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Carbon and nitrogen dynamics in bioenergy ecosystems: 2. Potential greenhouse gas emissions and global warming intensity in the conterminous United States

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Abstract

This study estimated the potential emissions of greenhouse gases (GHG) from bioenergy ecosystems with a biogeochemical model AgTEM, assuming maize (*Zea mays* L.), switchgrass (*Panicum virgatum* L.), and *Miscanthus* (*Miscanthus* × *giganteus*) will be grown on the current maize-producing areas in the conterminous United States. We found that the maize ecosystem acts as a mild net carbon source while cellulosic ecosystems (i.e., switchgrass and *Miscanthus*) act as mild sinks. Nitrogen fertilizer use is an important factor affecting biomass production and N_2O emissions, especially in the maize ecosystem. To maintain high biomass productivity, the maize ecosystem emits much more GHG, including CO_2 and N_2O, than switchgrass and *Miscanthus* ecosystems, when high-rate nitrogen fertilizers are applied. For maize, the global warming potential (GWP) amounts to 1–2 Mg CO_2eq ha^{-1} yr^{-1}, with a dominant contribution of over 90% from N_2O emissions. Cellulosic crops contribute to the GWP of less than 0.3 Mg CO_2eq ha^{-1} yr^{-1}. Among all three bioenergy crops, *Miscanthus* is the most biofuel productive and the least GHG intensive at a given cropland. Regional model simulations suggested that substituting *Miscanthus* for maize to produce biofuel could potentially save land and reduce GHG emissions.

Keywords: biofuel, carbon balance, global warming potential, maize, *Miscanthus*, modeling, nitrous oxide, switchgrass

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Introduction

Increasing concerns about energy security and environmental sustainability have prompted development of renewable energy. Currently, global energy supplies are dominated by fossil fuels, with very limited renewable sources. In 2010, the world total primary energy supply amounted to over 12 000 Mtoe yr^{-1} (Mtoe, million ton of oil equivalent), which is more than double the supply in 1973. More than 80% of energy supplies come from fossil fuels including oil (32.4%), coal/peat (27.3%), and natural gas (21.4%) (IEA (International Energy Agency), 2012). The increasing use of fossil fuels has directly led to increasing greenhouse gas (GHG) emissions. The IPCC reported that GHG emissions have increased by an average rate of 1.6% yr^{-1} over the last three decades, with growing carbon dioxide (CO_2) emissions from the use of fossil fuels at a rate of 1.9% yr^{-1} (Rogner *et al.*, 2007). The total annual CO_2 emissions have approximated to 30 gigatonnes in 2008, and still keep increasing (UN (United Nations), 2012). As of the year 2010, only a very small proportion of the world energy supply came from renewable energy sources like hydropower (2.3%). Energy from biofuels and biomass including those traditionally used for cooking and heating in the underdeveloped areas, however, account for about 10% of the world total energy supply, making it by far the most important renewable energy source (IEA (International Energy Agency), 2012).

In the United States, bioenergy production is receiving great attention from industry, government, and the scientific community. Ethanol production increased from 19 billion liters during the 1980s to 45 billion liters during the 1990s, and 174 billion liters during the 2000s. In 2011 alone, the annual production reached 52.6 billion liters, 2.6 times the total production of the entire 1980s, or 1.14 times of the 1990s (RFA (Renewable Fuels Association), 2012). As a comparison, the consumption of gasoline was about 500 billion liters in 2011 (EIA (US Energy Information Administration), 2012). The ethanol plant and production capacity have expanded enormously since the early 2000s. The United States is one of the world's largest energy producers and consumers in terms of fossil fuels as well as biofuels (IEA (International Energy Agency), 2012). Over 60% of world fuel ethanol is produced in the United States in 2011 (RFA (Renewable Fuels Association), 2012). According to the

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Energy Independence and Security Act of 2007 (US Congress, 2007), 136 billion liters (36 billion gallons) of renewable fuels, including 79 billion liters (21 billion gallons) of cellulosic ethanol, are expected to be produced annually by 2022. The fast bioenergy expansion increases societal, economic, and scientific concerns about food security, land availability, and carbon (C) mitigation.

In the United States, most of the current biofuels are made from food crops, such as maize grain and soybeans (*Glycine max* (L.) Merr.). Although the production of food crops has increased during the last several decades, due to crop variety improvement, technology advances, management optimization, and other factors, most food grain was used for human consumption, livestock feed, or other industrial uses. Only a limited proportion of the food crops, for instance, about 30% of maize grain (2009) (USDA (US Department of Agriculture), 2010), can be used for biofuel. The traditional crop grain alone cannot support the ambitious bioenergy goal without massive crop area expansion or a dramatic increase in grain productivity. In addition, the competitive consumption of resources such as land, water, and nutrients by biofuel crops could threaten food crops and therefore food security (Fargione *et al.*, 2010; Diffenbaugh *et al.*, 2012). From the perspective of climate change mitigation, the crop-based biofuel may increase GHG emissions due to the impacts of indirect land-use change from natural ecosystems to croplands to meet the increasing demand for land. Nitrogen (N) fertilizer application may also contribute to the GHG emissions when used in producing biofuel feedstocks (Searchinger *et al.*, 2008; Melillo *et al.*, 2009). Crutzen *et al.* (2008) reported that the production of commonly used biofuels, including bioethanol from maize, depending on plant N uptake efficiency, can contribute even more to global warming by N_2O emissions than mitigation by fossil fuel savings. N fertilizer contributes significantly to maize yield and yet produces the majority of N_2O emissions from the ecosystem (McSwiney & Robertson, 2005; Hoben *et al.*, 2011).

Cellulosic crops were introduced and tested in Europe (e.g., Clifton-Brown *et al.*, 2004; Fischer *et al.*, 2010) and the United States (e.g., Fike *et al.*, 2006b; Heaton *et al.*, 2008) for their higher productivity in producing biofuel biomass and higher environmental stress resistance relative to food crops. Two major cellulosic crops, switchgrass and *Miscanthus,* were selected as potential energy crops to substitute for maize grain for producing ethanol. Switchgrass is a perennial, warm-season lignocellulosic crop native to North America, with an annual yield ranging from 5 to 20 Mg dry matter (DM) ha^{-1} (Wright & Turhollow, 2010). *Miscanthus* is a genus of several species of perennial grasses, mostly native to subtropical and tropical regions of Asia, and introduced to the United States recently as an energy crop (Stewart *et al.*, 2009). Its yield normally ranges from 20 to 30 Mg DM ha^{-1}, with a maximum yield at 60 Mg DM ha^{-1} (Heaton *et al.*, 2008). These cellulosic crops are favored for their high efficiencies in making use of resources like land and nutrients. They require no or very limited amount of N fertilizer, while maize normally needs continuous N and other forms of fertilizer application to support growth (Lewandowski *et al.*, 2003; Fargione *et al.*, 2010). Relative to maize, cellulosic crops could potentially reduce N fertilization, and therefore mitigate N_2O emissions, and still provide competitive biomass feedstocks for biofuel production.

Compared with maize, the cellulosic crops may better serve as biofuel feedstocks in terms of GHG mitigation. Since most CO_2 absorbed by a plant via photosynthesis will eventually be emitted to atmosphere through biomass decomposition (e.g., litter fall or residues) or biofuel burning in case where plant is used for energy, the net C sequestered by the ecosystem is mostly located in soils. Field observations suggest that perennial energy crops could potentially sequester additional C into soils especially if established on former cropland. The ecosystems of cellulosic crops like switchgrass or *Miscanthus* have a generally larger soil C pool than the conventional annual crops (Kahle *et al.*, 2001; Dondini *et al.*, 2010; Don *et al.*, 2012). Assuming national cropland switched from maize to cellulosic crops, Qin *et al.* (2012) estimated that the average soil C density in switchgrass and *Miscanthus* increased two thirds of that in maize. For cropland, the N_2O-N emitted is about 1 percent of the N fertilizer applied (De Klein *et al.*, 2006). Assuming that maize normally received 100–200 kg N ha^{-1} fertilizer each year, the N_2O emissions from 30 Mha maize-producing areas in the United States could reach 30–60 Gg N_2O-N per year. Earlier estimates indicated that annual N_2O emissions from all crop and pasture lands ranged within 0.9–1.2 Tg N in 1990 (Li *et al.*, 1996), and were about 201 Gg N from soils of major commodity crops in 2007 (Del Grosso *et al.*, 2010). Switchgrass and *Miscanthus* may not necessarily have a lower N_2O emission factor relative to maize (Qin *et al.*, 2013), but they normally require much less N fertilizer (Lewandowski *et al.*, 2003; Heaton *et al.*, 2004; Clair *et al.*, 2008); therefore, the per hectare N_2O emissions could be lower. According to these field tests, cellulosic crops seem to be a promising alternative to maize, due to their high productivity of biomass feedstocks (e.g., Fike *et al.*, 2006b; Heaton *et al.*, 2008; Wright & Turhollow, 2010), and relatively low GHG emissions (e.g., Lewandowski *et al.*, 2003; Heaton *et al.*, 2004; Clair *et al.*, 2008).

Special attention should be given to extrapolating site-level understanding to regional scales. The spatial heterogeneity of climate and soil conditions may not allow a simple site-to-region extrapolation without considering environmental changes. For example, the N_2O emission factor may be applicable for some sites with a certain range of N fertilization, but not for some other sites, and especially not for those with high-N application rates (McSwiney & Robertson, 2005; Hoben *et al.*, 2011). Ecosystem modeling, on the contrary, is capable of addressing the problem of spatial heterogeneity. With spatially explicit data, models can simulate C and N dynamics using information describing climate, soil, and vegetation characteristics (Fargione *et al.*, 2010; Davis *et al.*, 2012). However, the model should still be cautiously selected and tested. General ecosystem models, especially those originally designed for natural ecosystems, may not work well in simulating a specific bioenergy-related agroecosystem without crop-specific calibration. Here, we parameterize and validate an agroecosystem model for specific crops to assess possible GHG emissions due to a potential large-scale expansion of bioenergy development in the United States. Specifically, we analyze the biomass and biofuel production and GHG emissions in bioenergy-related ecosystems, by assuming maize, switchgrass, and *Miscanthus* could be grown on the current maize-producing areas in the conterminous United States. Using an agroecosystem-based biogeochemical model, we (i) simulate spatially explicit C and N dynamics of each ecosystem, (ii) estimate C balance (i.e., net CO_2 emissions) and N_2O emissions during the crop growth and harvest periods, and (iii) examine the potential GHG emissions and global warming intensity due to bioenergy expansion.

Materials and methods

Model description

AgTEM is a process-based biogeochemical model to simulate C and N dynamics in agroecosystems at a daily time step using spatially explicit data of climate, vegetation, topography, and soils (Qin *et al.*, 2013). AgTEM inherits the model structure from TEM (e.g., Raich *et al.*, 1991; McGuire *et al.*, 1992; Zhuang *et al.*, 2003), with additional biogeochemical and ecophysiological processes incorporated to assess C and N fluxes and pools. Agricultural management is also considered (Qin *et al.*, 2013). Among many variables describing C and N cycling, two of them related to C are frequently used in ecosystem modeling studies. One is net primary production (NPP) to estimate crop biomass production. The other is net carbon exchange (NCE) to evaluate the net C balance at the ecosystem scale. NPP can be further used to assess crop grain (e.g., for maize) and harvestable biomass (e.g., for cellulosic crops) production, and eventually to calculate potential biofuel production from various biomass feedstocks. NCE accounts for the net C sink or source considering photosynthesis (e.g., aboveground- and belowground biomass accumulation), growth and maintenance respiration, soil respiration, and biomass harvest. A positive NCE indicates a net CO_2 sink, whereas a negative value indicates a net CO_2 source. Nitrogen fluxes, including nitrous oxide (N_2O), are also estimated considering both nitrification and denitrification processes in soils (Qin *et al.*, 2013).

AgTEM is a generic agroecosystem model with vegetation-specific parameters characterizing specific crop structures and processes. Most parameters used in this study have been either predefined (e.g., Raich *et al.*, 1991; McGuire *et al.*, 1992; Zhuang *et al.*, 2003) or calibrated for specific crops (e.g., Qin *et al.*, 2011, 2012; Zhuang *et al.*, 2013) in previous studies. The AgTEM version used here has been validated against observations from maize, switchgrass, and *Miscanthus* ecosystems. More information regarding AgTEM can be found in Qin *et al.* (2013).

Regional simulations on crop biomass and GHG fluxes

We assume that conventional grain crop, maize, and two cellulosic crops, switchgrass and *Miscanthus* will be grown separately as potential energy crops on currently available maize-producing areas in the conterminous United States (Fig. 1). Using spatially referenced data on location, climate, soil, and vegetation, the AgTEM was applied to simulate crop growth and C and N dynamics for each of these three cropping scenarios (i.e., maize, switchgrass, and *Miscanthus*). Spatial analyses were then conducted at both grid- and national-levels to assess biomass production and GHG emissions.

Spatial forcing data describing climate, CO_2, soils, vegetation conditions, and agricultural management were collected and organized at a 0.25° latitude × 0.25° longitude resolution for

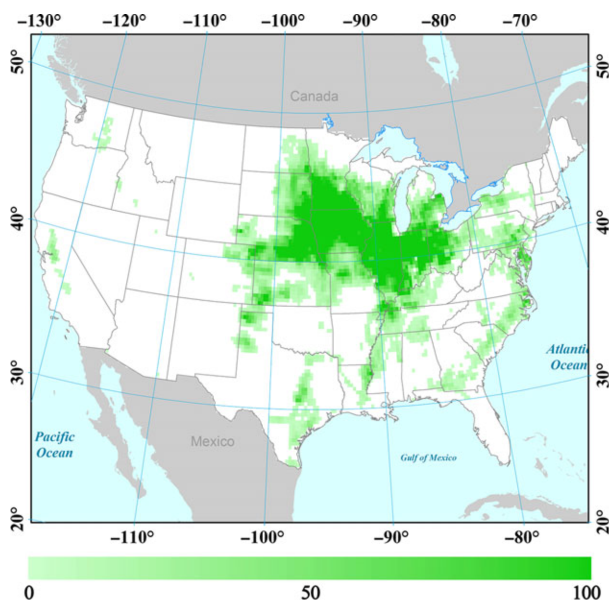

Fig. 1 Maize cropland in the conterminous United States in the year 2000. Value shows the harvested area as the proportion of each grid cell (%). Data are derived from Monfreda *et al.* (2008).

the study area. Specifically, climate data including the air temperature, precipitation, and cloudiness were obtained from the ECMWF (European Centre for Medium-Range Weather Forecasts) Data Server (www.ecmwf.int) and organized at a temporal resolution of 1 day from 1989 to 2008. CO_2 data were derived from averaged annual atmospheric CO_2 concentrations collected from the NOAA Mauna Loa CO_2 record (www.esrl.noaa.gov/gmd/ccgg/trends/). The original elevation data were derived from the Shuttle Radar Topography Mission (SRTM) (Farr *et al.*, 2007), and soil texture data were based on the Food and Agriculture Organization/Civil Service Reform Committee (FAO/CSRC) digitization of the FAO/UNESCO soil map of the World (1971). Vegetation data describing the current maize crop distribution (2000) in the conterminous United States (Fig. 1) were extracted from a global crop harvest area database (Monfreda *et al.*, 2008). For agricultural management, data indicating irrigation and fertilization were included in the simulations. Irrigation data were obtained from the average irrigation data in the USGS county-level database of estimated use of water in the United States (2005) (Kenny *et al.*, 2009). Since no data were available concerning the spatial heterogeneity of the N fertilization rate among different bioenergy crops, we selected the fixed N input as forcing data. However, to be more realistic, several different levels of N rate were assumed in simulations to examine crop response to N input. For maize, four N input levels were set at 0 (N0), 67 (N1), 134 (N2), and 246 g N ha^{-1} yr^{-1} (N3) according to field experiments (Mosier *et al.*, 2006; Halvorson *et al.*, 2008, 2010). Switchgrass and *Miscanthus* require less N inputs, with normal rates of 50–60 g N ha^{-1} yr^{-1} in many experimental tests (Fike *et al.*, 2006b; Behnke *et al.*, 2012). We set two levels at 0 (N0) and 67 g N ha^{-1} yr^{-1} (N1) to be comparable with maize.

To conduct regional simulations separately for maize, switchgrass, and *Miscanthus*, we ran AgTEM grid-by-grid to estimate spatial C and N dynamics at a daily time step from 1989 to 2008. For each land cover scenario under certain N input levels, we first ran AgTEM to equilibrium using the first year data to determine the initial conditions, and then spun-up the model for 100 years repeatedly using the first 10 years' data to reach equilibrium. Finally, the transient simulations from 1989 to 2008 were conducted to estimate changes of C and N fluxes and pools. Spatial analyses for both grid-level and national level were presented as average of the 1990s.

Evaluation of biofuel production, GHG emissions, and global warming intensity

Bioethanol produced from biomass feedstocks, either maize grain or cellulosic biomass, is determined by the biomass-to-biofuel conversion efficiency, which varies between feedstock types and may also change due to technology advances. For maize, both grain and biomass can be used as feedstocks, but for switchgrass and *Miscanthus*, only biomass is usable (Table 1, harvest index (HI) of grain is unavailable or set to zero). Currently, conversion technology for conventional biofuels is relatively well established. For example, about 416 l of ethanol can be produced from each ton (1 t = 1 Mg) of maize grain (Lynd *et al.*, 2008). However, technology of biomass conversion to second-generation biofuel is still new, and the conversion efficiency is relatively low, only two thirds of that for maize grain (Table 1). However, the conversion efficiency could be improved due to future technology advances, especially for cellulosic biomass. It is expected that, under improved efficiencies, cellulosic biomass could yield 40% more ethanol per unit feedstock than current production, while maize grain may increase only 2% in productivity (Table 1), making cellulosic crops very competitive to maize grain (Lynd *et al.*, 2008; Fargione *et al.*, 2010). In this study, we estimated biofuel productivity using both current and potential conversion efficiencies.

Table 1 Parameters used to estimate biomass harvest and biofuel production

	HI*		$C_{bio,crt}$†		$C_{bio,ptn}$‡	
	Grain	Biomass	Grain	Biomass	Grain	Biomass
Maize	0.53	0.14	416	282	424	399
Cellulosic crop	–	0.90	–	282	–	399

*HI, harvest index as defined in Qin *et al.*, 2013, dimensionless. †$C_{bio,crt}$ and ‡$C_{bio,ptn}$ are current and potential biomass-to-biofuel conversion efficiencies, respectively, L ethanol Mg^{-1} biomass. Cellulosic crops refer to switchgrass and *Miscanthus* in the study. References and data sources: Hicke *et al.*, 2004; Lynd *et al.*, 2008; Fargione *et al.*, 2010; Meyer *et al.*, 2010; Payne, 2010.

CO_2 and N_2O are two major GHG in agroecosystems contributing to climate change (Bondeau *et al.*, 2007; Smith *et al.*, 2012). The net production of these GHG was assessed separately, as the C or N balance at ecosystem scales. The contribution of GHG to climate warming was evaluated as global warming potential (GWP), which measures relative amounts of heat trapped by GHG in the atmosphere. The GWP of N_2O, in this study, was calculated in units of CO_2 equivalents (CO_2eq) over a 100-year time horizon assuming that one unit of N_2O mass is equivalent to 298 units of CO_2 (Forster *et al.*, 2007). For each ecosystem, the combined GWP for CO_2 and N_2O emissions was calculated as sum of contributions from NCE and N_2O produced in nitrification and denitrification (N_2O):

$$GWP_{tot} = \underbrace{-NCE \times \frac{44}{12}}_{GWP_{CO_2}} + \underbrace{298 \times N_2O \times \frac{44}{28}}_{GWP_{N_2O}}, \tag{1}$$

where GWP_{tot}, GWP_{CO2} and GWP_{N2O} are GWP for total GHG, CO_2, and N_2O, respectively. Positive GWP indicates a net GHG source, and a negative value refers to a net GHG sink of any particular ecosystem.

To relate agricultural practices to GWP, many studies used the term GHG intensity or global warming intensity by dividing GWP by crop yield (e.g., grain yield for maize) (Grassini & Cassman, 2012; Linquist *et al.*, 2012). Instead of relating GWP to crop yield, we applied a similar approach to address the contribution of GHG relative to biofuel yield. As in Eqn (2), GWP_i is the global warming intensity in terms of total GWP for

CO_2 and N_2O relative to biofuel produced (YLD_{bio}). For maize, switchgrass, and *Miscanthus* studied here, the biofuel is referred to ethanol and the units for GWP_i are kg CO_2eq l^{-1} E. A positive GWP_i value indicates a net source of CO_2 equivalents per unit of ethanol yield and a negative value indicates net sinks of GHG to the ecosystem.

$$GWP_i = \frac{GWP_{tot}}{YLD_{bio}} \quad (2)$$

Results

Role of N fertilization in biomass and biofuel production

To examine the response of crop growth to N fertilization, we use grain and biomass production estimated with the model at four N input levels of N0, N1, N2, and N3 (Table 2). The national NPP results suggest that maize is most sensitive to N rates among these bioenergy crops, and cellulosic crops, especially *Miscanthus*, are relatively less sensitive to changing N input. Maize is capable of producing 326 g C m^{-2} of NPP each year without N application, and additional 1.1–2.0 g C m^{-2} for each kg N fertilizer added. When the N rate is relatively high (e.g., N3 of 246 kg N ha^{-1} yr^{-1}) such that crop growth may no longer be limited by N, maize can reach a national average NPP of 702 g C m^{-2} yr^{-1}. Switchgrass responds positively to N addition at low-N input levels, and reaches its relatively high production level at N1. *Miscanthus*, however, does not respond to N addition at a significant level; its productivity is relatively stable with or without N application (Table 2). According to the fertilizer consumption and use for maize (USDA (US Department of Agriculture), 2012), the N application rate in the United States varies among regions, roughly ranging from 70–180 kg N ha^{-1} yr^{-1} in the 1990s, which is in between our estimates of N levels at N2 and N3. The model estimated crop NPP of 552–702 g C m^{-2} yr^{-1} with fertilizer input between N2 and N3 is comparable with NPP from national statistical data (FAOSTAT, 2012) of 540–730 g C m^{-2} yr^{-1} in the 1990s. The estimated biomass production of switchgrass at N1 and *Miscanthus* at N0 is also close to field observations (Fike *et al*., 2006b; Heaton *et al*., 2008; McIsaac *et al*., 2010; Nikièma *et al*., 2011). Our study suggests that the modeled N fertilization levels of N2–N3 for maize, N1 for switchgrass and N0 for *Miscanthus* may be reasonable to inform the current productivity of these biofuel crops in the United States.

Cellulosic crops generally have higher biomass production than maize. For example, with 67 kg N ha^{-1} N application, switchgrass produces 70% higher NPP than maize and *Miscanthus* produces twice as much NPP as switchgrass (Table 2). However, considering potential maize production from N addition, switchgrass may not necessarily be more productive than maize. *Miscanthus* can produce over 20 Mg of DM for each hectare of land, which is about twice as much as switchgrass or maize could produce at their highest productivity (Table 2). In terms of biofuel production, conversion efficiency is another factor determining the difference in productivity among crops. Maize, with relatively low biomass production, may produce considerable biofuel, compared with switchgrass; maize grain produces more unit-land-based ethanol than cellulosic biomass does. With an increasing N input, maize-based biofuel yield increases. Maize has the highest biofuel production at N3, producing about 2.7 and 3.5 kl ethanol per hectare of land, under current and potential conversion technologies, respectively (Fig. 2). Compared with maize, switchgrass is comparably productive when they are both grown under low-N levels (i.e., N0, N1). Because of its high biomass production, *Miscanthus* is still the most productive crop for biofuel among the three crops. Without N application, *Miscanthus* can produce 5.8–8.2 kl ethanol ha^{-1}, depending on conversion

Table 2 Model estimated annual net primary production (NPP), crop grain yield and harvestable biomass yield of bioenergy crops, in the conterminous United States

N input*	NPP (g C m^{-2} yr^{-1})			Harvest (Mg DM ha^{-1} yr^{-1})			
	Maize	Switchgrass	*Miscanthus*	Maize grain	Maize biomass†	Switchgrass	*Miscanthus*
N0	326 (38)	473 (56)	1440 (119)	3.3 (0.4)	0.9 (0.1)	5.5 (0.6)	20.5 (2.0)
N1	403 (42)	681 (59)	1482 (153)	4.0 (0.4)	1.1 (0.1)	7.9 (0.7)	21.1 (2.2)
N2	552 (52)	–	–	5.5 (0.5)	1.5 (0.1)	–	–
N3	702 (79)	–	–	7.0 (0.8)	1.9 (0.2)	–	–

*N0, N1, N2, and N3 are N input levels at 0, 67, 134, and 246 kg N ha^{-1} yr^{-1}, respectively; same hereafter in all tables and figures. Values presented are 10-year mean (SD, standard deviation) of the 1990s and may not total precisely due to rounding; same in tables 3 and 4.

†About 30% of total aboveground biomass (excluding grain) were harvested, and the rest were returned to soil for soil fertility sustainability (Payne, 2010).

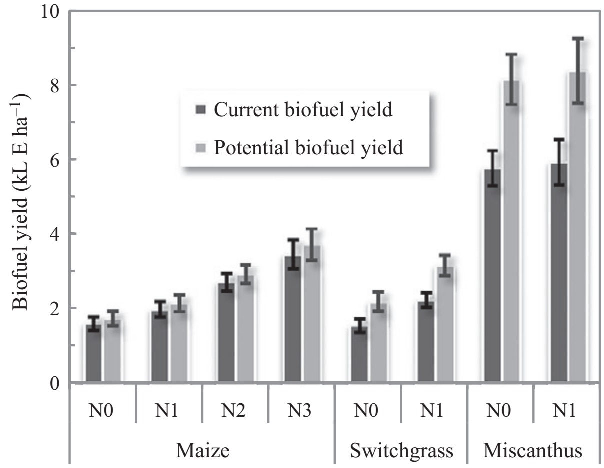

Fig. 2 Estimated biofuel produced from the maize, switchgrass, and *Miscanthus* ecosystems. Estimates are made for both grain and harvestable biomass for maize, and for harvestable biomass for switchgrass and *Miscanthus*. Error bar indicates SD.

technology. For *Miscanthus*, N fertilization does not affect its biofuel production as much as that for maize (Fig. 2).

Ecosystem C balance in the bioenergy ecosystems

Ecosystem C balance, accounting for net CO_2 exchange between the atmosphere and ecosystems, varies temporally and spatially under changing environment, such as climate and soil conditions. The annual NCE of any specific site/grid could be either negative or positive and its interannual variability depends on environmental factors (McGuire *et al.*, 2001). The average NCE across multiple years is mainly determined by management and land-use change, instead of natural causes such as interannual climate variations (Fig. 3). Generally, by growing maize and harvesting grain and biomass for biofuel use, the regional NCE tends to be negative in the Midwest areas where most maize is produced, and mostly positive in the southern regions (Fig. 3). That is, intensive maize cropping tends to result in a C source. With increasing use of N fertilizer, the spatial NCE changes dramatically. In many areas, C sinks weaken. For instance, as N rate increases from N0 to N1, the NCE of many areas in Kansas and Missouri states decreases from over 40 g C m^{-2} yr^{-1} (Fig. 3a) to less than 20 g C m^{-2} yr^{-1} (Fig. 3b). Some C sink areas even become net sources. For example, the NCE of Texas is above 80 g C m^{-2} yr^{-1} at zero N rate (Fig. 3a), and decreases to −10 to −40 g C m^{-2} yr^{-1} when N rate increases to N3 (Fig. 3d). In contrast with the maize ecosystem, cellulosic crop ecosystems sequester more C than they release in intensively cropped areas. For switchgrass, most areas act as or near C neutral, with 0 to ±5 g C m^{-2} yr^{-1} of NCE, when there is no N application (Fig. 4a). With the N rate increase to N1, the NCE-positive areas are strengthened and become relatively stronger C sinks (Fig. 4b). For *Miscanthus*, the N application does not impact the C balance significantly. In the crop intensive areas, the NCE is mostly above 20 g C m^{-2} yr^{-1}, and even reaches 160 g C m^{-2} yr^{-1} in some scattered areas in the Midwest (Fig. 4c). With additional N fertilizer application, only part of southern regions lower than 35°N (e.g., Texas and Mississippi states) changes from a C sink to a source (Fig. 4c and d).

Nationally, cellulosic crop-based ecosystems act as a net C sink and maize-based ecosystems as a net C source (Table 3). Maize ecosystems emit C at an average of 0.9–2.3 g C m^{-2} yr^{-1} or a total of 0.3–0.7 Tg C each year, depending on the actual N inputs. Switchgrass has an annual NCE of 0.8 g C m^{-2} without N application or 5.4 g C m^{-2} with moderate N input. *Miscanthus* holds a relatively high NCE of over 10 g C m^{-2} yr^{-1}, regardless of N fertilization. If growing *Miscanthus* on all currently available maize cropland areas, the C sink would reach more than 3 Tg C each year.

Potential N_2O emissions from bioenergy ecosystems

Maize ecosystems release enormous amounts of N_2O, especially for regions with intensive cropping and high-N fertilization rates. As a reference, the scenarios with no N application (N0) indicate background emissions of N_2O. For maize, the background N_2O is mostly 0.01–0.07 g N m^{-2} yr^{-1} as weighted by cropland area. The central Midwest has relatively higher N_2O fluxes because more maize is produced in these areas (Fig. 5a). Over the maize-producing areas, the average N_2O emissions are 0.06 g N m^{-2} yr^{-1} with a large variance of 0.01 g N m^{-2} yr^{-1} due to interannual variation and spatial heterogeneity (Table 4). With increasing use of N fertilizer, the N_2O emissions increase dramatically, especially in areas with already high N_2O fluxes. Nationally, the average annual N_2O flux is 0.1 g N m^{-2} at the N1 level (Fig. 5b), and increases by 124% when N fertilizer doubled (Fig. 5c). When maize is grown under the highest N input scenario (N3), N_2O emissions could reach a national average of 0.45 (±0.1) g N m^{-2} yr^{-1}, about 7.5 times that of the reference scenario (Table 4).

Similar to maize ecosystems, ecosystems of cellulosic crops also release N_2O. However, the total amount of N_2O emissions can decrease due to reduced use of N fertilizer. Spatially, the annual N_2O fluxes of cellulosic crops share a common pattern

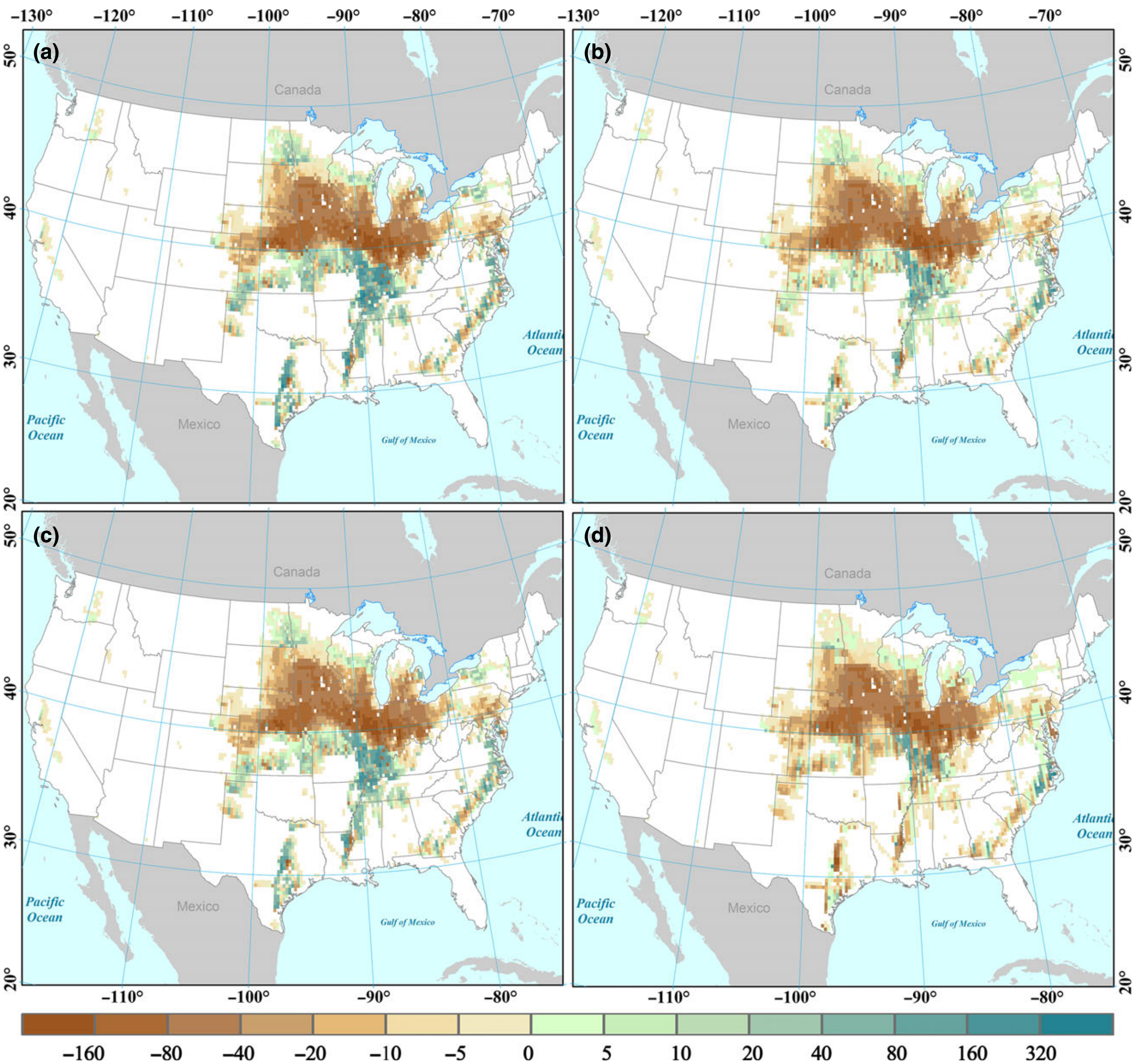

Fig. 3 Annual net carbon exchange (NCE) estimated for maize produced in the conterminous United States. The NCE fluxes ($g\ C\ m^{-2}\ yr^{-1}$) at different N input levels (a) N0, (b) N1, (c) N2, and (d) N3 are presented as averages of the 1990s. Value presented are weighted by cropland area; same hereafter in Figs 4–6, unless otherwise stated.

with maize, with higher emissions in the intensively cropped areas than areas with only small proportion of cropping (Fig. 6). Nationally, switchgrass and *Miscanthus* have comparable N_2O fluxes with maize, about 0.05–0.11 $g\ N\ m^{-2}$ each year depending on crop type and N applied (Table 4). The N_2O emission intensities, in terms of N_2O emissions per unit of land at the same N application rate, of switchgrass (Fig. 6a and b) and *Miscanthus* (Fig. 6c and d) are close to that of maize (Fig. 5a and b). However, to maintain a reasonably high yield, maize requires much more N input than switchgrass and *Miscanthus*, and the additional use of N fertilizer significantly increases N_2O emissions.

Growing switchgrass and *Miscanthus* could remarkably reduce N_2O emissions, which would otherwise be emitted by growing maize at the national level. At N2–N3 input levels, the total N_2O emissions would reach 66–138 Gg N, which is about 1/3–2/3 of the total soil N_2O emissions from major commodity crops in 2007 (201 GgN) (Del Grosso *et al*., 2010). However, if maize is replaced with cellulosic crops, the N_2O emissions will be greatly reduced (Table 4). Growing switchgrass across the United States results in N_2O emissions of 33 Gg N at

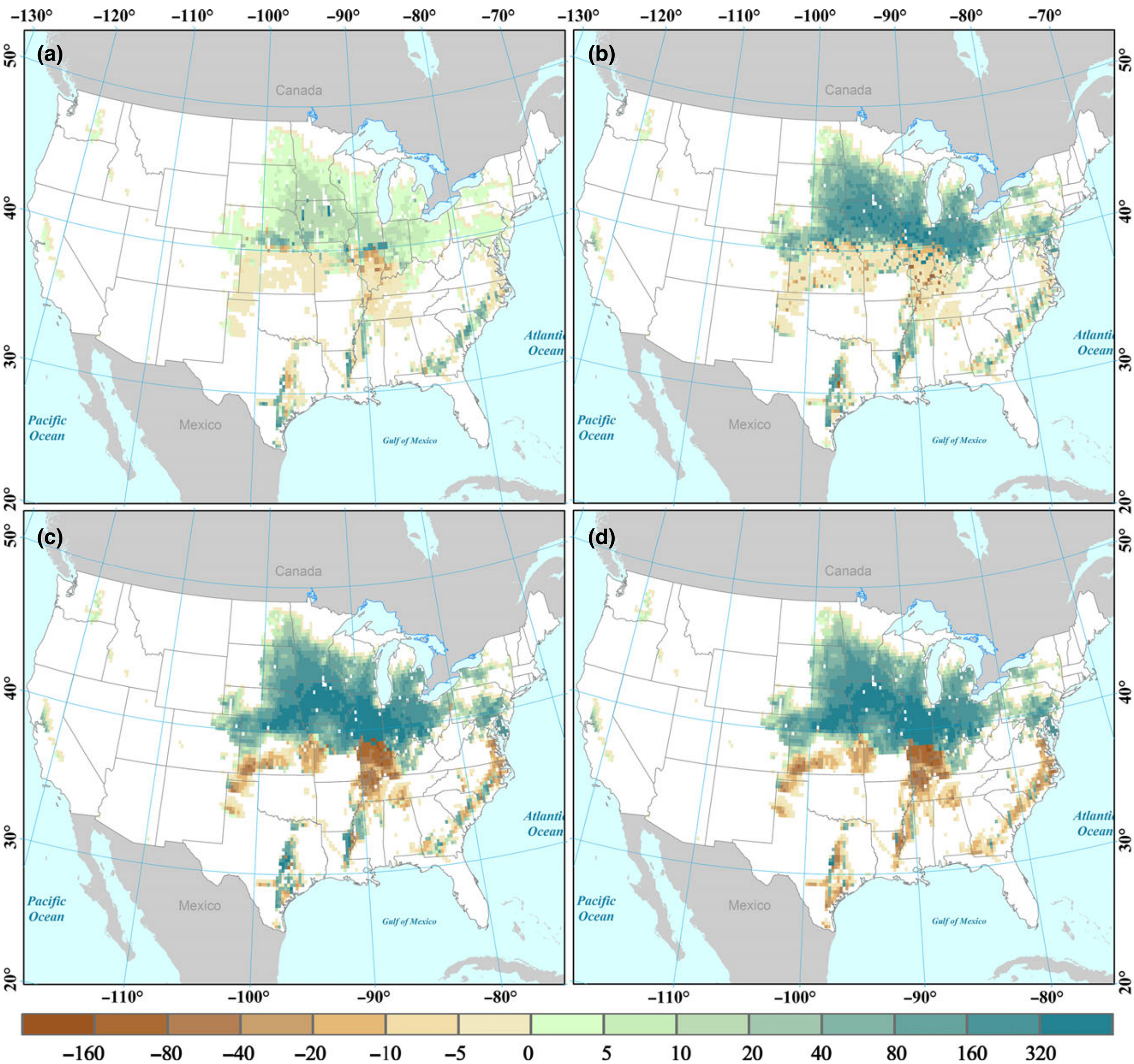

Fig. 4 Annual net carbon exchange (NCE) estimated for switchgrass and *Miscanthus* produced in the conterminous United States. The NCE fluxes (g C m^{-2} yr^{-1}) are presented for switchgrass at N input levels (a) N0 and (b) N1 and for *Miscanthus* at (c) N0 and (d) N1.

Table 3 Estimated average and total net carbon exchange (NCE) at different N input levels in the conterminous United States

N input	Average NCE (g C m^{-2} yr^{-1})			Total NCE (Tg C yr^{-1})		
	Maize	Switchgrass	*Miscanthus*	Maize	Switchgrass	*Miscanthus*
N0	−0.88 (0.09)	0.81 (0.09)	10.71 (1.20)	−0.27 (0.03)	0.25 (0.03)	3.31 (0.38)
N1	−1.46 (0.16)	5.38 (0.60)	10.42 (1.12)	−0.45 (0.05)	1.66 (0.18)	3.22 (0.35)
N2	−1.90 (0.20)	–	–	−0.59 (0.06)	–	–
N3	−2.34 (0.28)	–	–	−0.72 (0.08)	–	–

the most. If *Miscanthus* is substituted for maize, the total N_2O emissions will be even less (16 Gg N) when N is not applied, and yet the biomass production will not be greatly affected.

GHG emissions and global warming intensity

Greenhouse gas emissions, especially N_2O emissions caused mainly by N fertilizer use, directly contribute to

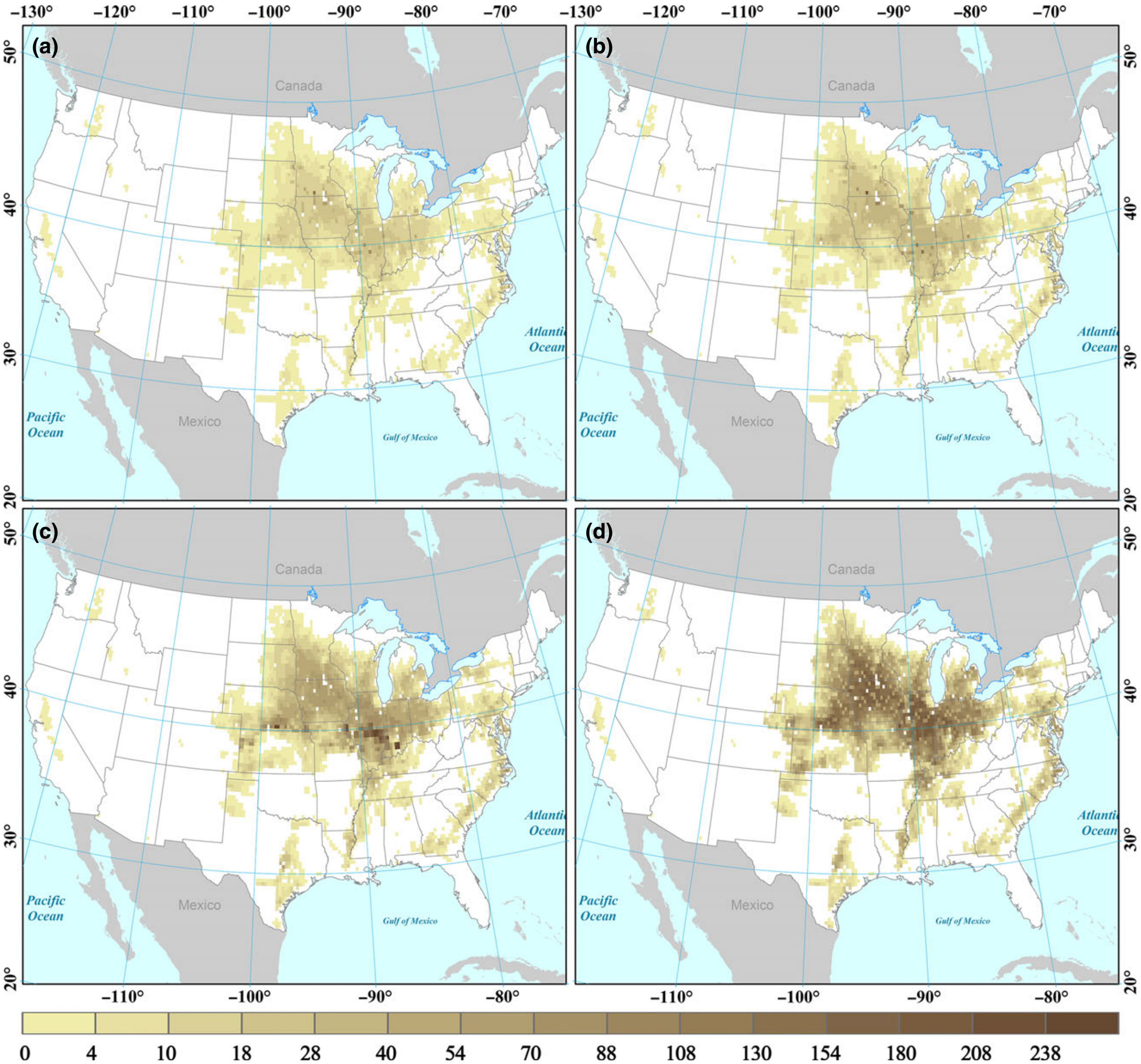

Fig. 5 Annual N_2O fluxes estimated for maize produced in the conterminous United States. Same N input levels as in Fig. 3. Unit: 10^{-3} g N m^{-2} yr^{-1}.

Table 4 Estimated average N_2O fluxes and total N_2O emissions at different N input levels in the conterminous United States

N input	Average N_2O flux (g N m^{-2} yr^{-1})			Total N_2O emissions (Gg N yr^{-1})		
	Maize	Switchgrass	*Miscanthus*	Maize	Switchgrass	*Miscanthus*
N0	0.06 (0.01)	0.05 (0.01)	0.05 (0.02)	18.4 (3.7)	17.0 (3.4)	15.8 (3.2)
N1	0.10 (0.02)	0.11 (0.02)	0.09 (0.01)	29.5 (5.9)	33.4 (6.7)	28.8 (5.8)
N2	0.22 (0.04)	–	–	66.4 (13.3)	–	–
N3	0.45 (0.09)	–	–	138.0 (27.6)	–	–

GWPs (Mosier *et al.*, 2006; Adviento-Borbe *et al.*, 2007). By summing up contributions from both NCE and N_2O sources, we separately estimated the total GWP for the three ecosystems considering plant growth throughout the growing stage, crop harvest, and management practices (Fig. 7a). Over currently available maize-producing

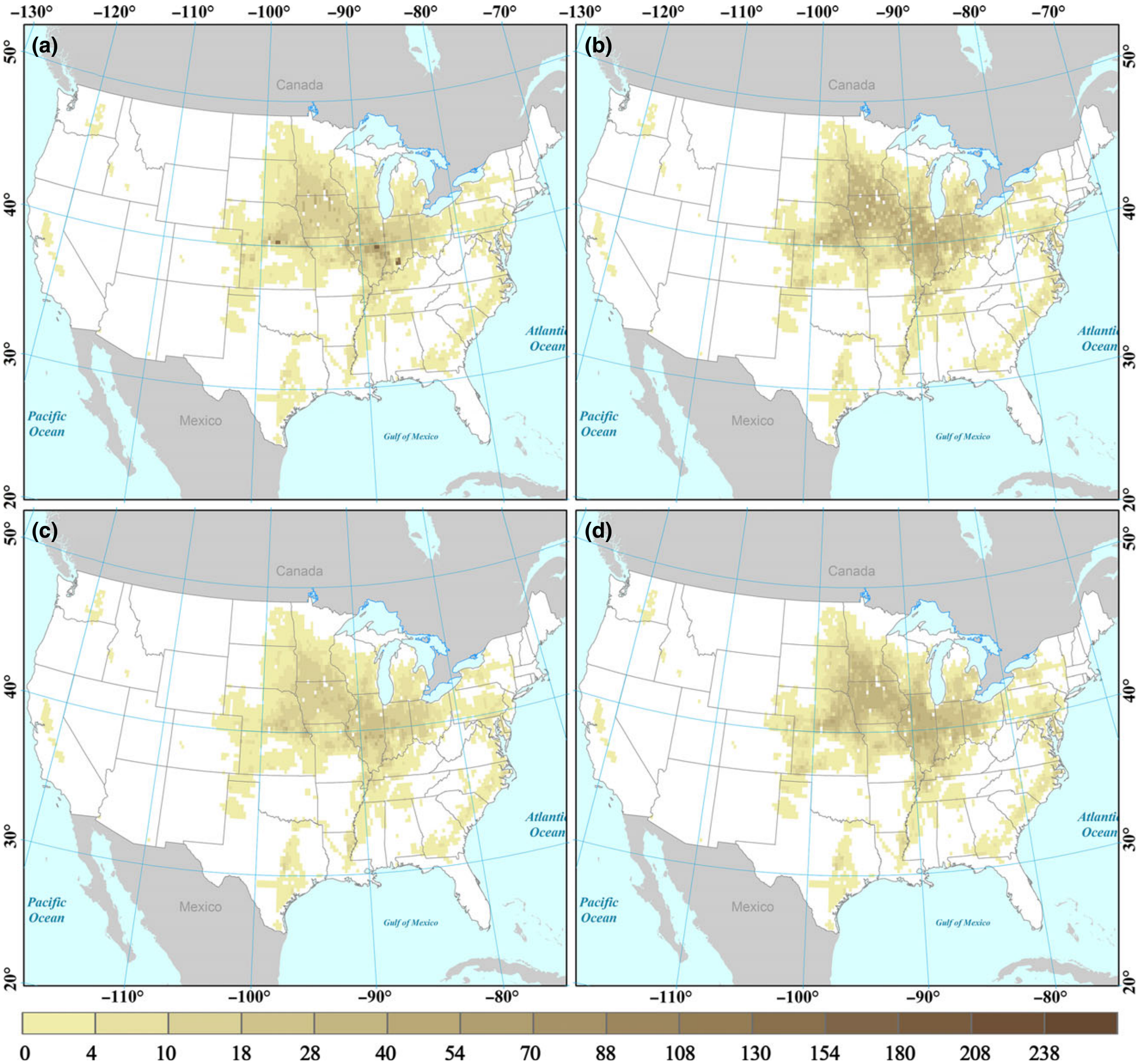

Fig. 6 Annual N_2O fluxes estimated for switchgrass and *Miscanthus* produced in the conterminous United States. Same N input levels for switchgrass and *Miscanthus* as in Fig. 4. Unit: 10^{-3} g N m^{-2} yr^{-1}.

areas in the United States, maize ecosystems in general act as net sources for both CO_2 and N_2O. N_2O emissions, in particular, dominate the GWP in maize, contributing over 90% of CO_2eq per unit land. With increasing N input, the proportion of GWP from N_2O also increases. At the reference scenario N0, the total GWP is about 0.3 Mg CO_2eq ha^{-1} yr^{-1}, but when the N input increases to relatively high levels (e.g., N2, N3), the total GWP would be enhanced significantly, reaching 1.1–2.2 Mg CO_2eq ha^{-1} yr^{-1}, close to an earlier estimate with a global average GWP of 1.4 (±0.4) Mg CO_2eq ha^{-1} yr^{-1} for the maize ecosystem (Linquist *et al.*, 2012). For cellulosic crops, the ecosystem NCE is positive and therefore offsets the GWP caused by N_2O emissions. In the switchgrass ecosystem, the total GWP is 0.2 Mg CO_2eq ha^{-1} yr^{-1} at the N0 level and 0.3 Mg CO_2eq ha^{-1} yr^{-1} at the N1 level. For the *Miscanthus* ecosystem, at the N0 level, the GWP of CO_2 overweighs GWP of N_2O, resulting in a net GWP of −0.2 Mg CO_2eq ha^{-1} yr^{-1}. Growing *Miscanthus* without N application could eventually mitigate global warming. Even with N application, the net GWP in *Miscanthus* is still much lower than in maize.

Taking biofuel productivity into consideration, GWP_i measures the relative GWP with respect to ethanol production (Fig. 7b). Our estimates over the United States

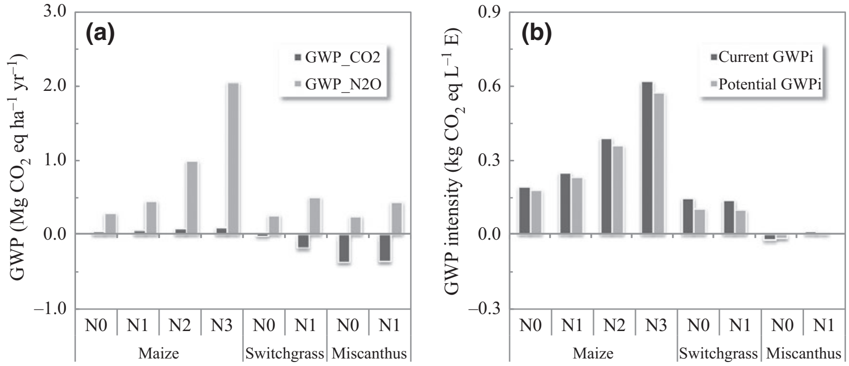

Fig. 7 National average global warming potential (GWP) and global warming intensity by developing maize, switchgrass and *Miscanthus* for bioenergy purpose. (a) GWP is for CO_2 and N_2O at different N input levels, and (b) global warming intensity (GWP_i) is GWP per unit biofuel produced under current or potential biomass-biofuel conversion efficiencies.

indicate that, maize has the highest GWP_i at all N levels, ranging from 0.2 kg CO_2eq l^{-1} E at the N0 level to 0.6 kg CO_2eq l^{-1} E at the N3 level. GWP_i increases with increasing N input, suggesting that the marginal rate of GHG emission outpaces that of ethanol production when the N level changes. However, in switchgrass ecosystems, the GWP_i at N1 is slightly lower than at N0 because the biofuel production increases greatly due to N application. By growing *Miscanthus* to produce biofuel, for each liter ethanol produced, the ecosystem generates 19–27 g CO_2eq of GHG 'credit' by sequestering C into agroecosystems if no N applied. The ecosystem will release only 6–9 g CO_2eq of GHG if N is applied. This suggests that substituting cellulosic crops for maize could make a great difference in reducing GHG emissions and therefore mitigating GWP. To produce one liter of ethanol under current technology, using switchgrass instead of maize would reduce 200–500 g CO_2eq of GHG emissions, and using *Miscanthus* would reduce an additional 100 g CO_2eq. Among the three bioenergy crops, *Miscanthus* produces the highest amount of biofuel and emits the lowest GHG using the same cropland.

Discussion

Advantages and disadvantages of cellulosic crops

Cellulosic crops, especially *Miscanthus*, can produce a comparable amount of biomass and yet release much less GHG than maize. High solar radiation interception and conversion of cellulosic crops are one of the most important characteristics contributing to their high productivity (Heaton *et al*., 2008). *Miscanthus*'s larger leaf area and longer duration outweighs maize in terms of the full potential of C4 photosynthetic productivity (Dohleman & Long, 2009). Even using the same NADP–malic enzyme C4 pathway, *Miscanthus* can maintain high photosynthetic quantum yields and biomass productivity in relatively unfavorable climate (e.g., low temperature), where maize growth is highly limited (Naidu *et al*., 2003). In addition, switchgrass and *Miscanthus* are tolerant to marginal soils, due to their relatively low demand of nutrient and highly efficient use of water. In fact, irrigation and fertilization are less frequently applied to switchgrass and *Miscanthus* than to maize (Lewandowski *et al*., 2003; Fike *et al*., 2006a; Stewart *et al*., 2009). This makes switchgrass and *Miscanthus* promising bioenergy crops in areas beyond current cropland area, especially those with less favorable climate and soil conditions for food crops.

One major difference between maize crop and cellulosic crops is that maize is an annual plant and survives for just one growing season, while switchgrass and *Miscanthus* are perennial plants. Maize is grown and eventually harvested and part of its biomass (e.g., residues) is left to maintain soil fertility (e.g., soil C). From the perspective of long-term C cycling, in the maize ecosystems, CO_2 sequestered from atmosphere is eventually released through respiration, decomposition, harvest, and burning, leaving only a small proportion of C stored in soils (Verma *et al*., 2005; West *et al*., 2010). Perennial plants, however, accumulate C into their roots in addition to soils, and the vegetation C pools could also contribute to the ecosystem C sink (Stewart *et al*., 2009). The GHG emissions from agroecosystems are mostly from N_2O fluxes caused by excessive use of N fertilizer. Switchgrass and *Miscanthus* release the amount of N2O similar to maize at a given N input (Table 4), but the formers require much less N than maize to produce the same or even high amounts of biomass. This makes these cellulosic crops favorable in reducing N_2O emissions while having the same amount of biomass. This may also partly explain the observations that the emission factor for switchgrass and *Miscanthus* is close to, if not larger than, that for maize (Qin *et al*., 2013).

However, it should be noted that large-scale commercialization and long-term ecological sustainability are still issues for growing cellulosic crops. For example, the widely studied *Miscanthus* × *giganteus* is a primary hybrid being selected as a potential energy crop, but its mass propagation may involve high costs (Stewart *et al.*, 2009). Growing cellulosic crops on cropland may compete with food crops for land, water, and nutrient resources, and jeopardize food security (Fargione *et al.*, 2010). Indirect land-use change due to bioenergy expansion may also impact ecological biodiversity and ecosystem services (Tilman *et al.*, 2009; Dale *et al.*, 2010). Large-scale cropping may lead to monoculture and destroy habitat of other species; additional use of labor and transport due to massive biomass production and harvest may cause indirect emissions of GHG (e.g., Hill *et al.*, 2009).

Global warming potential under 2022 bioenergy goal

To evaluate the economics of producing biomass-based ethanol to achieve the 2022 biofuel mandate, we calculated the demand of biomass and land, and also potential GHG emissions as a consequence of growing bioenergy crops (Table 5). Given currently available technologies, we need to use 191 Tg maize grain to produce the 79 billion liters of cellulosic ethanol, about 27–35 Mha cropland will be needed to support the crop biomass production. That is, if by applying low-N management, the current maize cropland (31 Mha) is insufficient to meet the biofuel production goal, or using high-N input, 88% of the maize cropland would be needed for biofuel purposes. Using both maize grain and biomass would still need 23–29 Mha of cropland. If *Miscanthus* is available, a total of 282 Tg of biomass would be needed to produce the mandated ethanol, but only 13–14 Mha cropland would be needed. More than half of current cropland could be saved if *Miscanthus* replaced maize as a biofuel crop. With potentially higher biomass-to-biofuel conversion efficiencies, 21–34 Mha of cropland would still be needed for maize-based ethanol production; N application rate and feedstock type determine the actual share of land for fuel use. However, due to significant advancement of conversion efficiency (Table 1), by growing *Miscanthus*, <10 Mha of cropland would be sufficient, which is only about one third of the currently available maize cropland.

Miscanthus ranks as the lowest GWP contributor among all three crops (Table 5). To produce 79 billion liters of ethanol, using maize for biomass feedstocks releases 37–59 Tg CO_2eq of GHG, accounting for 0.7–1.2% of the average national CO_2 emissions produced each year in the 1990s from the burning of fossil fuels and cement manufacture (5.2 Pg CO_2) (UN (United Nations), 2012). Increasing N use could somewhat improve crop productivity and therefore decrease the land use, but accelerates GHG emissions. In contrast with maize, the *Miscanthus* ecosystem releases a small amount of GHG and even acts as a sink for GHG if no N applied. Substituting *Miscanthus* for maize could reduce GHG emissions equivalent to the annual anthropogenic emissions produced by a small country (e.g., Norway, Denmark) (UN (United Nations), 2012). Among the three potential bioenergy crops, switchgrass offers significant GHG savings but has the least biofuel productivity and therefore used the largest amount of

Table 5 Resources needed and greenhouse gas (GHG) produced to reach the 2022 bioenergy goal

	Under current technology			Under potential technology		
Feedstock	Biomass (Tg DM)	Land (Mha)	GHG (Tg CO_2eq)	Biomass (Tg DM)	Land (Mha)	GHG (Tg CO_2eq)
Low-N fertilizer application*						
Maize grain	191	34.6	37.2	187	33.9	36.5
Maize total†	205	29.3	31.5	190	27.1	29.2
Switchgrass	282	51.4	11.7	199	36.3	8.2
Miscanthus	282	13.8	−2.1	199	9.7	−1.5
High-N fertilizer application*						
Maize grain	191	27.2	59.2	187	26.7	58.1
Maize total†	205	23.0	50.1	190	21.3	46.4
Switchgrass	282	35.7	11.0	199	25.2	7.8
Miscanthus	282	13.4	0.7	199	9.5	0.5

*Low-N scenarios are N2, N0, and N0 for maize, switchgrass, and *Miscanthus*, respectively; and high-N scenarios are N3, N1, and N1 for maize, switchgrass and *Miscanthus*, respectively. Estimates were made for 2022 biofuel target of 79 billion liters of cellulosic ethanol.

†Maize total accounts for both grain and biomass harvested.

cropland (Table 5). It may not be economically reasonable to substitute switchgrass for maize when grown on cropland.

What other options do we have for bioenergy development?

Land availability is a primary factor limiting biomass-based biofuel production. There is a total land area of nearly 0.92 billion hectares in the United States (2007), of which most are forestland, grassland and rangeland (57%), and only a small portion (18%) is used as cropland for crops, pasture, or other purposes (Nickerson *et al*., 2011). Considering possible economic, societal, and environmental problems such as food insecurity (Fargione *et al*., 2010), indirect land-use change, and associated C emissions (Searchinger *et al*., 2008; Melillo *et al*., 2009), using food grain to produce biofuel or switching productive food-based cropland to biofuel-based cropland is not a sustainable option for long-term energy supply from biofuel. Thus, the less productive land, or marginal land, seems to be a promising alternative for growing bioenergy crops. Marginal land usually has little or no potential for profit, and often has poor soil or other undesirable characteristics for growing food crops, but some marginal land can be further developed for growing cellulosic crops which require relatively less nutrients and water than food crops (Fargione *et al*., 2010; Qin *et al*., 2011; Gelfand *et al*., 2013). By classifying the land productivity according to soil productivity, topography, climate regimes, and other indicators, Cai *et al*., (2011) estimated a total of 43–123 Mha of land with marginal productivity in the United States. Other possible land sources including abandoned agricultural lands (Campbell *et al*., 2008), degraded grassland (Wicke *et al*., 2011) and Conservation Reserve Program grassland (Lee *et al*., 2013) may also contribute to the production of biomass. With crop-specific selection, these lands may potentially serve as land sources for planting cellulosic crops. Under these circumstances, *Miscanthus* or even switchgrass could be much more productive and environmentally sustainable than maize.

Using maize grain to produce ethanol could still reduce the GHG emissions by breeding a high-yield maize hybrid and improving agricultural management. An estimate based on on-farm data indicated that high-yield maize may receive large N fertilizer and irrigation water inputs, but could achieve higher grain and net energy yields (i.e., energy produced per unit land) and lower GHG intensity in terms of GHG emissions per unit maize yield than the regularly reported US maize system (Grassini & Cassman, 2012). Management practices, such as rotation (Halvorson *et al*., 2008), tillage (Halvorson *et al*., 2006; Omonode *et al*., 2011), irrigation and residue return (Liu *et al*., 2011) could directly or indirectly affect the ecosystem C balance and N_2O emissions (Venterea *et al*., 2012). Fertilizer N type, timing, placement, as well as N rate, may also affect N_2O emissions (Bouwman *et al*., 2002; Millar *et al*., 2010). Nitrification inhibitor (e.g., nitrapyrin) has been reported to be effective in prohibiting NO_3^- from accumulating in the soil (Bronson *et al*., 1992), reducing N_2O emissions (Zaman *et al*., 2009). By improving management practices, the existing maize-based biofuel cropland may eventually be able to reduce its GHG emissions.

It is worth noting that the actual N rate for maximum biomass production may vary over space, depending on local plant uptake, soil N availability, and N loss. It is possible that some locations may still respond to N levels higher than what we set in this study. Switchgrass, for instance, shows significant responses to N application (e.g., Table 2). Its biomass potential should be further investigated using long-term experiments with different N application levels. GHG emissions estimated in this study refer to the processes among crop growing stages in the ecosystem. Other processes outside ecosystem, such as fertilizer production, manufacturing, transportation, were not explicitly included. To account for these processes along the biofuel's life 'from-cradle-to-grave', we suggest to couple ecosystem modeling results with life cycle assessment to assess the efficiency and GHG impact of energy systems (Davis *et al*., 2009; Hillier *et al*., 2009).

Uncertainties and future needs

Agricultural management makes agroecosystem a more complicated system than the natural ecosystems. AgTEM incorporates major management factors, fertilization and irrigation, but other management practices, which may be also important, were not specifically considered due to inconsistent evidence, insufficient understanding (e.g., N type, N timing) (Millar *et al*., 2010) and data unavailability (e.g., rotation, planting density) (Felzer *et al*., 2004). This uncertain model structure and complex management could result in estimation uncertainty. In addition, model parameters and forcing data could also contribute to uncertainty (Chen & Zhuang, 2012; Qin *et al*., 2013). Thus, future study should consider improving the management module in AgTEM. The further uncertainty and sensitivity analysis at large scales should also improve our modeling capability (Qin *et al*., 2013).

It should also be noted that, ecosystem modeling may be useful for evaluating ecosystem services and environmental impacts, and the results could be informative for policy making concerning energy, food security and sustainability. However, the information derived from multiple-year and large-scale simulations may not be accurate. It should be cautious when using regional estimates to inform site-level practical cropping or agricultural management. Crop models, designed with the specific purpose of advising management practices (e.g., water management, Steduto *et al.*, 2009), together with spatially explicit high-resolution data, should be more useful for directing agricultural management and practice.

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