

Importance of biophysical effects on climate warming mitigation potential of biofuel crops over the conterminous United States

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Abstract

Current quantification of climate warming mitigation potential (CWMP) of biomass-derived energy has focused primarily on its biogeochemical effects. This study used site-level observations of carbon, water, and energy fluxes of biofuel crops to parameterize and evaluate the community land model (CLM) and estimate CO₂ fluxes, surface energy balance, soil carbon dynamics of corn (*Zea mays*), switchgrass (*Panicum virgatum*), and miscanthus (*Miscanthus × giganteus*) ecosystems across the conterminous United States considering different agricultural management practices and land-use scenarios. We find that neglecting biophysical effects underestimates the CWMP of transitioning from croplands and marginal lands to energy crops. Biogeochemical effects alone result in changes in carbon storage of -1.9 , 49.1 , and 69.3 g C m⁻² y⁻¹ compared to 20.5 , 78.5 , and 96.2 g C m⁻² y⁻¹ when considering both biophysical and biogeochemical effects for corn, switchgrass, and miscanthus, respectively. The biophysical contribution to CWMP is dominated by changes in latent heat fluxes. Using the model to optimize growth conditions through fertilization and irrigation increases the CWMP further to 79.6 , 98.3 , and 118.8 g C m⁻² y⁻¹, respectively, representing the upper threshold for CWMP. Results also show that the CWMP over marginal lands is lower than that over croplands. This study highlights that neglecting the biophysical effects of altered surface energy and water balance underestimates the CWMP of transitioning to bioenergy crops at regional scales.

Keywords: agricultural management, biofuel crops, biophysical effect, carbon sequestration, community land model, marginal land

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Introduction

Biomass energy has been widely considered a major renewable and sustainable energy source for increase energy security while contributing to mitigating climate change (Field *et al.*, 2008; Beringer *et al.*, 2011). Bioenergy from crop-based biofuels is currently a promising biomass feedstock for replacing fossil fuels, and its demand is expected to continually increase to meet the mandate targets for biofuel production (US Congress, 2007). However, traditional crop-based biofuels have many unintended consequences for feedstock availability, food security, environmental sustainability, and societal welfare. For example, converting lands occupied by natural ecosystems to managed ecosystems for biofuel production could contaminate water quality with agricultural pollutants and converting food crop

ecosystems for biofuel production could potentially threaten food supplies (Clifton-Brown *et al.*, 2007; Field *et al.*, 2008; Gibbs *et al.*, 2008).

Recently, perennial grasses such as switchgrass and miscanthus have been favored as a better alternative to traditional row crops because they have higher productivity and water use efficiency (Hickman *et al.*, 2010; Vanloocke *et al.*, 2010, 2012; Zeri *et al.*, 2013). They also accumulate and sequester carbon into the soil, enhancing soil organic matter storage (Clifton-Brown *et al.*, 2007; Anderson-Teixeira *et al.*, 2009; Qin *et al.*, 2012; Valentine *et al.*, 2012). Meanwhile, these grasses could provide abundant biomass but require relatively less nutrient than conventional food crops (Lewandowski *et al.*, 2003; Heaton *et al.*, 2004; Clifton-Brown *et al.*, 2007; Stewart *et al.*, 2009; Zeri *et al.*, 2013). Therefore, they can grow on degraded agricultural land, that is marginal land, including idle or fallow cropland, abandoned or degraded cropland, and abandoned pastureland, where most food crops may not survive due to

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poor soil or climate conditions (Cai *et al.*, 2010; Gopalakrishnan *et al.*, 2012; Bandaru *et al.*, 2013), which could avoid competing with food crops for land.

It has been widely recognized that perennial biofuel grasses could mitigate climate change by sequestering carbon, although the extent to which carbon can be sequestered will depend on the amount of carbon removed from the ecosystem and management practices employed (Zeri *et al.*, 2011; Anderson-Teixeira & Delucia, 2011; Liska *et al.*, 2014). Biophysical effects of land-use change are also critical to consider due to the potential for altered surface energy budgets which may feed-back on local climate (Loarie *et al.*, 2011; He *et al.*, 2014; Peng *et al.*, 2014; Zhang *et al.*, 2014). Land management and land conversion each can impact surface temperature at comparable magnitudes (Luyssaert *et al.*, 2014). The direct climatic effect can be significant to climate warming mitigation and has been investigated in the field of deforestation and afforestation (Lee *et al.*, 2011; Loarie *et al.*, 2011; Peng *et al.*, 2014), but little research has been conducted within the framework of biofuel lifecycle analysis under different scenarios (Anderson-Teixeira *et al.*, 2012).

Presently, many crop models have been developed to estimate regional or global scale biomass production and greenhouse gas (GHG) emissions for biofuel crops (Nair *et al.*, 2012; Qin *et al.*, 2014; Surendran *et al.*, 2012; Thomas *et al.*, 2013). However, there are still large uncertainties in the simulated carbon and water balance such as biomass production, GHG emissions, and water demand (Liu *et al.*, 2015). These uncertainties are due to the different model parameterizations including feedstock chosen, cultivation practices, harvesting dates, fertilizer application, and land-use conversion pattern (Hudiburg *et al.*, 2015). A fully coupled earth system model can provide a comprehensive evaluation of both biogeochemical and biophysical effects due to land cover change on climate. However, significant challenges to these models exist and particularly related to computational resources need to run these coupled models. In contrast, most ecosystem models are sufficient to quantify carbon balance of biofuel ecosystems but often cannot accurately capture the high-frequency variation of surface energy due to their simplified surface energy balance schemes. Thus, land surface models which have a higher time frequency and detailed carbon and surface energy parameterization scheme are a more favorable compromise.

Using data collected at the University of Illinois Energy Farm, we parameterize and validate an advanced version land surface model CLM4.5 to evaluate carbon flux, biomass production, and surface energy balance of switchgrass and miscanthus. We then conducted an explicit spatial estimation of biogeochemical

and biogeophysical effects for corn, switchgrass, and miscanthus across the conterminous United States. Model simulations were conducted to quantify responses of surface energy and carbon balance to different land-use scenarios and management practices compared to current land-use patterns. The surface energy and carbon balance changes were then integrated into calculations of CWMP. We hypothesize, at the regional scale, that (1) compared to maize and annual C₃/C₄ grasses, switchgrass and miscanthus will have higher productivity and sequester more carbon into soils, (2) CWMP of planting biofuels will be enhanced when accounting for evaporative cooling effects, and (3) agricultural management practice such as fertilization and irrigation will result in higher total carbon uptake, higher below ground biomass, and substantial evaporative cooling due to the sufficient water supply, consequently yielding a higher CWMP.

Materials and methods

Site description

The observational data were obtained at University of Illinois Energy Farm located in central Illinois (40.064°N, 88.197°W, ~220 m above sea level). This experiment consists of four ecosystems of 4 Ha (200 m × 200 m) each instrumented with eddy covariance and micrometeorological instrumentation at the center of each plot (a full site description is provided in Zeri *et al.*, 2011). In 2008, four ecosystems: corn–soybean rotation, miscanthus, switchgrass, and a mix of native prairie species were planted, with a replantation of miscanthus in 2010 after poor establishment, to examine bioenergy production and the associated environmental services. Above-ground biomass of each ecosystem was determined from harvested dry biomass at the end of the growing season. Leaf area index (LAI) of all species was measured optically (LAI-2200; LI-COR Biosciences, Lincoln, NE, USA) at weekly intervals during the period of active canopy development. The eddy covariance systems were established with a three-dimensional sonic anemometer (model 81000 V; R.M. Young Company, Traverse City, MI, USA) and an infrared gas analyzer (model LI-7500; LI-COR Biosciences, Lincoln, NE, USA) and were adjusted in height following plant growth. This system collected high-frequency data (10 Hz) of wind speed, and fluxes of CO₂ and H₂O analyzed using the Alteddy software package. The high-frequency data were corrected for coordinate alignment, humidity effects of the temperature measurements by the sonic anemometer, and density fluctuations of the infrared gas analyzer. A double-rotation scheme was used to align the coordinate system to the main wind direction and make the average vertical velocity zero (Kaimal & Finnigan, 1994). Data were also corrected for high-frequency data losses due to sensor separation (Moore, 1986). Data collected at low turbulence conditions were removed from the dataset and filtered by the u*-threshold (Aubinet *et al.*, 2001; Foken *et al.*, 2005). The footprint model of (Hsieh

et al., 2000) was applied to identify periods when the fluxes were outside the edges of the plots and records removed if less than 70% of cumulative flux came from within the plot area. Quality control of the data filtered out unreasonable fluxes (Zeri *et al.*, 2011). Missing data were gap-filled and fluxes partitioned from net ecosystem exchange into ecosystem respiration (R_{eco}) and gross primary production (GPP) (Reichstein *et al.*, 2005; Zeri *et al.*, 2011). Other essential meteorological variables to drive the gap-filling and partitioning model, including solar radiation (shortwave and longwave, both incoming and outgoing components; CNR1, Kipp & Zonen, the Netherlands), precipitation, air temperature, pressure, and relative humidity (HMP-45C; Campbell Scientific, Logan, UT, USA), were also collected at the center of each plot. A full site description with details about data analysis and quality control has been published previously (Zeri *et al.*, 2011, 2013; Joo *et al.*, 2016). The data collected in 2011 were used for model parameterization and evaluation.

Model description and improvement

Model simulations were performed using CLM4.5 to simulate the effects of climate, land-use change and agricultural management on carbon and surface energy budgets in bioenergy ecosystems. CLM was initially developed by concurrent effort at NCAR, merging community-developed land model focusing on biogeophysics to expand NCAR Land Surface Model (Bonan, 1996). CLM was incorporated with a number of biophysical processes for different plant functional types (PFT) including stomatal physiology, photosynthesis, energy and momentum fluxes with vegetation canopy and soil, heat transfer in soil and snow, and hydrology of canopy, soil, and snow. Carbon allocation and developmental stages are based on temperature thresholds and the accumulation of growing degree-days which is dynamic throughout the growing season. Soil organic carbon (SOC) is estimated from the turnover of soil organic matter pools, which change with decomposition rate. Version CLM4.5 was released as the land surface component of Community Earth System Model (CESM) with many improvements, including a revised canopy radiation scheme and canopy scaling of leaf processes, colimitations on photosynthesis and updated photosynthetic parameters (Bonan *et al.*, 2011). In CLM4.5, there is already a crop submodel, inherited from Agro-IBIS (Foley *et al.*, 1996; Kucharik *et al.*, 2000) to represent the role of agriculture in land surface processes. Processes of land management such as crop type, planting, harvesting, fertilization, and irrigation were added. In this study, the two major agricultural management practices, fertilization, and irrigation are accounted for, because these two management practices are considered to be crucial in determining carbon sequestration potentials of biofuel crops (Elshout *et al.*, 2015). The irrigation parameterization scheme is based loosely on the implementation of Ozdogan *et al.* (2010). This parameterization did not account for timing and background climate conditions, and it responds dynamically to climate. Irrigation can significantly influence the surface water and energy balances partition in the model and thus has an evident biophysical effect (Ozdogan *et al.*, 2010). Thus, water can be added to soil through irrigation so that a target soil moisture is

reached. Interactive fertilization is also enabled in this version, and nitrogen is added directly into the soil mineral nitrogen pool to meet crop demands. Total nitrogen fertilizer amounts are 150 kg N ha⁻¹ for maize, 80 kg N ha⁻¹ for temperate cereals, and 25 kg N ha⁻¹ for soybean, representative of central US annual fertilizer application amounts. For biofuel crops, 100 kg N ha⁻¹ is applied based on previous field experiments (Fike *et al.*, 2006; Heaton *et al.*, 2008; Propheter *et al.*, 2010; Nikièma *et al.*, 2011).

To reach our research goal, a new parameterization scheme for CLM is necessary for those perennial grasses including switchgrass and miscanthus, which have different physiological traits. Unlike annual crops, perennial grasses allocate a large amount of resources to belowground organs such as rhizomes (Anderson-Teixeira *et al.*, 2009; Atkinson, 2009). The new scheme was calibrated by adjusting relevant model parameters based on observations of switchgrass and miscanthus in 2011 to compare simulation results against observations. Several key parameters and their corresponding values (Table 1) in switchgrass and miscanthus parameterization were incorporated into the model. These parameters can be generally grouped into parameters controlling photosynthesis capacity including $V_{\text{cmax}25}$, Q , and slatop ; phenology parameters including lfemerg , hybgdd , mxmat , baset , $\text{min_NH_planting_date}$, min_planting_temp ; and allocation parameters including Astem , Aroot , fleafi , Cnleaf . We combined the carbon allocated to rhizome with those to roots to minimize the change of the original model structure. Meanwhile, as perennial biomass crops usually needs 2–5 year to reach full maturity, we first run the model for 5 years without harvesting to allow carbon allocation to rhizomes to stabilize. The harvest frequency is one time per year. The current model does not consider recultivation and tillage that may be necessary for long-term bioenergy production. At site level, the model was run at a half-hour intervals to correspond with the eddy covariance data. The collected meteorological forcing data during 2011 is used to drive the model. At least 500 years of model spin-up is established to allow soil carbon pools to reach equilibrium.

Regional experiments under various land-use and management scenarios

Regional simulations were run at half-hourly time step from 2000 to 2010 at 0.5° × 0.5° spatial resolution. This recent 10-year time period was selected to capture the effects of interannual variations in climate. The regional spin-up procedure was the same as the single site and used current vegetation map for each grid cell. In the control run (cntl), each grid cell is initialized with a distribution of plants from current vegetation maps generated from the International Geosphere Biosphere Programme's 1-km DISCover (IGBP) land cover dataset (Loveland & Belward, 1997). For the remaining 12 simulations, the marginal land distribution utilizes the map estimated from Cai *et al.* (2010). In their study, global marginal lands were classified according to the marginal agricultural productivity based on land suitability indicators such as topography, climate conditions, and soil fertility. The first scenario in Cai *et al.* (2010) was used in this study. This scenario included marginal, abandoned, mixed crops, and vegetation land yet does not sacrifice

Table 1 New parameter values for switchgrass and miscanthus calibrated from site observational data

Parameter name	Description	Switchgrass	Miscanthus
Vcmax25	Maximum rubisco activity at 25 °C at top of canopy ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	75	92
Q	Intrinsic quantum efficiency (dimensionless)	0.04	0.04
Slatop	Specific leaf area ($\text{m}^2 \text{g C}^{-1}$) at top of canopy	31	70
Laimx	Maximum leaf area index (LAI) allowed ($\text{m}^2 \text{m}^{-2}$)	6.5	8.5
hybgdd	Maximum growing degree-days (base 0 °C) required for physiological maturity	3700	3820
mxmat	Maximum number of days allowed past planting for physiological maturity to be reached	260	260
Fleafi	Fraction of assimilated carbon allocated to leaves	0.6	0.7
Astem	Fraction of assimilated carbon allocated to stems	0.2	0.2
Aroot	Fraction of assimilated carbon allocated to roots	0.15	0.12
Cnleaf	C:N ratio of leaf biomass	100	80
Baset	Base temperature for GDD calculation	0	0
min_planting_temp	Average 5 day daily minimum temperature needed for planting (K)	274.1	275
min_NH_planting_date	Minimum planting date for the Northern Hemisphere	301	301
lfemerg	Leaf emergence parameter	0.02	0.03

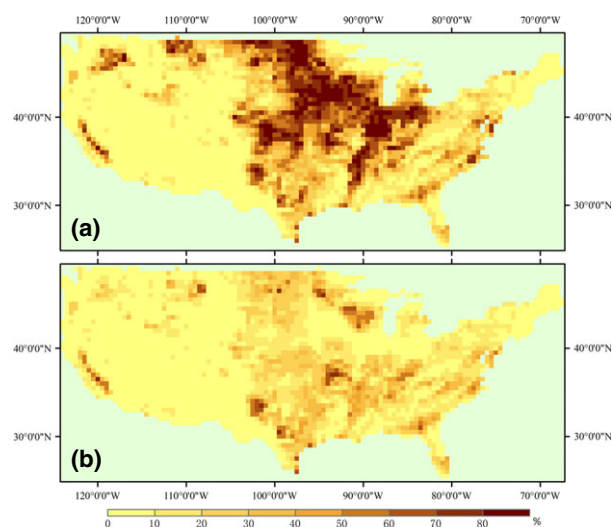


Fig. 1 Two scenarios showing of land conversion percentages for the study domain: (a) both marginal lands and croplands are converted, (b) only marginal lands are converted. Numbers in the color bar represent the proportion (%) of each grid cell that is converted to biofuel crops.

large amounts of current crop and natural ecosystems (forest and grassland) to bioenergy production. This scenario was considered as baseline land-use conditions and was used here to represent the spatial distribution of marginal lands in the United States. The data in Cai *et al.* (2010) were aggregated to $0.5^\circ \times 0.5^\circ$ spatial resolution, and then, two land conversion scenarios were generated according to the proportion of marginal lands and croplands in each grid: One scenario (Fig. 1a) in which both marginal lands and croplands are converted and one scenario (Fig. 1b) in which only marginal lands are converted. The darker pixels in the figure represent higher fractions of convertible land. Compared to the first scenario (Fig. 1a), most of croplands in the second scenario remain

unchanged and only the scattered marginal lands are converted (Fig. 1b). Soil texture and soil color class for each 0.5° grid cell are based on the Harmonized World Soil Database (HWSD, Wieder *et al.*, 2014) and are used by CLM4.5 to determine soil hydraulic and thermal properties. The climate data needed to drive simulations at the half-hourly time steps were obtained from CLM4.5 standard atmospheric forcing data sets CRUNCEP (Viovy, 2011), which is a combination of two existing datasets: the CRU TS3.2 $0.5^\circ \times 0.5^\circ$ monthly data covering the period 1901 to 2002 (Mitchell & Jones, 2005) and the NCEP reanalysis $2.5^\circ \times 2.5^\circ$ 6-hourly data covering the period 1948 to 2010. For all model runs, harvest is set to once per year and without recultivation over the length of the experiment. The full perennial crop lifetime is determined by GDD and the related parameters have been calibrated according to observed LAI. Since the analytical time frame is 50 years, analysis focused on the period after the perennial crops reached maturity, which can minimize the albedo effect of the first year of cultivation in the energy balance analysis.

Twelve experiments were conducted to assess climate warming mitigation potential under different combinations of land conversion scenarios and agricultural management practices (Table 2). Applying extensive agricultural management, particularly irrigation, is not practical, even risky, considering its environmental impacts. However, the management scenarios present an upper boundary of reachable climate warming mitigation relative to the baseline. In addition, the proportion of crop residues removal could have a noticeable impact on soil carbon pool (Liska *et al.*, 2014). In the control run, in addition to total crop grain harvest, 20% of residue was removed to represent SOC loss by soil disturbance from cultivation, which is neglected in CLM (Levis *et al.*, 2014). For the remaining 12 experiments, 70% of above-ground biomass was removed to simulate harvest for lignocellulosic biofuel crops. This removal rate is considered to maintain sustainable utilization while maximizing yields. Across all of the 13 simulations, natural and crop ecosystems in each grid cell were modeled separately and then aggregated based on their fractions within each grid

Table 2 A list of model experiments allowing for variation in biofuel crop types, land conversion scenarios, and altered management practices associated with irrigation and fertilization

Experiments	Biofuel type	Land conversion scenarios	Management practices
corn1	Corn	Marginal land and cropland	No
corn2	Corn	Marginal land	No
corn3	Corn	Marginal land and cropland	Yes
corn4	Corn	Marginal land	Yes
sw1	Switchgrass	Marginal land and cropland	No
sw2	Switchgrass	Marginal land	No
sw3	Switchgrass	Marginal land and cropland	Yes
sw4	Switchgrass	Marginal land	Yes
mx1	Miscanthus	Marginal land and cropland	No
mx2	Miscanthus	Marginal land	No
mx3	Miscanthus	Marginal land and cropland	Yes
mx4	Miscanthus	Marginal land	Yes

cell. Comparisons of CWMP were based on the differences of 10-year average for the 12 experiments from the control.

Climate mitigation potential metrics

CWMP of growing biofuel crops was often quantified using net GHG fluxes and SOC change, both are important in the life cycle analysis of biofuel carbon balance. However, the contribution of biophysical effects to CWMP was overlooked in previous research (Qin *et al.*, 2012, 2015; Albanito *et al.*, 2015). Here, we combine carbon fluxes, soil carbon pool changes, evaporative cooling effects, and net radiation (R_n is the balance between incoming and outgoing long-wave and short-wave radiation, mainly determined by albedo) changes to construct a synthetic CWMP metric using carbon as the currency. Both biophysical effects and biogeochemical effects can be converted to radiative forcing effects, that is biogeochemical effects influence the capacity of absorbing long-wave radiation while biophysical effects concerns short-wave radiation and latent heat flux:

$$T \frac{\Delta E}{S} = \frac{\Delta C_e / M_c}{A} R_e \quad (1)$$

where ΔE is the surface energy change (W m^{-2} ; $\Delta E = \Delta LE - \Delta R_n$). ΔC_e is the equivalent carbon change. $A = 1.78 \times 10^{20}$ mol is the moles of air in the atmosphere. $R_e = 1.4 \times 10^4$ nW m^{-2} ppb^{-1} is the effective radiative forcing efficiency of CO_2 . $S = 5.1 \times 10^{14}$ m^2 is the global surface area, here acting as scale factor to convert the local ΔE to global radiative forcing effects. M_c is the molar mass of carbon. As radiative forcing of CO_2 has cumulative effect, here T is multiplied as the time frame to balance the two sides. We choose T to be 50 years as used previously (Anderson-Teixeira *et al.*, 2012) to account for the residence time of CO_2 in atmosphere. An additional time frame is

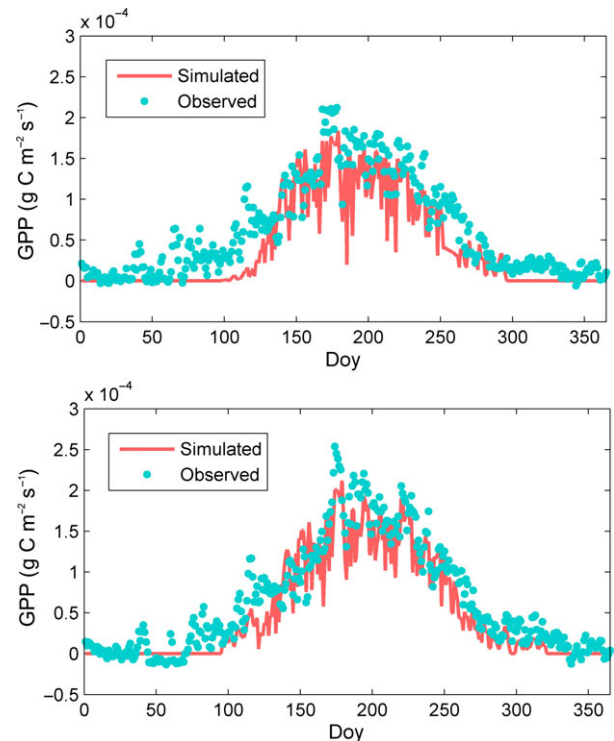


Fig. 2 Simulated vs. observed daily gross primary productivity (GPP) over the 2011 growing season for switchgrass (upper panel, model = $0.92 \times \text{obs} + 0.000017$, $R^2 = 0.71$, $\text{RMSE} = 4.47 \times 10^{-6}$ $\text{g C m}^{-2} \text{s}^{-1}$) and miscanthus (lower panel, model = $0.94 \times \text{obs} + 0.000013$, $R^2 = 0.75$, $\text{RMSE} = 3.78 \times 10^{-6}$ $\text{g C m}^{-2} \text{s}^{-1}$).

needed to allow for SOC changes be comparable with the change of annual net carbon fluxes and also set to 50 years. Thus, CWMP can be defined as:

$$\text{CWMP} = \Delta C_e + \Delta \text{NEP} + \frac{\Delta \text{SOC}}{50} \quad (2)$$

According to Eqn (1), the surface energy change of 1 W m^{-2} is roughly equal to 6 g C m^{-2} over a 50-year time span. More technical details of these conversions could be found in Anderson-Teixeira *et al.* (2012). The CWMP of each grid cells occurring in biofuel crops expansion is finally aggregated based on land conversion rate.

Results

Model evaluation at site

The simulated GPP compared well with measurements for both switchgrass and miscanthus with a slight underestimation during the maximum carbon uptake period in 2011 (Fig. 2). Simulated GPP captures the annual variation in productivity over the whole growing season, including the initial increase after leaf emergence, the timing of peak values, and decline after leaf senescence (Fig. 2). For switchgrass, simulated timing

occurs later than observations for leaf onset but leaf senescence matches better with the observations. The model performs well for miscanthus in capturing the timing of leaf onset and senescence. The model explained 71% and 75% of observed GPP for switchgrass and miscanthus, respectively. Miscanthus showed a longer growing season due to its later leaf senescence date, leading to a higher annual GPP of 2.88 kg C m^{-2} relative to 2.34 kg C m^{-2} for switchgrass.

The timing and magnitude of simulated latent heat (LE) matched well with the observed values at a half-hour time step. Simulated NEE matched the eddy covariance measurements by capturing the transition from winter dormancy to spring uptake to summer maximum uptake (Figs 3 and 4). Compared to eddy covariance measurements, the simulated LE and NEE were slightly overestimated. The annual LE differences between simulation and observation were 4.7 W m^{-2} and 4.1 W m^{-2} , while the NEE differences were 32.2 g C m^{-2} and 24.3 g C m^{-2} for switchgrass and miscanthus, respectively. All of these differences were within the 10% of the annual observation.

Model projections of biofuel crop carbon and energy balance

Carbon balance for growing biofuel crops. Simulating corn grown for harvesting both grain and stover for biofuel

production showed that soils acted as a carbon source when no management practices were applied, primarily owing to the higher rate of residue removal for biofuel production (Fig. 5). Higher productivity and a longer growing season led to increased soil litter inputs for switchgrass and miscanthus and correspond to accumulation in soil carbon despite above-ground biomass removal (Figs. 6 and 7). Corn agroecosystem showed higher soil C accumulation in the north, while switchgrass and miscanthus tended to gain more SOC in the south, consistent with previous results (Miguez *et al.*, 2012). There was a substantial increase in SOC when the arid areas (e.g., western United States) were fertilized and irrigated. Areas planted with corn had a moderate increase in net carbon fluxes relative to natural vegetation and miscanthus had the largest carbon sequestration potential, followed with switchgrass and corn (Fig. 8). All of the three biofuel crops showed increased carbon sequestration with increased management to 49.3 , 66.0 , and $84.9 \text{ g C m}^{-2} \text{ y}^{-1}$ compared with -1.9 , 49.1 , and $69.3 \text{ g C m}^{-2} \text{ y}^{-1}$ without management for corn, switchgrass, and miscanthus, respectively. Carbon sequestration capacity was generally larger for crops than for marginal lands due to nutrient limitation in marginal lands. These results suggest that for a given mitigation target, more marginal lands are required for conversion to bioenergy compared with croplands. However, converting marginal lands will not interfere

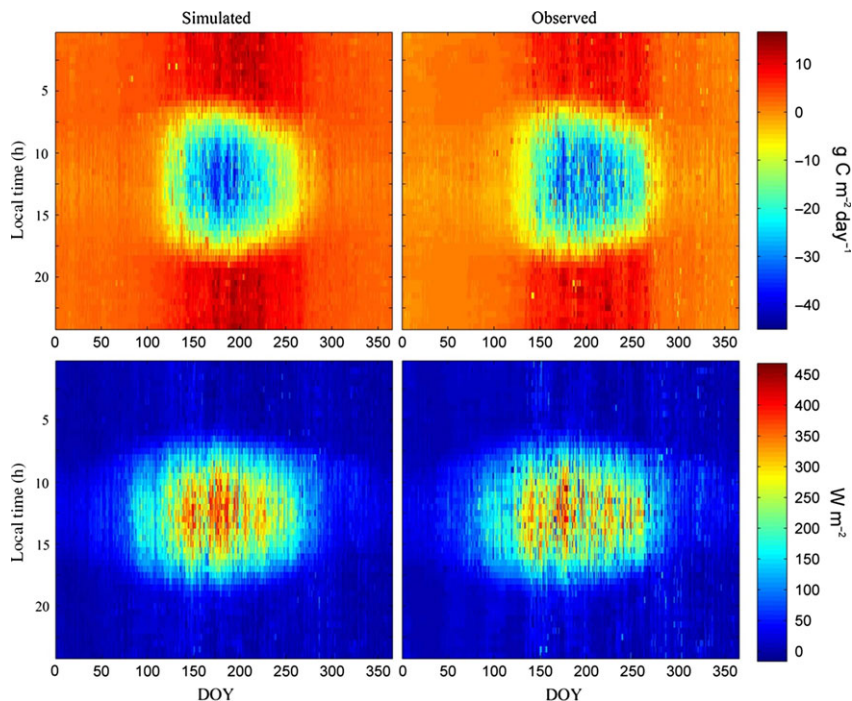


Fig. 3 Observed (left column) and simulated (right column) net ecosystem exchange (NEE $\text{g C m}^{-2} \text{ day}^{-1}$, top row) and latent heat flux (LE W m^{-2} , bottom row) at half-hour intervals for mature switchgrass in 2011.

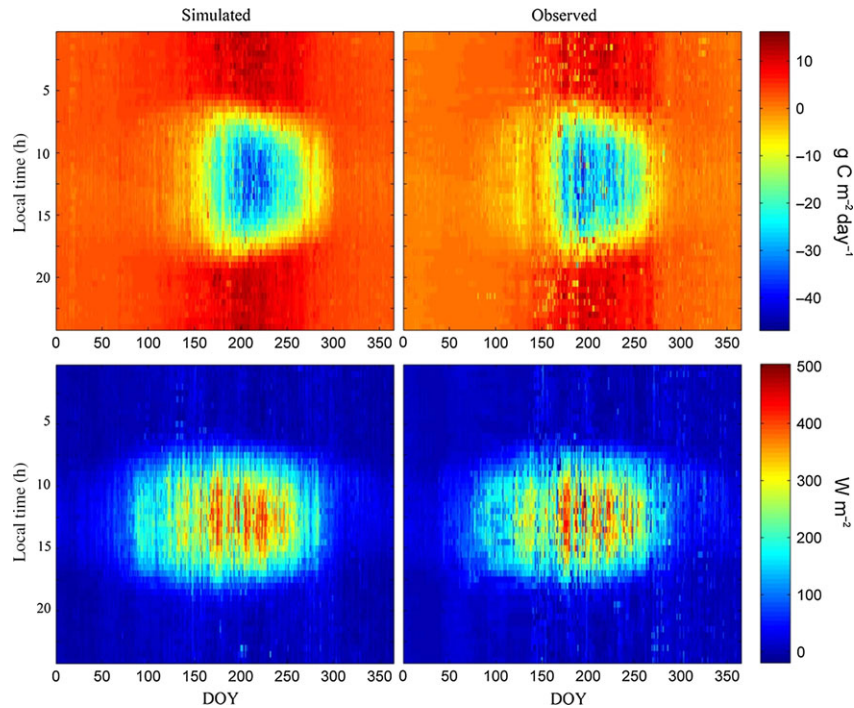


Fig. 4 Observed (left column) and simulated (right column) NEE ($\text{g C m}^{-2} \text{ day}^{-1}$ top row) and LE (W m^{-2} bottom row) at half-hour interval for mature miscanthus in 2011.

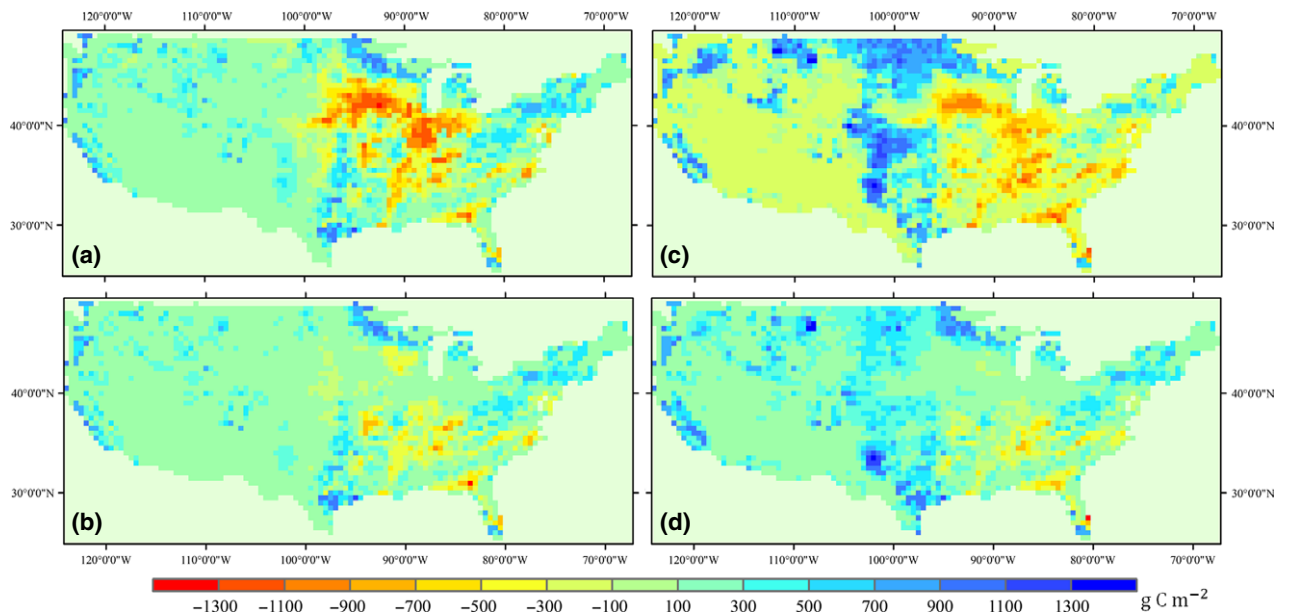


Fig. 5 Simulated differences in SOC (g C m^{-2}) based on 10-year (2000–2010) climate forcing data when the soil carbon pool reaches equilibrium for corn1-cntl (a), corn2-cntl (b), corn3-cntl (c), corn4-cntl (d).

with food production. Our simulations were generally consistent with previous findings (Qin *et al.*, 2012, 2015; Elshout *et al.*, 2015), suggesting that switchgrass and miscanthus could increase carbon sequestration.

Changes of energy balance. The spatial pattern in simulated Rn and LE was generally consistent with previous modeling results, indicating that annual cumulative ET for switchgrass and miscanthus was larger than corn

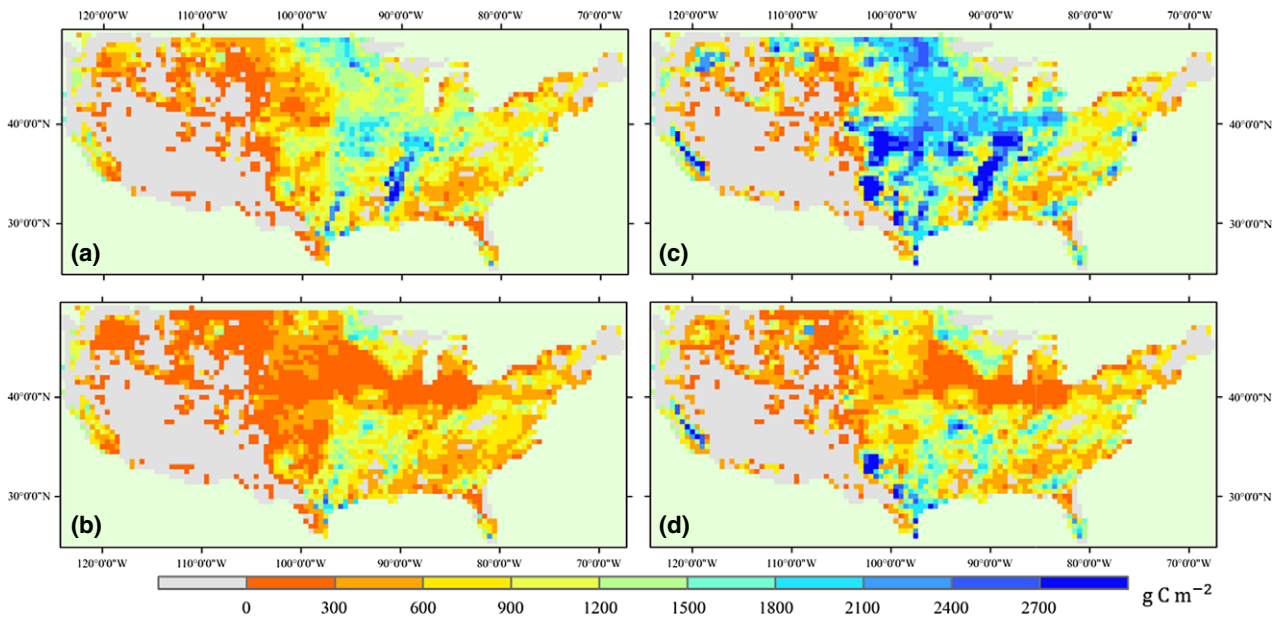


Fig. 6 The simulated difference of SOC (g C m^{-2}) based on 10-year (2000–2010) climate forcing data when the soil carbon pool reaches equilibrium for sw1-cntl (a), sw2-cntl (b), sw3-cntl (c), sw4-cntl (d).

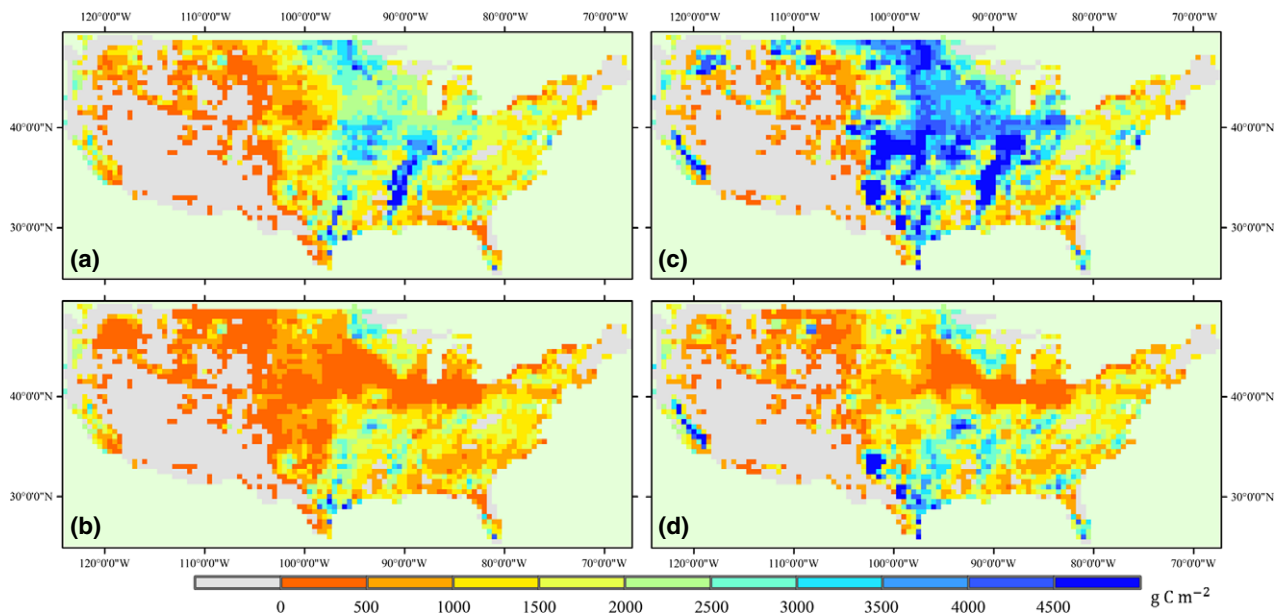


Fig. 7 The simulated difference of SOC (g C m^{-2}) based on 10-year (2000–2010) climate forcing data when the soil carbon pool reaches equilibrium for mx1-cntl (a), mx2-cntl (b), mx3-cntl (c), mx4-cntl (d).

due to their longer growing season and higher rate of evapotranspiration (Hickman *et al.*, 2010; Vanlooche *et al.*, 2010; Zeri *et al.*, 2013; Joo *et al.* submitted to Plant Physiology). The distribution of ΔLE showed a similar spatial pattern to carbon flux, implying there was a tight nexus between carbon and energy exchanges (Fig. 9). The three biofuel crops had larger LE than existing vegetation due to their higher plant transpiration.

Switchgrass and miscanthus showed a higher net radiation, indicating a lower albedo due to higher LAI. ΔLE of corn, switchgrass, and miscanthus growing on marginal lands and croplands without management are 3.8 W m^{-2} , 5.2 W m^{-2} , and 5.2 W m^{-2} , respectively. Maximum ΔLE of switchgrass and miscanthus were 8.8 W m^{-2} and 9.3 W m^{-2} in the southeast of the United States, which corresponded with a higher ΔRn

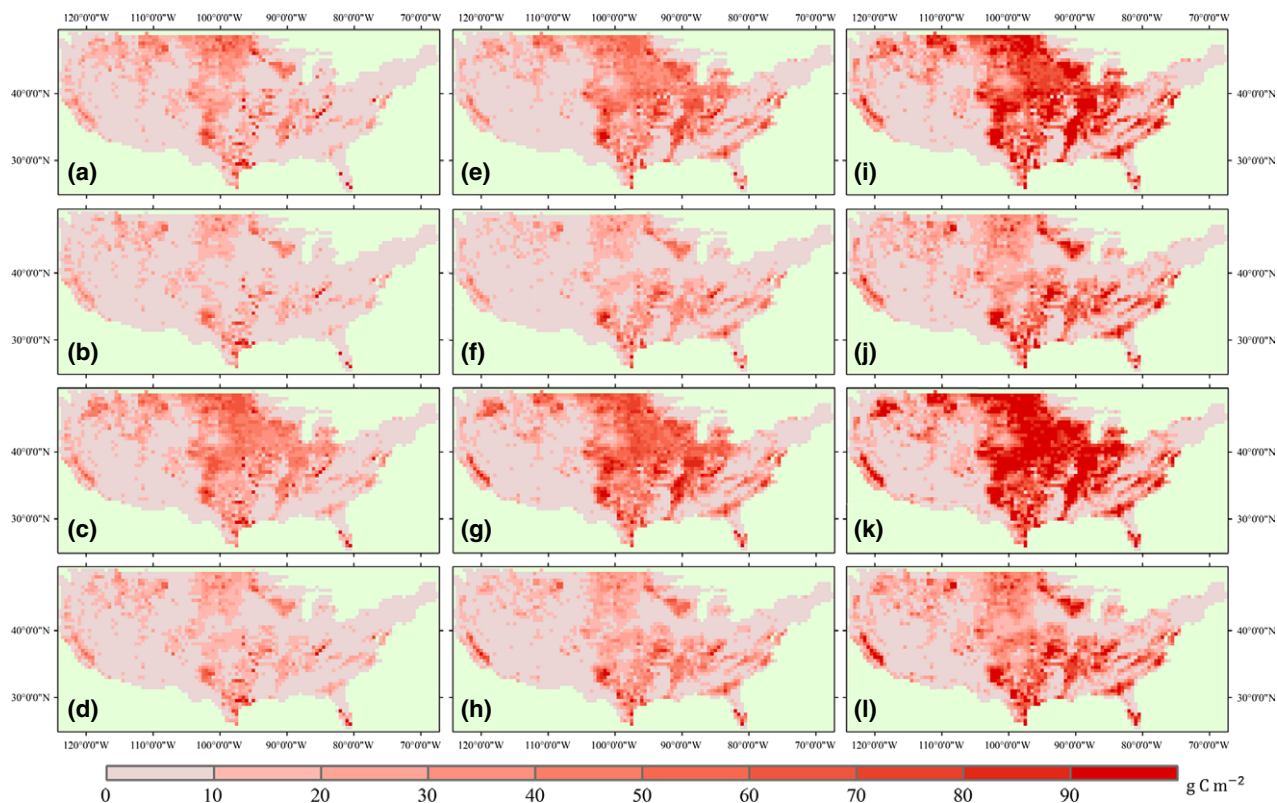


Fig. 8 The simulated difference of annual net carbon flux (g C m^{-2}) based on 10-year (2000–2010) climate forcing data among each experiment (a–l) corresponds to the difference between corn1, corn2, corn3, corn4, sw1, sw2, sw3, sw4, mx1, mx2, mx3, mx4, and cntl, respectively.

Table 3 Simulated CWMP change based on 10-year (2000–2010) means under various modeled scenarios

Experiment	Carbon				
	flux (g C m^{-2})	SOC (g C m^{-2})	LE (W m^{-2})	Rn (W m^{-2})	CWMP (g C m^{-2})
corn1	24.4	−26.3	4.3	0.30	20.5
corn2	21.5	−8.3	3.8	0.26	33.0
corn3	37.5	11.8	5.8	0.38	79.6
corn4	32.1	8.2	4.9	0.32	65.9
sw1	30.6	18.5	5.6	0.35	78.5
sw2	28.7	16.3	5.2	0.32	71.3
sw3	39.2	26.8	6.2	0.42	98.3
sw4	34.1	22.2	5.8	0.37	86.7
mx1	38.5	30.8	5.7	0.67	96.2
mx2	32.4	27.2	5.1	0.55	85.1
mx3	47.2	37.7	6.9	0.87	118.8
mx4	43.5	32.4	6.3	0.68	107.3

(Figs 9 and 10). The spatial variation of Rn was similar for switchgrass and miscanthus as both are perennial grasses and had relatively similar physiological and phenological traits compared with corn. However, the

mean value of switchgrass was lower than miscanthus. In most regions covered by biofuel crops, ΔLE typically outweighed ΔRn such that the biophysical effects of land conversion are dominated by localized evaporative cooling. When agricultural management was applied, the increase of LE was much greater than Rn, leading to a higher cooling effect. This could be attributed to (1) irrigation maintaining high soil moisture and/or (2) fertilization leading to higher LAI and thus increased transpiration. The spatial pattern of LE change showed larger enhancement in the southern United States for the three biofuel crops, which was possibly attributed to the higher evaporative demand.

CWMP under various alternative scenarios. Our simulated annual CWMP under various alternatives (Table 3) indicated that CWMP could be significantly improved when biophysical effects were added. The corn ecosystem changed from carbon source to sink in the corn1 experiment, which affirmed the previous research that biophysical effects of bioenergy crops can be even larger than biogeochemical effects at regional scales (Georgescu *et al.*, 2011; Anderson-Teixeira *et al.*, 2012). This improvement can be mainly explained by an increase in LE for biofuel crops leading to cooling effects that contribute to

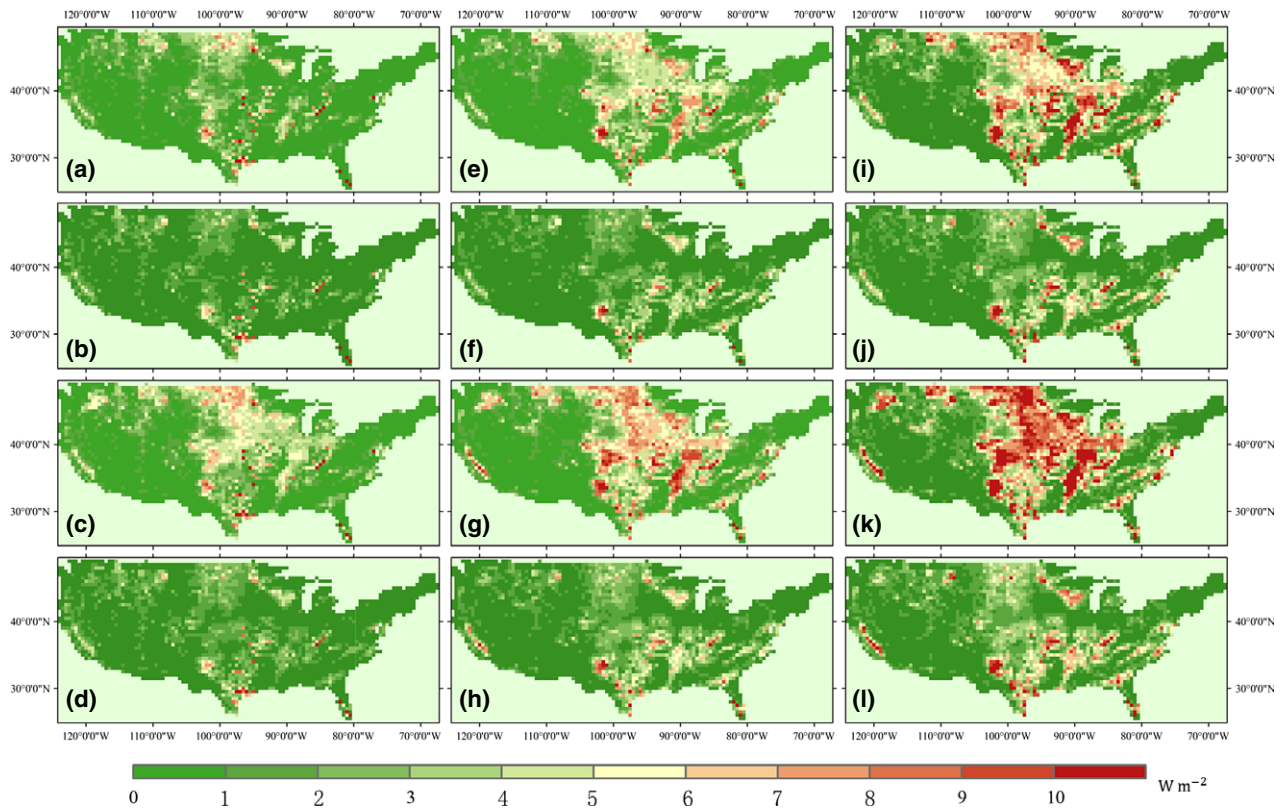


Fig. 9 The simulated difference of annual mean LE (W m^{-2}) based on 10-year (2000–2010) climate forcing data among each experiments, (a–l) corresponds to the difference between corn1, corn2, corn3, corn4, sw1, sw2, sw3, sw4, mx1, mx2, mx3, mx4, and cntl, respectively.

climate warming mitigation. The synergistic effect of fertilization and irrigation significantly improves the CWMP of biofuel crops, especially for corn, similar to previous studies (Lee *et al.*, 2012). This management triples CWMP of corn from 20.5 g C m^{-2} to 79.6 g C m^{-2} in the scenario where both croplands and marginal lands were converted to bioenergy crops. This result is consistent with previous research and confirmed high input could reduce carbon payback time of crop-based biofuel (Elshout *et al.*, 2015). If biofuel crops were planted only on marginal lands with no management, their CWMP ranged from 33.0 g C m^{-2} to 85.1 g C m^{-2} while this range shifts to 20.5 g C m^{-2} to 96.2 g C m^{-2} when cropland is also converted, implying CWMP over marginal lands is lower than that over croplands. The highest CWMP of 118.8 g C m^{-2} is achieved by mx3, which is $\sim 50\%$ higher than if biogeochemical effects are considered alone (84.9 g C m^{-2}). The simulated CWMP of switchgrass lies between corn and miscanthus.

Discussion

In this study, we used the revised land surface model, CLM4.5, to evaluate the climate regulation service of the

grain and cellulosic crops across conterminous United States over a multiyear time frame. The results show that harvesting corn grain and residue for biofuel production under a scenario without any agricultural management will progressively deplete the soil carbon pool. Previous research concluded that cultivation of switchgrass and miscanthus increased SOC on average $10\text{--}100 \text{ g C m}^{-2}$ per year in the top 30 cm (Anderson-Teixeira *et al.*, 2009). Our modeled SOC change of $16.3\text{--}37.7 \text{ g C m}^{-2}$ per year fell within this range. Results confirmed that cellulosic crops, which normally had higher nutrient use efficiency and higher water use efficiency, sequester more carbon and produce more biomass for bioenergy feedstocks (Davis *et al.*, 2011; Vanloocke *et al.*, 2012; Jones *et al.*, 2015). This suggests that these biofuel crops are more promising in areas that extend beyond current croplands. The results demonstrate high spatial variation in carbon sequestration ability controlled by the climatic and soil conditions as well as the type of land being replaced. Previous research demonstrated that the conversion of tropical and temperate forests, savannahs, and peatland for biofuel production could cause net carbon emissions because of the large amount of stored carbon released

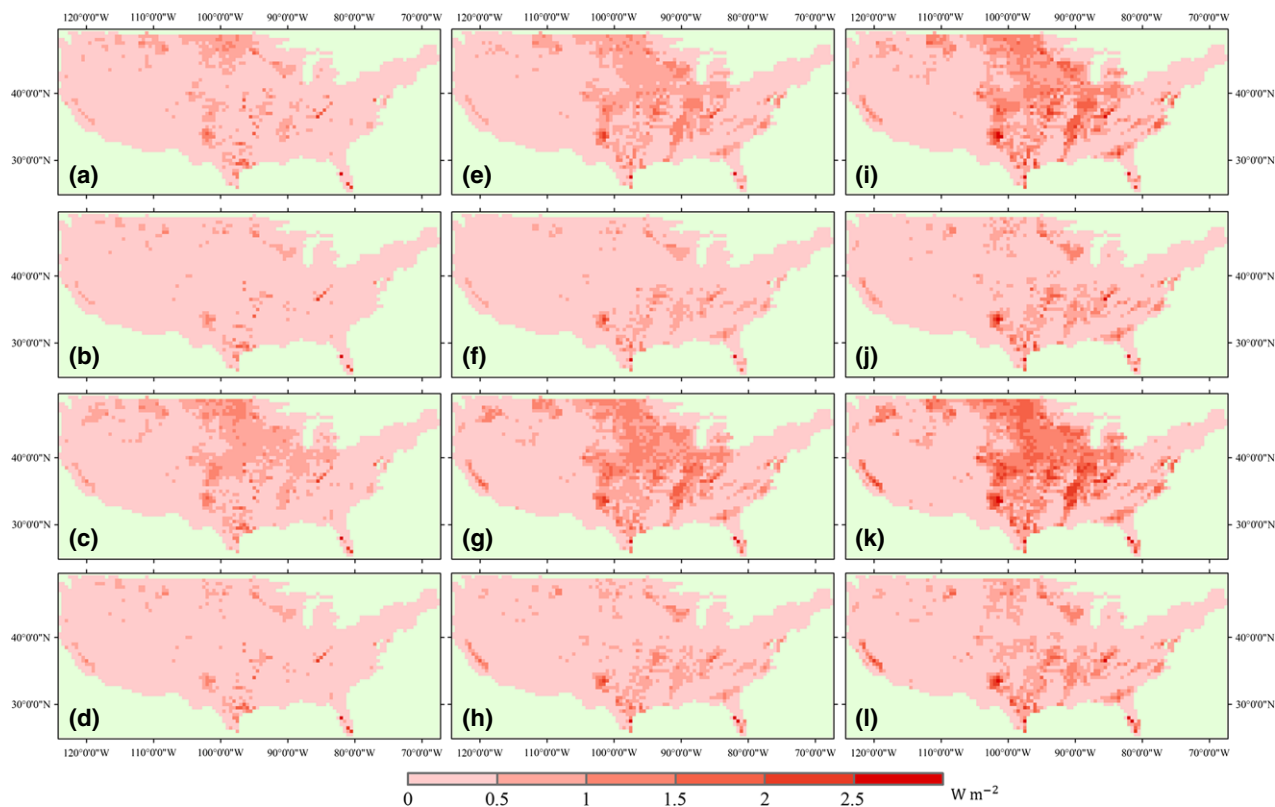


Fig. 10 The simulated difference of annual mean R_n ($W m^{-2}$) based on 10-year (2000–2010) climate forcing data among each experiments, (a–l) corresponds to the difference between corn1, corn2, corn3, corn4, sw1, sw2, sw3, sw4, mx1, mx2, mx3, mx4, and cntl, respectively.

(Fargione *et al.*, 2008; Elshout *et al.*, 2015). In this study, only marginal land and cropland were taken into account for land conversion. These scenarios therefore present a practical approach based on previous experimental conclusion that cultivation of biofuels on marginal land can enhance productivity while minimizing environmental degradation (Bhardwaj *et al.*, 2011). This and previous research highlights that marginal land is less fertile and can sustain lower carbon sequestration capacity (Gelfand *et al.*, 2013); therefore, more marginal land is needed to achieve mitigation targets. Our model simulation only considered 100% land conversion fraction, which can be viewed as an upper limit. Lower fraction of land conversion will dampen the CWMP of biofuels crops observed here, similar to previous results (Vanloocke *et al.*, 2010).

The proposed CWMP here covered carbon fluxes, carbon storage, and surface energy change, which presents a complete perspective of evaluating climate mitigation of biofuel crops (Anderson *et al.*, 2010; Knoke *et al.*, 2012). CWMP of both cellulosic crops and corn significantly increased when accounting for both biogeochemical and biophysical, rather than just biogeochemical, effects. One biophysical component, R_n which is

dominated by albedo, increased when current land cover was displaced by biofuel crops. Evaporative cooling of miscanthus and switchgrass, therefore, is augmented by higher albedo, consistent with previous results (Anderson-Teixeira *et al.*, 2012). However, observed experiment data indicated that miscanthus and switchgrass have a higher albedo than corn during the growing season, thereby reducing R_n in bioenergy crops (Miller *et al.*, 2015). This discrepancy likely originates from the current model being unable to predict albedo of these perennial grasses through improper parameterization of leaf transmittance and reflectance, leaf angle, and canopy structure (Lawrence *et al.*, 2011). Thus, further efforts are needed to improve surface energy processes of these biofuel crops. The albedo effects, however, are secondary to the effects of crop type on LE, which is a major component of the water cycle. Both crop productivity and LE are strongly influenced by irrigation, particularly in arid environments (Roncucci *et al.*, 2014). Experiments suggest miscanthus has larger transpiration due to the higher stomatal conductance to support its high carbon assimilation rate (Dohleman *et al.*, 2009), which is consistent with our results. Higher LE induced by the expansion of biofuel crops are likely to impact the

hydrological cycle although this influence spatially variable based on a range of factors (Vanloocke *et al.*, 2010; Abraha *et al.*, 2015).

While this study indicates that both biogeochemical and biophysical feedbacks need to be considered in evaluating biofuel crops, several limitations to the analysis still exist. First, this model neglects other important GHGs from agroecosystems particularly N₂O. Higher N₂O emissions are expected with increased fertilization. However, previous results show that perennial systems leak less N₂O through leaching and denitrification (Smith *et al.*, 2013; Hudiburg *et al.*, 2015). Thus, our estimates of the climate change mitigation potential are likely conservative. Our results also neglect environmental impact of increasing nitrate leaching induced by fertilization application (e.g., Chamberlain *et al.*, 2011). Second, soil carbon storage is heavily dependent on crop residue remove rate (Smith *et al.*, 2012; Liska *et al.*, 2014), and we set crop residue remove rate as a constant across the United States. More realistic and/or flexible removal rates should be introduced in the future research. Third, the irrigation in CLM4.5 is automatically triggered based on soil water status. Although irrigation is shown to improve CWMP of biofuel crops and might save more lands, its possible threat to local water resource is not accounted. Recent research highlights the need to institute policies to balance the water and land requirements during bioenergy production (Bonsch *et al.*, 2014). Finally, we used land surface energy change to represent total cooling effects of growing biofuel crops on the climate. It is desirable to use dynamic climate models to examine how these land-use change and management scenarios affect the climate in terms of air temperature and precipitation. For instance, altered evapotranspiration due to growing biofuel crops will impact atmospheric vapor pressure deficit and its consequences on plant physiology, meteorology, and climate (Lobell *et al.*, 2009; Puma & Cook, 2010). For example, an increase in cloud formation will affect short-wave radiation and air temperature, the processes that current land surface models neglect.

Previous research has demonstrated that integrating the ideal farming management practices (e.g., improved harvesting techniques, harvest timing, organic matter amendments, reduced-till, and/or rotating cereals with grain legumes) can reduce GHG emissions and improve soil carbon sequestration capacity and soil quality. This can lead to environmental protection and biodiversity conservation (Gan *et al.*, 2014; Cheng *et al.*, 2014; Hudiburg *et al.* 2015; Davis *et al.*, 2013). Our research confirmed the importance of agricultural management in enhancing CWMP especially when accounting for biophysical effects. In addition to climate mitigation, improving current farming practices can lead to improved

ecosystem services while maximizing bioenergy production. Faced with increasing land-use pressures driven by growing population, our spatially explicit results accounting both biophysical and biogeochemical effect enable policymakers to make wiser decisions on the landscape planning of biofuel crops expansion to accomplish climate mitigation target (Campbell *et al.*, 2010).

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