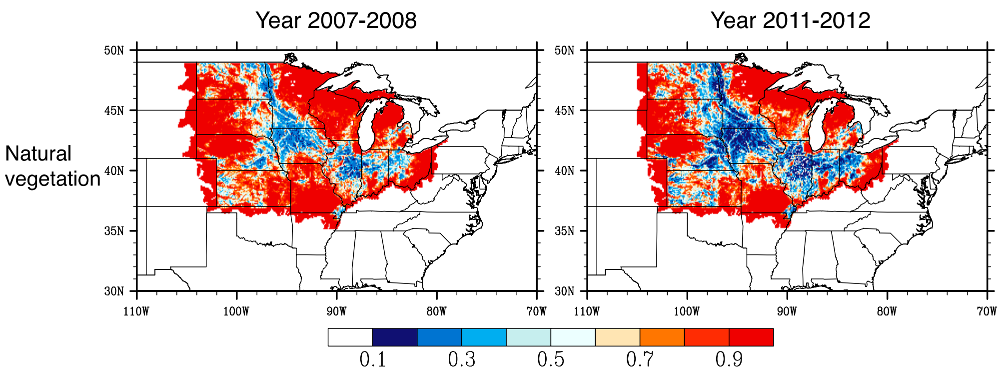

Figure 2. Area fraction (AF) per grid cell for the USDA 2007–2008 and 2011–2012 scenarios for natural vegetation.

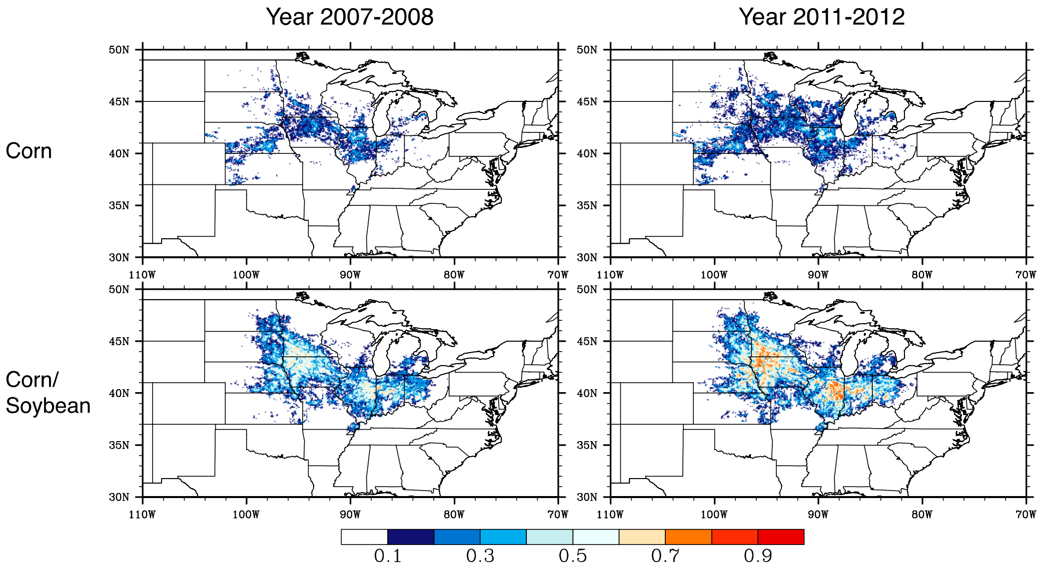

Figure 3. Area fraction (AF) per grid cell for the USDA 2007–2008 and 2011–2012 scenarios for corn and corn/soybean rotation.

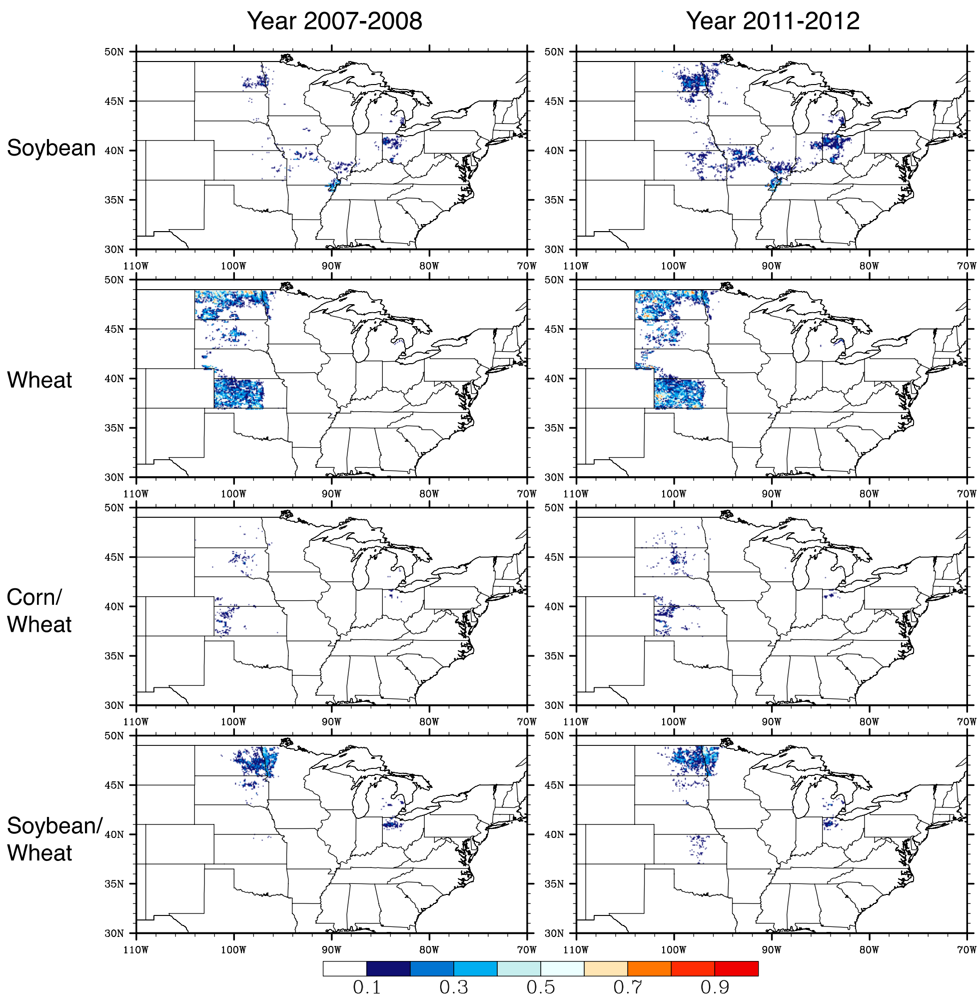

Figure 4. Area fraction (AF) per grid cell for the 2007–2008 and 2011–2012 scenarios for soybean, wheat, corn/wheat, and soybean/wheat rotation.

2.2. Agro-IBIS Model

Agro-IBIS [14] is a successor of the original IBIS model [17,18], which incorporates a wide range of processes including water, energy, and carbon exchange between the land surface and atmosphere; leaf and canopy physiology (photosynthesis and respiration); plant phenology (leaf emergence, grain fill, and senescence); vegetation dynamics (growth and competition among different vegetation types) and nutrient cycling (carbon and nitrogen transport) in both natural and managed ecosystems. The model represents trees, shrubs, and grasses, along with three major annual crops (corn, soybean, wheat), two perennial grasses managed for biofuel production (switchgrass and miscanthus), and sugarcane [12,13,19]. The model is capable of simulating crop growth and behavior by taking into account management such as irrigation, fertilizer application, planting and harvest date, and cultivar selection. After harvest, the crop residue is left on the field and assumed to be immediately put belowground to decompose. Assimilated carbon is partitioned among leaf, stem, root, or grain based on the physiological stage of the plant. Crop growth stage is determined by the total growing degree days relative to the crop planting date. The crop planting date is determined by comparing the 10-day running means of daily mean air temperature and minimum temperature with the threshold values but also could be prescribed. An adjustable multilayer (up to 11 soil layers and 2.5 m depth) soil formulation is used in Agro-IBIS. Parameters related to soil physical and hydraulic properties are assigned based on the soil texture type (classified into 12 categories) in each soil layer. The plants extract water and nitrogen from each soil layer based on the availability and root distribution. Agro-IBIS can be driven by site-specific atmospheric forcing or gridded data defined at any spatial resolution. Kucharik et al. (2000) validated the performance of Agro-IBIS comprehensively through comparing the model simulation with global-scale observations of water balance and carbon balance [18]. Agro-IBIS has been used to evaluate corn yield against field observations and USDA census data across the USA Corn Belt [16,20,21] and soybean yield in Brazil [22], as well as to evaluate the crop growth, daily net ecosystem productivity, and ecosystem respiration against measurements at an Ameriflux site [23]. The model has been used to explore crop production and nitrate export in the Mississippi River basin [24,25], river discharge and seasonal and interannual variations in water balance [26,27], and environmental issues related to switchgrass and miscanthus production for bioenergy [12,13,28].

2.3. Data and Regional Simulation

To drive the Agro-IBIS model, we used a 5-min spatial resolution daily atmospheric forcing dataset developed by ZedX Inc. (Bellefonte, PA, USA), which includes solar radiation, precipitation, air temperature, wind speed, and relative humidity for the period 1948–2007 [29]. Hourly values were calculated through empirical formulations [30]. This dataset has been used to examine the climate-induced changes in biome distribution, net primary productivity, hydrology in the upper Midwest [29], and crop residue management on soil temperature [28]. The soil texture data used in this study were derived from the USDA State Soil Geographic Database (STATSGO) 1 km resolution dataset [31] and aggregated to 5 min to match the atmospheric forcing.

We ran Agro-IBIS at an hourly time step from 1951 through 2007 following a spin-up period of 200 years (1751–1950). In the spin-up run, the model selected random years from the 1948–2007 dataset of climate forcing for years before 1948. The spin-up period contained an accelerated soil routine that allowed soil carbon pools to reach near-equilibrium conditions. Irrigation was not considered in the model simulations as the relatively small spatial coverage of irrigated corn (i.e., mainly in Nebraska [32]) were not major factors in our results and analysis. We used the natural vegetation map developed by Mehaffey et al. [14] based on the National Land Cover Database (NLCD) [33] and LANDFIRE existing vegetation layers [34] for the year 2001 when simulating the USDA landscape scenarios (2007–2008 and 2011–2012). Each land cover scenario was run through the entire climate period to allow each scenario to experience the range of climate that occurred over the 1951–2007 period. We then averaged model output to obtain a 40-year average (1968–2007) value of each variable at each grid cell for each landscape scenario. The grid cell values of each variable represent the linear average of all vegetation types. For example, the average annual evapotranspiration (ET) from a grid cell containing 40% tree and 60% corn/soybean rotation is calculated as 40% the average annual value of tree ET over all model years and 60% the value of crop ET, where crop ET is the sum of ET from corn for half the model years and soybean for half the model years.

We examined the annual mean evapotranspiration ratio (ET/P), which is defined as the ratio of mean annual evapotranspiration (ET) to average annual precipitation (P). We also examined the mean annual soil organic carbon (SOC) to 1 m depth of soil and the mean annual net biome productivity (NBP). NBP is defined as the net ecosystem exchange (NEP) of croplands after subtracting carbon from the harvested biomass (grain). NBP quantifies the net carbon flux between the ecosystem and atmosphere and is therefore an indicator of carbon sequestration. NBP is the same as NEP for natural vegetation in the study as there is no biomass harvest in natural ecosystem. Hereafter, we use NBP to refer to the net productivity in both croplands and natural ecosystems. We also examined the annual mean dry matter yield (YIELD) and aboveground residue (RESID) in the study domain.

3. Results

3.1. Water Budget Change

In our baseline land cover, when averaged over the 40-year time period, simulated average annual ET/P (Figure 5a) indicates that vegetation in the western half of the domain uses nearly all available water, with the ratio of ET/P close to one. This ratio decreases towards the eastern half of the domain (ranging from 0.5 to 0.8). After conversion from the 2007–2008 to 2011–2012 land use scenarios, the ET/P decreases throughout much of the domain, with the eastern side tending to have a larger decrease, with magnitudes ranging from 0% to 10% (Figure 5c). These results imply a decrease in ET, as mean annual precipitation remains the same in both the 2007–2008 and 2011–2012 landscape scenarios. Throughout the eastern side of the domain, this is the result of a conversion from forest to either continuous corn or corn/soybean rotation and, in North Dakota and Kansas, from a conversion from grassland to wheat (Figure 5a,b), with all of these cropping systems evapotranspiring less water to the atmosphere than forest or grasses. The increases (around 5%) in ET/P that occur along the eastern border of Nebraska and the southern border of Iowa are a result of a conversion from grasslands to corn and corn/soybean rotation (Figure 5b,c), with these two cropping systems evapotranspiring more water to the atmosphere than grasses in those regions.

In the study domain, as shown in Table 2, the total reduction of the annual mean ET due to the landscape change is about 1.04×10^{10} $m^3 \cdot year^{-1}$. The areal decrease of natural vegetation leads to a decrease in ET of 1.12×10^{11} $m^3 \cdot year^{-1}$ in natural ecosystems, while the ET of the two dominant crop types increases with 2.58×10^{10} $m^3 \cdot year^{-1}$ for continuous corn and 5.23×10^{10} $m^3 \cdot year^{-1}$ for corn/soybean rotation. Other crops also show increasing ET, as they all expand from 2007–2008 to 2011–2012. The changing magnitudes are relatively smaller except for soybean, which has a comparative increase of ET (1.43×10^{10} $m^3 \cdot year^{-1}$) as corn and corn/soybean rotation. This is due to the moderate areal change of soybean (Figure 4).

Table 2. Annual mean ET, SOC, and NBP for each biome within the study domain for USDA landscape scenarios. Values for each variable are sums of every grid cell containing a particular vegetation type and averaged over grid cell area.

Vegetation Class/Variables	ET ($m^3 \cdot Year^{-1}$)			SOC (kg)			NBP ($g \cdot Year^{-1}$)		
	2007–2008	2011–2012	Difference	2007–2008	2011–2012	Difference	2007–2008	2011–2012	Difference
Natural vegetation	9.48×10^{11}	8.36×10^{11}	-1.12×10^{11}	1.07×10^{13}	9.39×10^{12}	-1.28×10^{12}	7.29×10^{13}	6.57×10^{13}	-7.23×10^{12}
Corn	5.20×10^{10}	7.79×10^{10}	2.58×10^{10}	6.96×10^{11}	1.04×10^{12}	3.42×10^{11}	4.68×10^{12}	7.18×10^{12}	2.50×10^{12}
Soybean	1.83×10^{10}	3.26×10^{10}	1.43×10^{10}	2.16×10^{11}	3.75×10^{11}	1.59×10^{11}	-1.02×10^{12}	-1.45×10^{12}	-4.27×10^{11}
Spring wheat	1.31×10^{10}	1.53×10^{10}	2.17×10^{9}	1.20×10^{11}	1.35×10^{11}	1.49×10^{10}	-3.67×10^{11}	-3.16×10^{11}	5.15×10^{10}
Winter wheat	1.71×10^{10}	2.11×10^{10}	3.96×10^{9}	8.27×10^{10}	1.02×10^{11}	1.90×10^{10}	-2.52×10^{11}	-3.36×10^{11}	-8.45×10^{10}
Corn-soybean	1.33×10^{11}	1.85×10^{11}	5.23×10^{10}	1.72×10^{12}	2.38×10^{12}	6.52×10^{11}	2.49×10^{12}	3.93×10^{12}	1.43×10^{12}
Corn-spring wheat	2.86×10^{9}	3.60×10^{9}	7.44×10^{8}	3.10×10^{10}	3.84×10^{10}	7.33×10^{9}	2.47×10^{11}	3.10×10^{11}	6.32×10^{10}
Corn-winter wheat	4.84×10^{9}	5.64×10^{9}	8.02×10^{8}	4.46×10^{10}	5.02×10^{10}	5.60×10^{9}	-6.62×10^{10}	-3.89×10^{10}	2.74×10^{10}
Soybean-spring wheat	6.46×10^{9}	7.62×10^{9}	1.16×10^{9}	8.04×10^{10}	9.58×10^{10}	1.54×10^{10}	-3.35×10^{11}	-3.98×10^{11}	-6.22×10^{10}
Soybean-winter wheat	3.77×10^{9}	4.36×10^{9}	5.94×10^{8}	4.18×10^{10}	4.39×10^{10}	2.08×10^{9}	-3.74×10^{11}	-3.53×10^{11}	2.15×10^{10}
Total	1.20×10^{12}	1.19×10^{12}	-1.04×10^{10}	1.37×10^{13}	1.36×10^{13}	-6.03×10^{10}	7.79×10^{13}	7.42×10^{13}	-3.70×10^{12}

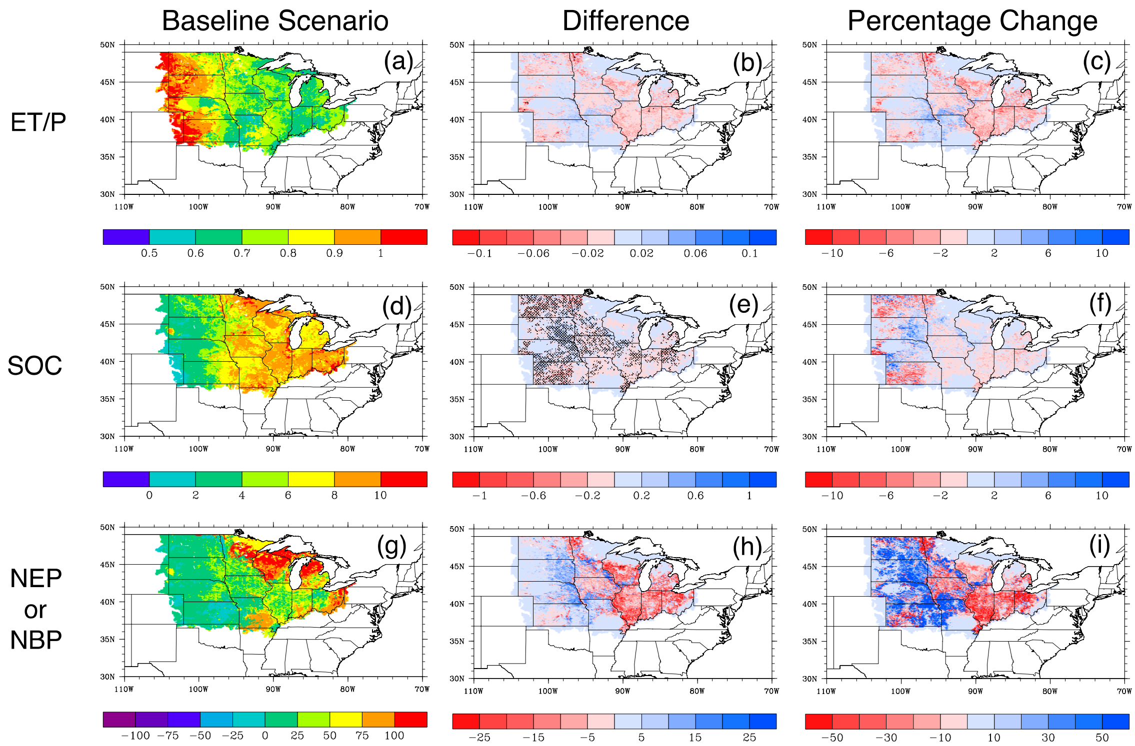

Figure 5. Simulated 40-year annual mean ET/P, soil organic carbon (SOC) (kg·m^{-2}), and net ecosystem exchange (NEP)/ net biome productivity (NBP) (g·C·m^{-2}·year^{-1}) (**a**,**d**,**g**) for the 2007–2008 United States Department of Agriculture (USDA) landscape scenario (baseline scenario); (**b**,**e**,**h**) The difference between 2007–2008 and 2011–2012 land use and (**c**,**f**,**i**) the percentage change (%). The difference is defined as values in 2011–2012 landscape scenario minus that in 2007–2008 landscape scenario. Grid cells with statistically significant differences ($p \leq 0.05$) show crosshatches. Percentage change is defined as the difference divided by the absolute value in the 2007–2008 landscape scenario.

3.2. Soil Carbon Change

Soil carbon content is influenced by many factors such as soil type, vegetation, temperature, and precipitation [35]. In our baseline land cover, when averaged over the 40-year time period, simulated average annual SOC increases from west to east in the domain with a range from 1 to 12 kg·m^{-2} (Figure 5d). Crop expansion between 2007–2008 and 2011–2012 results in a decrease in SOC throughout most of the domain, except in some areas of South Dakota and near the border of Kansas and Nebraska (Figure 5e). The decreasing magnitude is generally within 10%, and up to 15% in some areas of North Dakota and Kansas (Figure 5f). The same conversion patterns that lead to a decrease (increase) in ET/P lead to decreases (increases) in SOC. However, changes in SOC are more statistically significant than changes to ET/P (Figure 5b,e). The conversion of forest to corn or corn/soybean (in the eastern domain) and the conversion of grassland to wheat (in North Dakota and Kansas) lead to decreases (0%–15%) in SOC between 2007–2008 and 2011–2012, while the conversion of grassland to corn or corn/soybean (in parts of South Dakota and Kansas) lead to an increase of about 0.2 kg·m^{-2} (or 5%) in SOC. This is in contrast to some empirical studies [35,36], which are related to the inability to simulate tillage and lack of crop residue removal in our model simulations.

The SOC decreases about 60 Tg (6.03 $\times$ 10^{10} kg) across the domain (Table 2) between 2007–2008 and 2011–2012. Although the conversion of grass to continuous corn or corn/soybean rotation leads to increases in SOC in some grid cells, these are outweighed in the domain average by the reduction of SOC associated with the loss of forest.

3.3. Carbon Flux Change

In our baseline land cover, when averaged over the 40-year time period, the largest annual average net carbon sinks (i.e., net carbon flux into the ecosystem, defined as a positive value of NBP) are found in the northern states of Minnesota, Wisconsin, and Michigan, with values decreasing towards the south and from east to west (Figure 5g). The NBP of forests ranges from 60 g·C·m^{-2}·year^{-1} to 120 g·C·m^{-2}·year^{-1}, while the NEP of grasslands is closer to 10 g C·m^{-2}·year^{-1}. Small net carbon sources (NBP < 0) are seen in parts of North Dakota and Kansas where wheat is grown. Our model simulations show NBP to increase (generally around 10–20 g·C·m^{-2}·year^{-1}) wherever grassland is replaced by corn or corn/soybean rotation and to decrease (ranging from 0 to 30 g·C·m^{-2}·year^{-1}) wherever forest is replaced by corn or corn/soybean rotation (Figure 5h). In addition, an expansion of wheat (mainly in North Dakota and Kansas) acts to decrease NBP (within 10 g·C·m^{-2}·year^{-1} in general), thereby strengthening the carbon source (Figure 5h).

The loss of natural vegetation leads to a significant carbon loss from the ecosystem of about 7 Tg·year^{-1} over the entire domain. The expansion of corn into lower producing grid cells (such as grasslands) compensates for about half of this carbon loss (Table 2). Thus the entire domain remains a carbon sink between 2007–2008 and 2011–2012, but this sink is reduced.

3.4. Crop Production Change

The largest average annual values of YIELD and RESID are found in Iowa (7 Mg·ha^{-1}) and Illinois (5 Mg·ha^{-1}), respectively, where corn is mostly grown. Both YIELD and RESID increase as a result of crop expansion (Figure 6b,e). The increasing magnitude ranges from 10% to 30% in the center of the Corn Belt and approaches 100% at the edge of the Corn Belt, where crops replace natural vegetation (Figure 6c,f). The total production of annual mean crop yield over the domain is 2.49 × 10^8 Mg in the 2007–2008 landscape scenario and increases about 41% between scenarios, while the total production of annual mean residue is 2.44 × 10^8 Mg in the 2007–2008 landscape scenario and increases 43% with the land cover change.

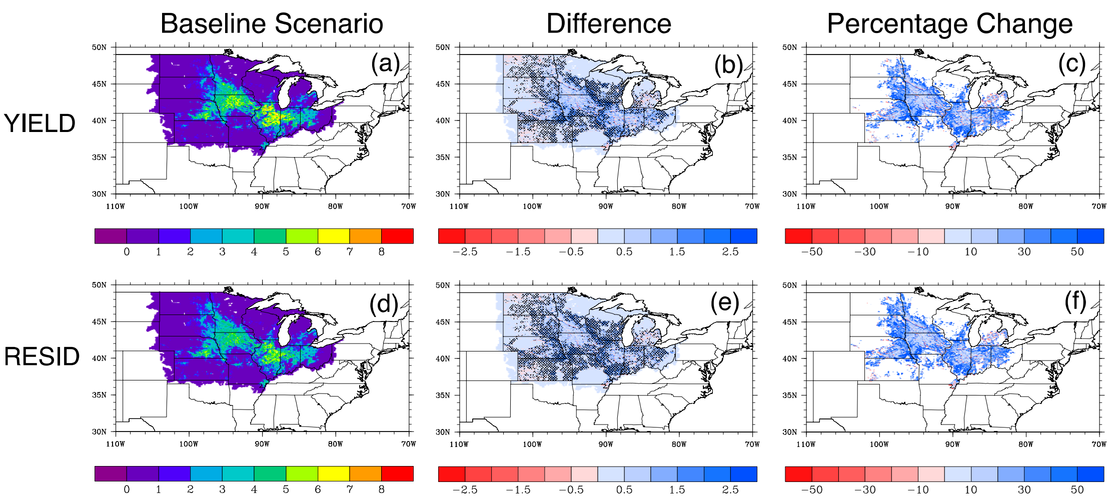

Figure 6. Simulated 40-year annual mean dry matter yield (YIELD) and dry matter residue (RESID) in Mg·ha^{-1} (**a**,**d**) in the 2007–2008 landscape scenario (baseline scenario); (**b**,**e**) Difference; and (**c**,**f**) percentage change (%) of each variable between the 2007–2008 and 2011–2012 landscape scenarios. In the percentage change plots, areas with YIELD or RESID below 1 Mg·ha^{-1} in 2007–2008 are masked out to highlight the changes in the major crop areas.

4. Discussion

Simulated ET decreased as forest or grassland was converted to cropland during the land use changes (from 2007–2008 to 2011–2012) in the Midwest. The overall reduction of ET is mainly due to less vegetation cover in cropland than forest. Our simulation results suggest that recent crop expansion reduced the water consumption of the ecosystem and might benefit the water yield, especially in the dry areas in the domain, consistent with previous studies [37,38]. However, it is important to note that some impacts of land cover change on the local water budget are not simulated within our model structure. This includes infiltration ability related to changes in soil structure (e.g., compaction or erosion) and impacts to drainage related to management (e.g., tile drainage, buffers, and irrigation infrastructure) [39]. Both the positive and negative impacts of deforestation on water cycle in agricultural areas across different scales have been studied and documented widely [40–43].

Zhang et al. (2011) suggested that the grasslands of the Great Plains are a small carbon sink with an average annual NEP of 24 $g{\cdot}C{\cdot}m^{-2}{\cdot}year^{-1}$ during 2000–2008 [44]. Our model results show that the 1968–2007 average value of NBP (same as NEP in natural ecosystem) in these grasslands is around 10 $g{\cdot}C{\cdot}m^{-2}{\cdot}year^{-1}$. Our model results also indicate that forests are a relative large carbon sink with a 1968–2007 average value of NBP between 60 and 120 g C m^{-2} $year^{-1}$. This is close to the measurement of an eddy-flux tower site in old-growth forest in Wisconsin with an observed NEP value around 72 $g{\cdot}C{\cdot}m^{-2}{\cdot}year^{-1}$ in 2002 and 147 $g{\cdot}C{\cdot}m^{-2}{\cdot}year^{-1}$ in 2003 [45]. Kucharik & Twine (2007) evaluated Agro-IBIS at the Ameriflux site in Nebraska and found that simulated soybean was a small carbon source (2002–2004 average NEP around -21 $g{\cdot}C{\cdot}m^{-2}{\cdot}year^{-1}$) and that corn was a carbon sink (three year average NEP around 581 $g{\cdot}C{\cdot}m^{-2}{\cdot}year^{-1}$) [23]. Kutsch et al. (2010) integrated observed NEP and NBP of five crop rotations and two monocultures in Europe over 2004–2007 and found wheat to be a carbon source if carbon lost by fires and carbon removed by harvest are taken into account [46]. Taking the grain harvest into account, our model results show that the Corn Belt acts as a carbon sink in all areas except where wheat is grown (Figure 5g).

In our simulation results, crop expansion led to a decline in SOC throughout the domain, the largest declines of which were found in North Dakota and Kansas (more than a 10% decrease) (Figure 5e,f). These decreases in SOC are associated with greater effluxes of carbon to the atmosphere (Figure 5h). Wright & Wimberly (2013) examined the land use change in the Western Corn Belt and indicated that the rapid loss of grassland (1.0%–5.4% of area annually) may reduce carbon stocks and biodiversity [47]. Corn stover is also used in cellulosic ethanol production [48,49], and, given that about half the carbon in the aboveground biomass is contained within corn stover [50], this could be a substantial source of carbon to the atmosphere. Note that we did not consider crop residue removal in our model simulations. Future simulation analyses will quantify potential SOC, given a variety of residue removal options for cellulosic ethanol from corn, beginning with our baseline maximum stock simulated here. Removing crop residue for biofuel production may lead to a series of environmental concerns (e.g., less carbon sequestration, soil erosion, and quality degradation) and also lower crop yield [48,51–54]. To maintain a balance between optimal biofuel production and sustainability of natural resources, the spatial information of crop residue distribution is needed to determine the quantity of residue that should be removed from the field.

5. Conclusions

In this study, we quantified the environmental impacts of LULCC in the Midwest USA on water and carbon budgets. The results from a simulation model show that a crop expansion between 2007–2008 and 2011–2012 led to a decrease in evapotranspiration and soil organic carbon throughout the study domain. SOC is important in agricultural lands in terms of promoting soil fertility, increasing soil water-holding capacity, and enhancing microbial activities that serve nutrient cycling and plant growth [55,56]. In addition, sequestrating more carbon in soil helps to reduce carbon in the atmosphere. Farming practices that reduce SOC, for example burning, tillage, overgrazing, etc., should be limited.

Despite the effects on water and carbon budgets, LULCC (mainly crop expansion in this case) potentially affects other aspects of the ecosystem (e.g., vegetation coverage, surface temperature, and habitat quality) as well as the economic and social aspects of sustainability [57].

This study provides useful information in terms of quantifying the change of water consumption and carbon sequestration spatially in the Midwest USA due to recent landscape changes. In addition, it could help to guide the development of future landscape scenarios in order to minimize some environmental consequences, such as better management of water resources and maintenance of soil carbon. Future studies will analyze the model results in a future landscape scenario and evaluate the effects of corn stover removal on water and carbon budgets in the Midwest USA.

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