Frontiers in Ecology and the Environment

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Front Ecol Environ 2011; doi:10.1890/110003

Impact of second-generation biofuel agriculture on greenhouse-gas emissions in the corn-growing regions of the US

Sarah C Davis[1,2], William J Parton[3], Stephen J Del Grosso[4], Cindy Keough[3], Ernest Marx[3], Paul R Adler[5], and Evan H DeLucia[1,2*]

In the US, 95% of biofuel is produced from corn (*Zea mays* L), an intensively managed annual crop that is also grown for food and animal feed. Using the DAYCENT model, we estimated the effects on ecosystem services of replacing corn ethanol feedstocks with the perennial cellulosic feedstocks switchgrass (*Panicum virgatum* L) and miscanthus (*Miscanthus* × *giganteus* Greef et Deuter). If cellulosic feedstocks were planted on cropland that is currently used for ethanol production in the US, more ethanol (+82%) and grain for food (+4%) could be produced while at the same time reducing nitrogen leaching (–15 to –22%) and greenhouse-gas (GHG) emissions (–29 to –473%). The GHG reduction was large even after accounting for emissions associated with indirect land-use change. Conversion from a high-input annual crop to a low-input perennial crop for biofuel production can thus transition the central US from a net source to a net sink for GHGs.

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Debate over the use of biofuels often centers on its potential competition with food crops and the unknown environmental effects of converting land from current agricultural use to the production of bioenergy crops. One persistent argument against the use of biofuel is based on the perception that food crops will be displaced by fuel feedstocks to land that was previously uncultivated or under different use (Searchinger *et al.* 2008), causing greenhouse-gas (GHG) emissions that offset the benefits of low-emission biofuels. Such an argument overlooks the possibility of careful land-use planning. Indeed, many studies point to benefits that can be gained through cellulosic biofuel feedstocks (eg Heaton *et al.* 2008; Dale *et al.* 2010; Davis *et al.* 2011). Here, we present an analysis of the effects on nitrogen (N) leaching, GHG fluxes, and yield of growing alternative biofuel crops (Figure 1) on agricultural land already devoted to ethanol production from *Zea mays* L (corn) grain in the US.

According to the US Energy Independence and Security Act of 2007, the amount of corn grain that can be used for biofuel production is limited by the Renewable Fuel Standard (a mandate for national biofuel production) to 15 billion gallons, and all renewable fuels beyond this amount must be derived from cellulosic sources or other advanced renewable fuels. Cellulosic feedstocks can be sourced from grasses that do not produce large grains or that have concentrated carbohydrates. Although there is no mandate to replace current corn grain ethanol with cellulosic sources, there is evidence to suggest that the amount of fuel produced per unit land area would be greater if perennial cellulosic crops replaced annual row crops (Heaton *et al.* 2008; Somerville *et al.* 2010). This approach could result in less spatially extensive land management and consequently less unwanted land-use change (Davis *et al.* 2011).

Indirect land-use change (ILUC) – defined as the conversion of uncultivated land to cropland that would supplement crops displaced by bioenergy agriculture – is one of the most controversial and highly uncertain environmental consequences of biofuel production (Dale *et al.* 2010; Plevin *et al.* 2010; Davis *et al.* 2011). In reality, ILUC is driven by many variables and cannot be explained solely by economic drivers resulting from biofuel crop expansion. The establishment of higher-yielding perennial biofuel crops on land already devoted to corn production for ethanol could minimize ILUC by reducing the land footprint per gallon of ethanol (Heaton *et al.* 2008).

Thirty percent of corn grain grown in the US in 2009 was sold as ethanol feedstock (USDA 2010). Although corn grain is considered a food crop, only 8% of the grain harvested is used directly to feed humans (USDA 2010). Most corn is sold for livestock feed (43%), ethanol (30%), or other industrial uses. A cover change or species replacement on land already devoted to feedstocks for biofuel may therefore maximize productivity and reduce negative environmental impacts.

We analyzed two perennial grass species that are widely considered to be possible alternatives to corn as cellulosic energy crops in temperate regions. Switchgrass (*Panicum*

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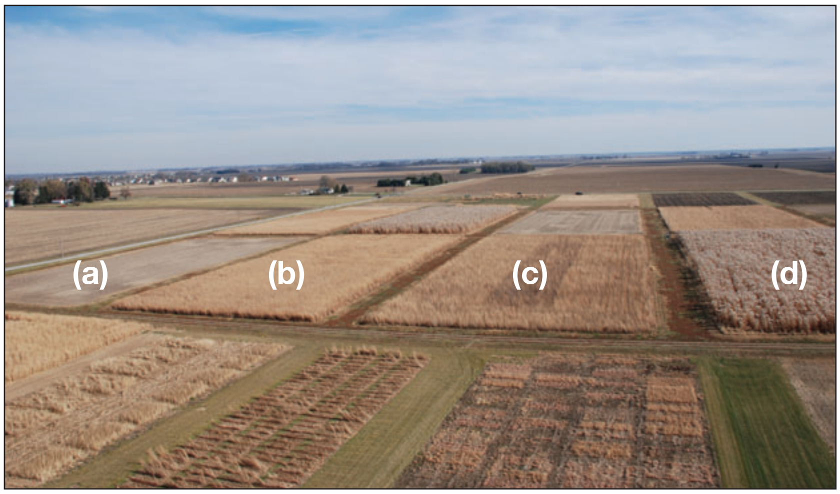

Figure 1. *Research plots of potential bioenergy crops – miscanthus, switchgrass, and restored prairie – next to plots that alternate between corn and soybean at the University of Illinois' Energy Biosciences Institute Energy Farm. The image was taken in November after soybean was harvested but before the energy crops were harvested. In the center of the image are large plots of (a) harvested soybean, (b) switchgrass, (c) restored prairie, and (d) miscanthus.*

virgatum L) is a grass native to the US that is being studied as an alternative bioenergy crop. Switchgrass is grown without fertilizers on Conservation Reserve Program lands (government-subsidized land set aside for habitat and water-quality maintenance) and prairie restoration sites but is usually fertilized when cultivated as a biomass crop (WebPanel 1). Miscanthus (*Miscanthus* × *giganteus* Greef et Deuter) is a sterile hybrid of two grasses that are native to Asia and is a promising bioenergy crop because it is high-yielding without the need for N additions (Heaton *et al.* 2008; Davis *et al.* 2010).

In this study, we evaluated the environmental impacts of planting perennial grass species for cellulosic biofuel in place of corn in the major corn-producing areas of the central US (~30 megahectares [Mha], where 1 Mha equals 1×10^6 ha). We simulated the conversion of 30% of corn agriculture, equal to ~9 Mha, to three alternative biofuel crops: (1) switchgrass, (2) switchgrass with fertilizer treatments, and (3) miscanthus. We calculated the feedstock production potential that would result from each case and estimated the difference from current practices in GHG emissions, soil carbon (C) sequestration, and N leaching over 10 years. Switchgrass was simulated both with and without N fertilizer additions, to investigate whether gains in biomass and soil quality with fertilization outweigh losses in nitrous oxide (N_2O) emissions and N leaching.

Methods

Simulations of biofuel crop cultivation in the major corn-growing regions of the US were conducted with DAYCENT (a version of the CENTURY model that runs on a daily timestep; Del Grosso *et al.* 2005). This model simulates exchanges of C, nutrients, and trace gases among the atmosphere, soil, and plants, as well as management practices such as fire, grazing, cultivation, and organic matter or fertilizer additions. The ability of DAYCENT to simulate crop yields, N_2O emissions, and nitrate (NO_3^-) leaching has been validated by comparing model outputs with measurements from agricultural systems in North America (Del Grosso *et al.* 2005; US EPA 2010a).

For this study, the previous land use was assumed to be corn cropping with rotations of soy and wheat in counties where this was the dominant practice. We simulated corn cropping for ethanol as a baseline, and then conversion of existing corn cropland to miscanthus, unfertilized switchgrass, or fertilized switchgrass. Simulated land conversion occurred in 2010 and results reported are means for 2011–2020. No life-cycle analysis of GHG fluxes was conducted in this study. The GHG fluxes are estimated based on the terrestrial biogeochemistry of the crops only. A detailed description of model parameterization and assumptions is available in WebPanel 1.

Model testing

This is the first study to our knowledge that uses DAYCENT to simulate regional miscanthus and switchgrass growth in the central US (Figure 2 a and b). Regression analysis demonstrated the predictive ability of the model to simulate variation in aboveground production of the grass species with different fertilizer levels (for corn and switchgrass only), and across different soil and climate conditions (Figure 2c: $r^2_{miscanthus} = 0.543$; $r^2_{switchgrass} = 0.680$; $r^2_{corn} = 0.679$). Model simulations accurately characterize the variance of soil C and N pools in these crops at six sites in Illinois that differ in soil type and climate ($r^2_{carbon} = 0.648$, $r^2_{nitrogen} = 0.655$; data not shown). Simulations of N_2O fluxes were tested against observed N_2O fluxes from trial plots of corn as well as switchgrass and other perennial grasses (Del Grosso *et al.* 2005; Figure 2d). Simulated soil N_2O emissions were highly correlated with observed data (Figure 2d: $r^2 = 0.97$). A more detailed description of model results is presented in WebPanel 1.

Results and discussion

Conversion from conventional corn ethanol feedstocks to perennial grass feedstocks

If perennial grasses were planted on only the land that is currently used to grow corn for ethanol in the central US (~9 Mha), model predictions indicate that GHG emissions would be reduced and the amount of both C sequestration and biomass for bioenergy would increase (Table 1; Figure 3). Modeled GHG emissions associated with growing unfertilized switchgrass was 17 teragrams of carbon equivalents per year (Tg C_{eq} yr^{-1}), greatly reducing the flux of GHG to the atmosphere relative to that of corn (26 Tg C_{eq} yr^{-1}). Fertilized switchgrass was nearly GHG neutral (–0.05 Tg C_{eq} yr^{-1}) and high-yielding miscanthus resulted in a shift of this region from a net source of GHG to a strong sink of –97 Tg C_{eq} yr^{-1} (Table 1; Figure 3).

The low GHG emissions of the perennial grasses were caused by both the reduction of fertilizer use and increased C sequestration relative to corn (WebFigure 1). Fertilizer application rates are greater in corn cropping systems and are correlated with emissions of N_2O, a GHG with 310 times the warming potential of carbon dioxide (CO_2). Crutzen *et al.* (2008) found that N_2O emissions from fertilized corn production for biofuels completely offset the reduction of GHG from replacing fossil fuels. We found that perennial cellulosic crops that require much less fertilizer (eg switchgrass and miscanthus) are a better option for GHG reduction.

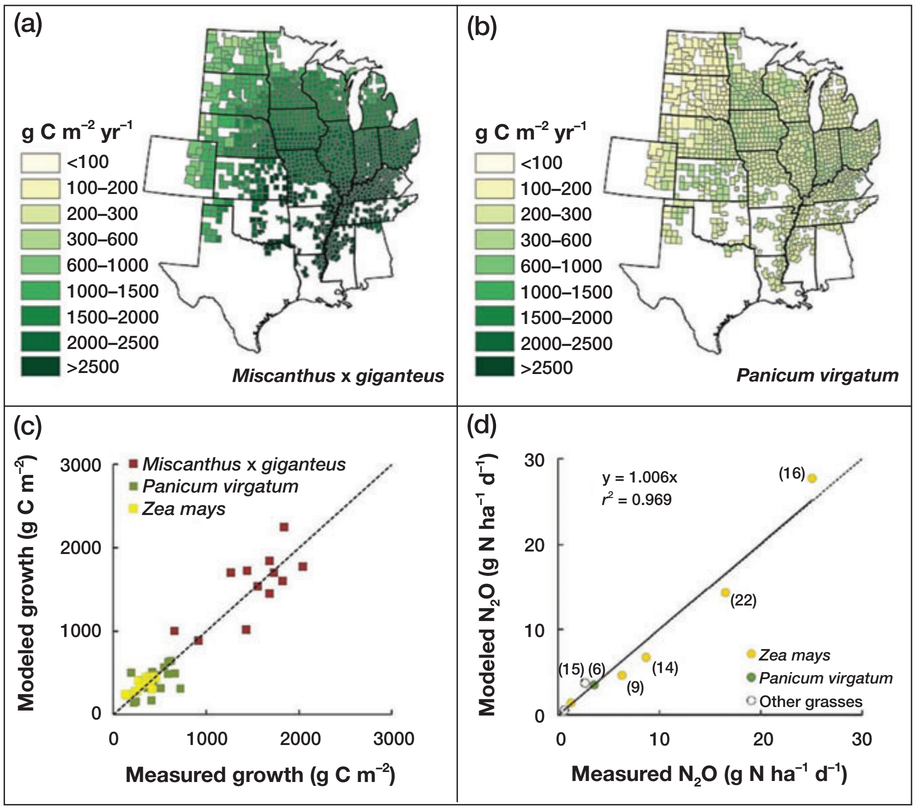

Figure 2. *Spatial variation in modeled potential production of (a)* Miscanthus × giganteus *and (b)* Panicum virgatum *if grown on cropland currently used for* Zea mays*; (c) regressions of the production modeled by DAYCENT against measurements of* Miscanthus × giganteus *(r^2 = 0.543), P virgatum (r^2 = 0.680), and Z mays (r^2 = 0.679) production measured in Illinois (Heaton* et al. *2008), Iowa, and Nebraska (Del Grosso* et al. *2005), where each point represents a mean (n ≤ 4 plots) and the dotted line is a 1:1 line; and (d) N_2O fluxes modeled by DAYCENT against recent measurements of N_2O fluxes in Pennsylvania and previously published measurements in Colorado, Iowa, Michigan, Tennessee, Wisconsin, and Canada (reviewed in Del Grosso* et al. *2005), where each point represents a mean of measurements made in different years at each site, 2 ≤ n ≤ 18, and the dotted line is a 1:1 line. Numbers in parentheses indicate fertilization rates specific to each field trial (g N m^{-2}); if no number is specified, then no fertilization was applied.*

Carbon storage by the perennial root systems of switchgrass and miscanthus contributed to the GHG reduction that we estimated here. Over the 10-year simulation period, soil organic carbon (SOC) declined in 24% of the counties in the study region and increased overall by only 11 Tg C_{eq} yr^{-1} under corn. In contrast, model simulations indicated that miscanthus and fertilized switchgrass almost always resulted in increased SOC, with overall SOC in the region increasing by 173 and 27 Tg C_{eq} yr^{-1}, respectively. Relative to corn, this resulted in a 19% and 1.9% change in total SOC with miscanthus and fertilized switchgrass, respectively, at the end of 10 years (Table 1). Because of the considerable investment in root biomass (WebFigure 2), soil C sequestration by miscanthus was notably high, as was also observed by Hansen *et al.* (2004) and Schneckenberger and Kuzyakov (2007). Past studies have demonstrated that switchgrass under varied management practices also leads to SOC accumulation, but this accumulation is substantially reduced with annual harvests (Anderson-Teixeira *et al.* 2009).

Application of N fertilizer in excess of that needed by the crop contributes to nitrification and NO_3^- leaching from corn fields (David *et al.* 1997). Model simulations indicated that a 0.7 to 0.8 Tg N yr^{-1} reduction of N leached through the soil profile could be accomplished by planting perennial grasses for bioenergy feedstocks in place of corn for ethanol (Table 1; WebFigure 3). This reduction resulted from lower amounts of fertilizer applied to perennial crops relative to corn crops. If switchgrass was fertilized, as commonly practiced, then the N leaching was reduced by 0.6 Tg N yr^{-1} relative to that associated with corn agriculture. The large anoxic zone that occurs in the Gulf of Mexico results largely from agricultural runoff, with ~52% of the N flowing into the Gulf originating from corn and soybean cultivation (Alexander *et al.* 2008). Reducing the N export from corn agriculture by one-quarter (or ~12% of the total N load from all sources) would save money spent to mitigate nutrient enrichment in aquatic ecosystems, while also offsetting the fuel demand that is indirectly responsible for environmental damage caused by petroleum exploration in the Gulf of Mexico.

If the diversion of corn grain to ethanol production initiated ILUC, then total GHG emissions from corn ethanol would be greater than our initial estimates. On the basis of

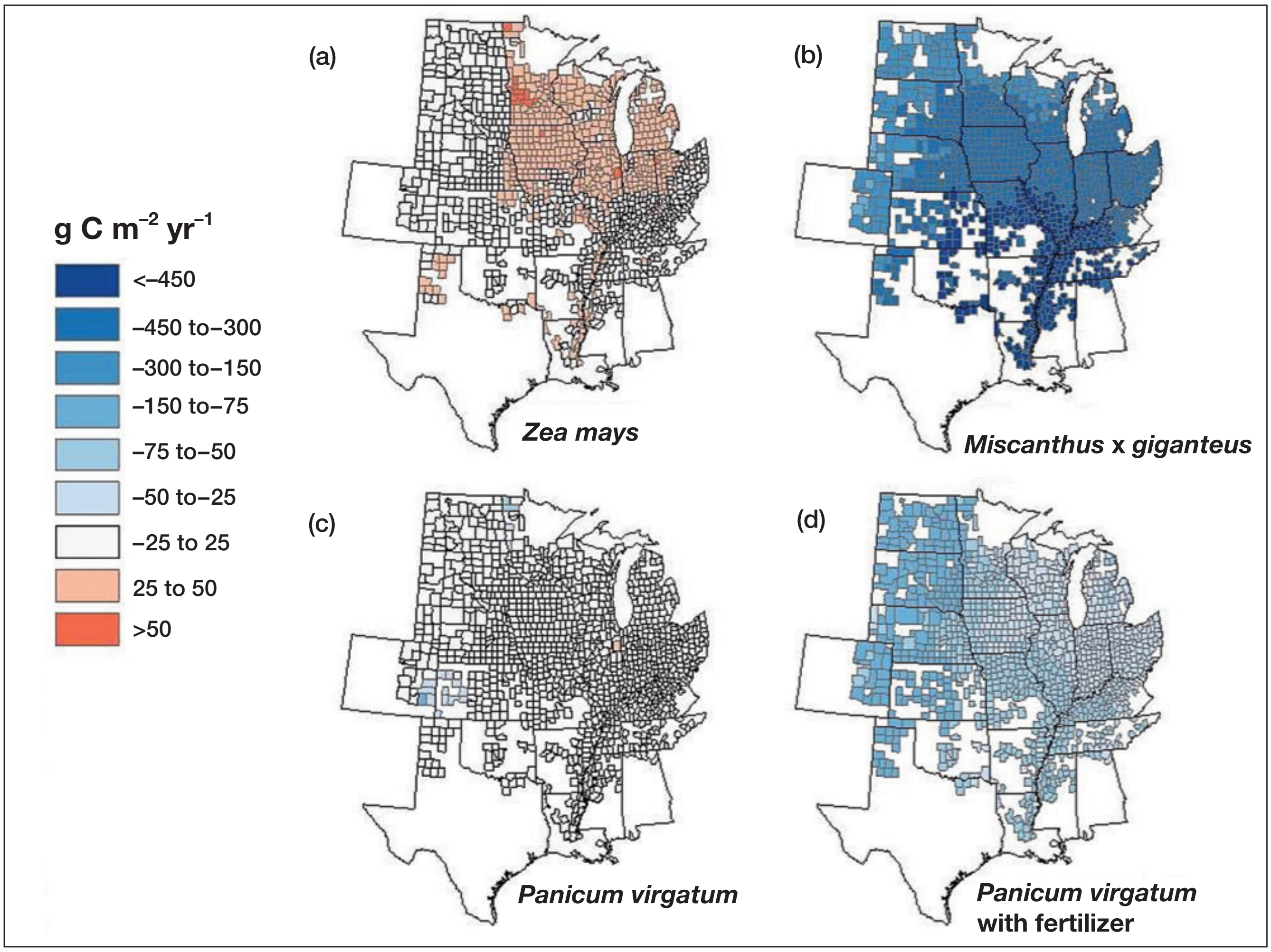

Figure 3. *County-resolution estimates of mean modeled annual greenhouse-gas (GHG) fluxes (2011–2020) for (a)* Zea mays *(corn), (b)* Miscanthus × giganteus *(miscanthus), (c)* Panicum virgatum *(switchgrass) without fertilizer, and (d)* P virgatum *with fertilizer if grown on* Z mays *cropland in the central US. Negative values indicate a sink of GHG to the land (removal from the atmosphere). The GHG flux is the sum of N_2O, nitrogen oxides, methane (CH_4), and CO_2 fluxes after conversion to C equivalents.*

ILUC accounting recommended by the California Air Resources Board (30 grams of CO_2 equivalent per megajoule of ethanol [gCO_2e per MJ ethanol]; CARB 2009) and the revised Renewable Fuel Standard (34 gCO_2e per MJ ethanol; US EPA 2010b), the additional GHG emissions from ILUC caused by diverting 30% of corn land in the central US (~ 9 Mha) to ethanol production would be 4.7–5.3 Tg C (assuming an energy content of 21.1 MJ per liter; http://bioenergy.ornl.gov/papers/misc/energy_conv.html), or 30.7–31.3 Tg C_{eq} yr^{-1} total. Notably, GHG emissions from ILUC are highly uncertain and depend on the amount of fuel produced, crop yields, land availability, ease of conversion, and the responses of imports and exports to price changes (eg Plevin *et al.* 2010; WebPanel 1).

With perennial grasses, no land-use change occurred relative to the baseline because our simulation assumes no new uncultivated land is adopted for ethanol production; there is simply a cover change from corn to cellulosic feedstocks for ethanol production. Even if ILUC-based emissions are counted against the perennial grasses, the change in GHG emissions is minimal as compared with the net differences between the perennial grasses and corn (Table 1).

Aboveground production and harvestable biomass only increased under the scenario where miscanthus replaced corn for ethanol production. Model simulations indicate that harvested biomass for bioenergy would be increased by 83% with miscanthus grown as a feedstock, which equates to ~12 billion gallons of ethanol with no displacement of current food crops. In many counties, switchgrass biomass was greater than corn grain yields, but there was little difference between yields of either crop when their values were aggregated over the entire study area, because regions where switchgrass yields were lower than corn yields represented a larger area than regions where switchgrass yields were greater than corn yields.

Although we did not simulate corn stover (ie stems and leaves) as a biofuel feedstock in our scenarios, 50% corn stover removal could enhance ethanol production from corn crops by 35% above what we estimate here for grain alone (Adler *et al.* 2007). Stover removal could, however, cause a decline in soil C relative to our projections. Also, there would be a loss of dry distillers grains and solubles (DDGS) that are produced as a co-product of ethanol from

Table 1. Ecosystem services of various bioenergy crop alternatives

(a)

	Leached N		GHG		Soil C pool		Crop production		Harvested biomass		Ethanol equivalent*
	Tg N yr^{-1}	%Δ	Tg C_{eq} yr^{-1}	%Δ	Tg C	%Δ	Tg C yr^{-1}	%Δ	Tg C yr^{-1}	%Δ	(10^9 gallons)
Zea mays	3.2	na	26 *(31)*	na	840	na	193	na	60	na	7.3
Miscanthus × giganteus	2.5	–22	–97 *(–92)*	–473 *(–452)*	1002	19	321	66	111	83	12.3
Panicum virgatum	2.4	–24	17 *(22)*	–35 *(–15)*	835	–0.6	168	–13	52	–14	5.8
Panicum virgatum (fertilized)	2.6	–17	–0.5 *(5)*	–102 *(–81)*	856	1.9	194	0.7	60	–1.0	6.6

(b)

	Leached N		GHG		Soil C pool		Crop production		Harvested biomass		Corn grain for non-ethanol products	
	Tg N yr^{-1}	%Δ	Tg C_{eq} yr^{-1}	%Δ	Tg C	%Δ	Tg C yr^{-1}	%Δ	Tg C yr^{-1}	%Δ	Tg C	%Δ
Zea mays	3.2	na	26 *(31)*	na	840	na	193	na	60	na	42	na
Miscanthus × giganteus	2.6	–20	–92 *(–87)*	–452 *(–435)*	1001	17	321	66	110	82	44	4.4
Panicum virgatum	2.5	–22	19 *(24)*	–29 *(–8)*	836	–0.5	170	–12	53	–12	44	4.4
Panicum virgatum (fertilized)	2.7	–15	0.2 *(6)*	–99 *(–78)*	858	2.8	198	2	61	1.1	44	4.4

Notes: Contrast of environmental services provided by alternative bioenergy feedstock crops grown in place of corn for ethanol on (a) 30% of all corn cropland (~9 Mha) in the central US and (b) the 30% least productive of all corn cropland in the central US. The percentage change (%Δ) is the change relative to the baseline condition that is defined by the scenario with *Zea mays*. The baseline in this table assumes that current practices continue over the next 10 years, and the differences are calculated with the annual average from projections of the alternative crops over the next 10 years. Greenhouse-gas (GHG) emissions are the sum of N_2O, NO_x, CH_4, and CO_2 fluxes after conversion to C equivalents. Values in parentheses represent the adjusted GHG emission or uptake if an additional ILUC emission of 34 g CO_2e per MJ ethanol (as recommended by the California Air Resources Board), or 5.3 Tg C_{eq} was added to the source or subtracted from the sink of GHG fluxes from the biofuel feedstocks. The adjustment is applicable to the diversion of corn to biofuel only, but it is included in each of the cropping scenarios because the assumption of the other scenarios is that the perennial grasses are planted only on land that is already devoted to biofuel and the ILUC cost of that land diversion in the past must still be paid. *Ethanol equivalents are calculated based on conversion rates for corn grain to ethanol of 111 gallons per metric ton and for lignocellulosic biomass to ethanol of 100 gallons per metric ton. na = not applicable. As of the publication of this article, >13 billion gallons of ethanol are produced from corn grain nationwide, representing >40% of the total corn production in the US. The estimate here reflects the amount that was produced from only 30% of the corn agriculture in the Midwestern region as reported in 2009.

corn grain if perennial grasses were to replace corn. DDGS is used for livestock feed and would presumably not be available from cellulosic feedstocks.

Converting only the least productive corn croplands

If perennial feedstock crops were selectively planted on land where corn production is suboptimal, model projections indicate that both energy feedstocks and corn production for food would increase (Table 1b). If only the 30% least productive corn cropland were converted to miscanthus, an 82% increase in bioenergy feedstocks would be realized, and there would be a 4% increase in corn grain yields that could be used for food or other purposes (partially offsetting the 7% potential losses in DDGS). This 4% increase in corn grain could also be achieved by planting switchgrass on the least productive corn land, but the bioenergy feedstock from switchgrass would be similar to current yields from corn grain (12% less if unfertilized and 1% more if fertilized). With cellulosic feedstocks planted on low-yielding corn lands, there would be less reduction in N leaching (15–22% reduction) than in the case where prime corn cropland was converted because less fertilizer is applied in areas with less productive corn. There would, however, be a similar reduction in GHG emissions because the increase in C sequestration with perennial grasses would be greatest in areas where corn production would be less optimal.

Weighing the risks and benefits of crop alternatives

A detailed discussion of the risks and benefits associated with biofuel crop alternatives is beyond the scope of this paper. Briefly, there are varied risks associated with biological invasions, gene flow to native populations, and economics of the different cropping scenarios. In the US, miscanthus and corn are both non-native species that carry a lower risk of gene flow to surrounding native plant populations if grown commercially than the risk associated with switchgrass, which is native to the US and closely related to many other native grasses. Miscanthus is a sterile hybrid that is native to Asia, and although there is no risk of invasion by seed because of its sterility, it is closely related to known invasive species. Finally, the establishment of switchgrass and miscanthus requires 3 years and thus results in a delayed return on investments in these new crops. Ultimately, these potential risks must be considered alongside the environmental benefits that are the focus of this study.

Because perennial grasses are not a major commodity, there are processing considerations that must be overcome for these crops to be mass produced as corn grain is today. The first commercially scaled cellulosic ethanol processing plant is now being built by Vercipia Biofuels in Florida, and expansion of cellulosic feedstock production can be expected in the near future. Still, developments are needed to streamline production, harvest, storage, and transport. Although these challenges will require some innovation, they are unlikely to result in a reduction of the GHG benefits calculated here for perennial grasses relative to corn. For example, equipment for harvesting switchgrass results in a 74% reduction in CO_2 emissions relative to equipment used for corn grain harvests (Adler *et al*. 2007; WebTable 1). If we add to this the GHG emissions from manufacturing fertilizers, the disparity between corn ethanol emissions and perennial cellulosic ethanol emissions grows even larger. Fertilizer applied to corn (varying from 85 to 219 kg ha^{-1} across the Midwest region analyzed here) would incur manufacturing emissions of 127 to 327 kg CO_2 ha^{-1} (1.49 kg CO_2 per kg N; US DOE 2000). Although emissions from the full production chain of biofuels is also beyond the scope of this research, the GHG reduction caused by cellulosic biofuel crops that require little fertilizer (switchgrass; WebPanel 1) or no fertilizer (miscanthus) extend beyond the terrestrial fluxes detailed here.

Conclusions

Replacing corn ethanol in the central US with low input, high-yielding perennial grasses could potentially increase the regional productivity of food (+4%) and feedstocks for fuel (+82%) without causing additional ILUC. US federal policy mandates that cellulosic crops will soon add to the feedstock supply that is currently composed mostly of corn. Although there is at present no policy that encourages the replacement of current corn agriculture with perennial crops, a land-cover change from corn to perennial grasses for ethanol feedstock can improve environmental quality while increasing land-based resource supplies in the central US. Feedstock options will diversify in the future as cellulosic feedstock conversion advances (Somerville *et al*. 2010), and we expect the bioenergy debate to shift from the question "Are biofuel crops beneficial?" to that of "Which biofuel crops are beneficial in a given location?". This new question will promote landscape design that maximizes the potential benefits of biofuels.

Acknowledgements

The Energy Biosciences Institute and the Department of Plant Biology, University of Illinois at Urbana-Champaign, supported this research.

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WebPanel 1. DAYCENT model description

DAYCENT (the daily version of the CENTURY model; Parton *et al.* 1998; Del Grosso *et al.* 2005; Del Grosso *et al.* 2006) is a process-based model of intermediate complexity. It simulates exchanges of carbon, nutrients, and trace gases among the atmosphere, soil, and plants, as well as events and management practices such as fire, grazing, cultivation, and organic matter or fertilizer additions. Required model inputs are: soil texture, current and historical land use, and daily maximum/minimum temperature and precipitation data. Plant growth is a function of soil nutrient and water availability, temperature, and plant-specific parameters (such as maximum growth rate, minimum and maximum biomass carbon-to-nutrient ratios, and above- versus belowground carbon allocation). Soil carbon levels fluctuate according to inputs from senesced biomass (after accounting for biomass removal during harvest operation and disturbance events) and manure amendments and losses from respiration and leaching. Nitrogen gas emissions (N_2O, NO_x, N_2) from nitrification and denitrification are controlled by soil mineral nitrogen levels (nitrate and ammonium), water content, temperature, pH, plant nitrogen demand, and labile carbon availability. Nitrate leaching losses are controlled by plant nitrogen demand, soil NO_3^- availability, saturated hydraulic conductivity, and water inputs from rainfall, snowmelt, and irrigation. Although plant root interactions with water and nutrient availability are simulated, the feedbacks between root and soil are limited and do not directly simulate root architectural effects on sediment and nitrogen losses.

DAYCENT model testing and applications

The ability of DAYCENT to simulate crop yields, N_2O emissions, and NO_3^- leaching has been validated by comparing model outputs with measurements from various cropped and grassland systems in North America (Del Grosso *et al.* 2005; US EPA 2010). In addition to plot-level measurements, DAYCENT grain and hay yields have also compared favorably with state-level estimates obtained from the US Department of Agriculture (USDA) National Agricultural Statistics Service (Del Grosso *et al.* 2005). More recently, the model was shown to accurately simulate biomass yields for switchgrass and miscanthus grown in Illinois (Davis *et al.* 2010), as well as NO_3^- leaching losses from a corn and soybean agroecosystem also grown in Illinois (David *et al.* 2009).

DAYCENT has been applied to simulate soil greenhouse-gas fluxes at scales ranging from plots to regions to the globe (Del Grosso *et al.* 2005; Del Grosso *et al.* 2009). The model has been used since 2005 to calculate N_2O emissions from agricultural soils for the US National Greenhouse Gas Inventory compiled by the Environmental Protection Agency (EPA) and reported annually to the UN Framework Convention on Climate Change (US EPA 2010). These reports provide the parameterization for historical agriculture and the baseline scenario of corn growth in this study. Monte Carlo analysis has been performed to evaluate the uncertainty of DAYCENT-simulated greenhouse-gas fluxes from US croplands associated with model input variables and observed datasets (Del Grosso *et al.* 2010). The 95% confidence interval was estimated to be –35% to +50% for annual N_2O emissions aggregated to the national scale.

Model calibration and testing for perennial biofuels

Model calibration for miscanthus and switchgrass yields, soil carbon, and soil nitrogen was accomplished previously at one site in Urbana, Illinois (Davis *et al.* 2010). In the current study, model predictions of switchgrass and miscanthus yields were tested against measurements at six sites across a latitudinal gradient in Illinois and switchgrass and corn fertilizer trials in Nebraska and Iowa (Figure 2c). Simulations of N_2O fluxes across the region have been previously published (Del Grosso *et al.* 2005). Since that time, additional measurements were made in perennial biofuel plots in Pennsylvania with different fertilizer treatments (unpublished data). To test the simulated N_2O fluxes against a wider range of conditions, we compared model results with independent measurements made in trial plots of corn as well as switchgrass and other perennial grasses in Pennsylvania, in addition to previously published measurements in Colorado, Iowa, Michigan, Tennessee, Wisconsin, and Canada (Del Grosso *et al.* 2005). These locations are characterized by a range of soil types and climate conditions. Mean annual precipitation across sites ranged from 402–1393 mm and mean annual temperatures ranged from 7–15˚C. Simulated soil N_2O emissions were highly correlated with observed data (Figure 2d: r^2 = 0.97). Soil N_2O emissions generally increased with nitrogen-fertilized corn and were higher than soil N_2O fluxes from perennial grasslands treated with a similar amount of nitrogen fertilizer.

Biofuel simulations

For this study, the previous land use was assumed to be corn cropping. For each county simulated, the land area was identified where corn row crops were the dominant agricultural land use. We assumed that 30% of corn grain produced over the central US region for biofuel, when aggregated, is representative of corn grain grown on 30% of the corn agricultural land in the region in a given year. The land area in each county with corn production was intersected with spatial weather and soils data (from National Oceanic and Atmospheric Administration [NOAA] and USDA Soil Surveys, respectively) to extract model inputs for these environmental variables. No attempt was made to account for changing climate and weather for 2011–2020; climate conditions instead were recycled from 1980–1989. Annual fertilizer additions for corn varied regionally from 85–219 kg N ha^{-1} based on county-level crop yield data. Land management for corn was assigned according to the dominant practice in a given region. For example, corn/soybean rotations were simulated in most regions, but corn was part of a 4-year rotation in the northern plains, while continuous corn was simulated in some other regions. Results of corn projections for 2011–2020 were based on annual means of corn years only. Management for the perennial crops was uniform across regions and the fertilized switchgrass was simulated with nitrogen additions annually equivalent to 70 kg N ha^{-1}. We chose this level of fertilizer application because fertilizer trials from Nebraska and Iowa suggest that switchgrass fails to respond to fertilizer additions greater than 60–120 kg N ha^{-1} and 70 kg N ha^{-1} represents the conservative side of this range.

There are several limitations associated with these simulations. Impacts of landscape position, topography, and other factors were not included. This is important from a biogeochemical perspective because landscape position affects the lateral transport of water and nutrients. In addition, farmers choose to grow different crops on different parcels of land based on expected eco-

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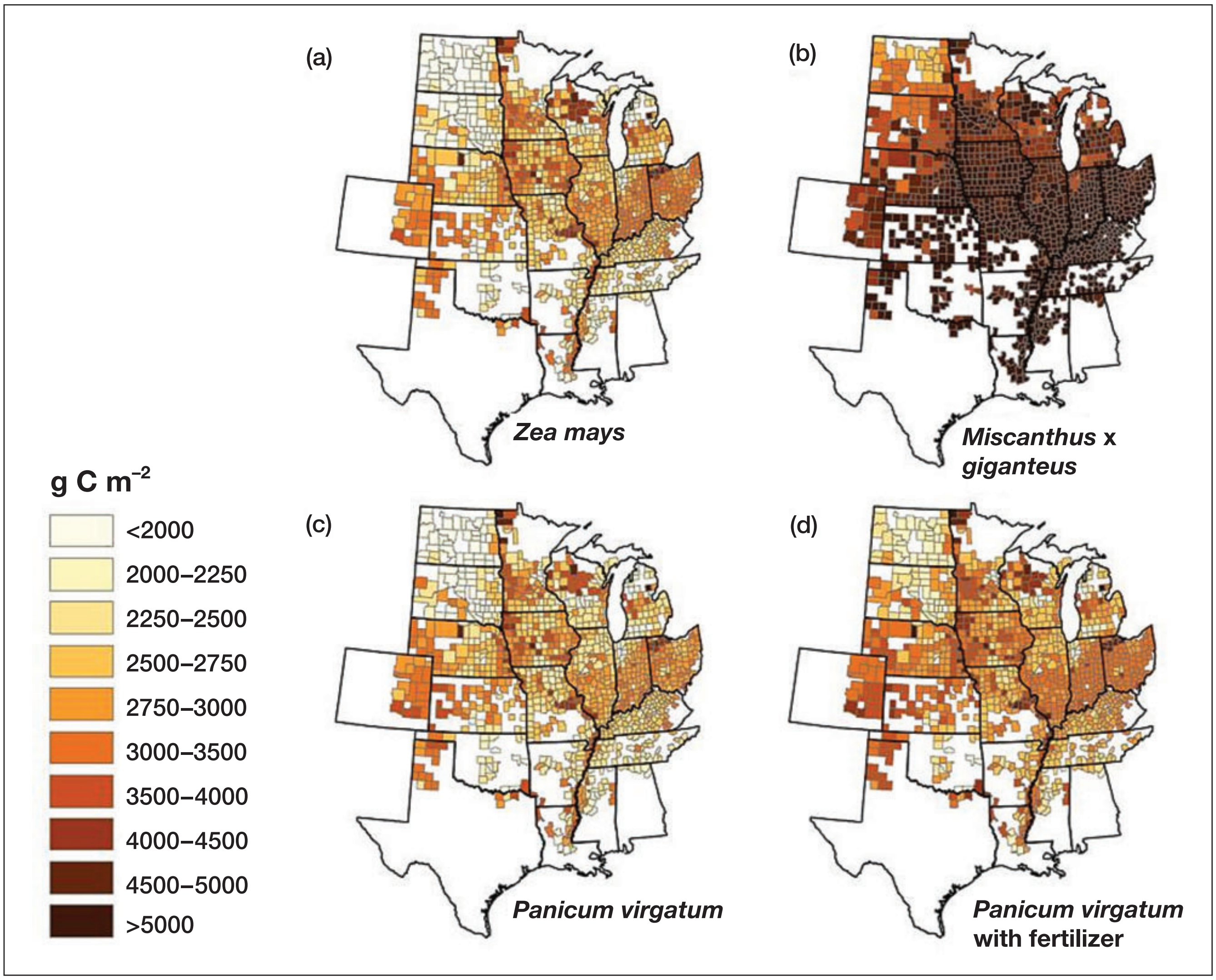
WebPanel 1. DAYCENT model description – *continued*

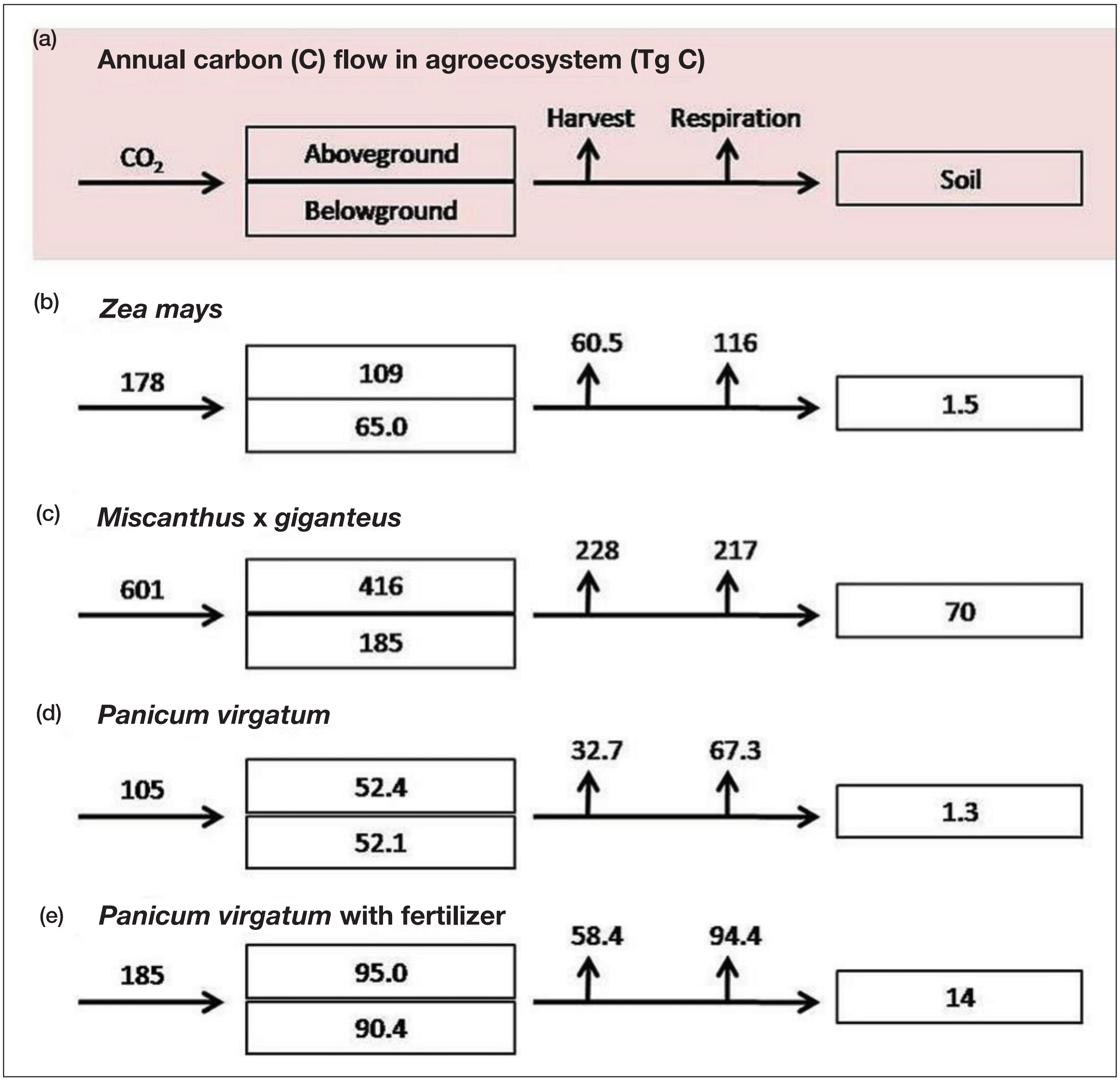
nomic returns, erosion susceptibility, real-time weather patterns, and other factors. We assumed that 30% of the land currently used for corn ethanol cropping would be converted to perennial biomass production without considering the factors that affect what crops farmers decide to grow on particular parcels of land. We also assumed that crop cultivars did not vary across the corn-growing regions in the central US, and that management for the perennials was uniform. This assumption may be correct for miscanthus, but fertilizer rates for switchgrass would likely vary based on expected biomass production. However, because no regional datasets exist for recommended fertilizer rates for switchgrass, we made the simplifying assumption that switchgrass was always fertilized at 70 kg N ha^{-1} and only one variety was simulated across the region. As data from switchgrass and miscanthus trials performed at different locations become available, future model runs could account for regionally specific management of these crops.

Emissions from indirect land-use change (ILUC): assumptions and limitations

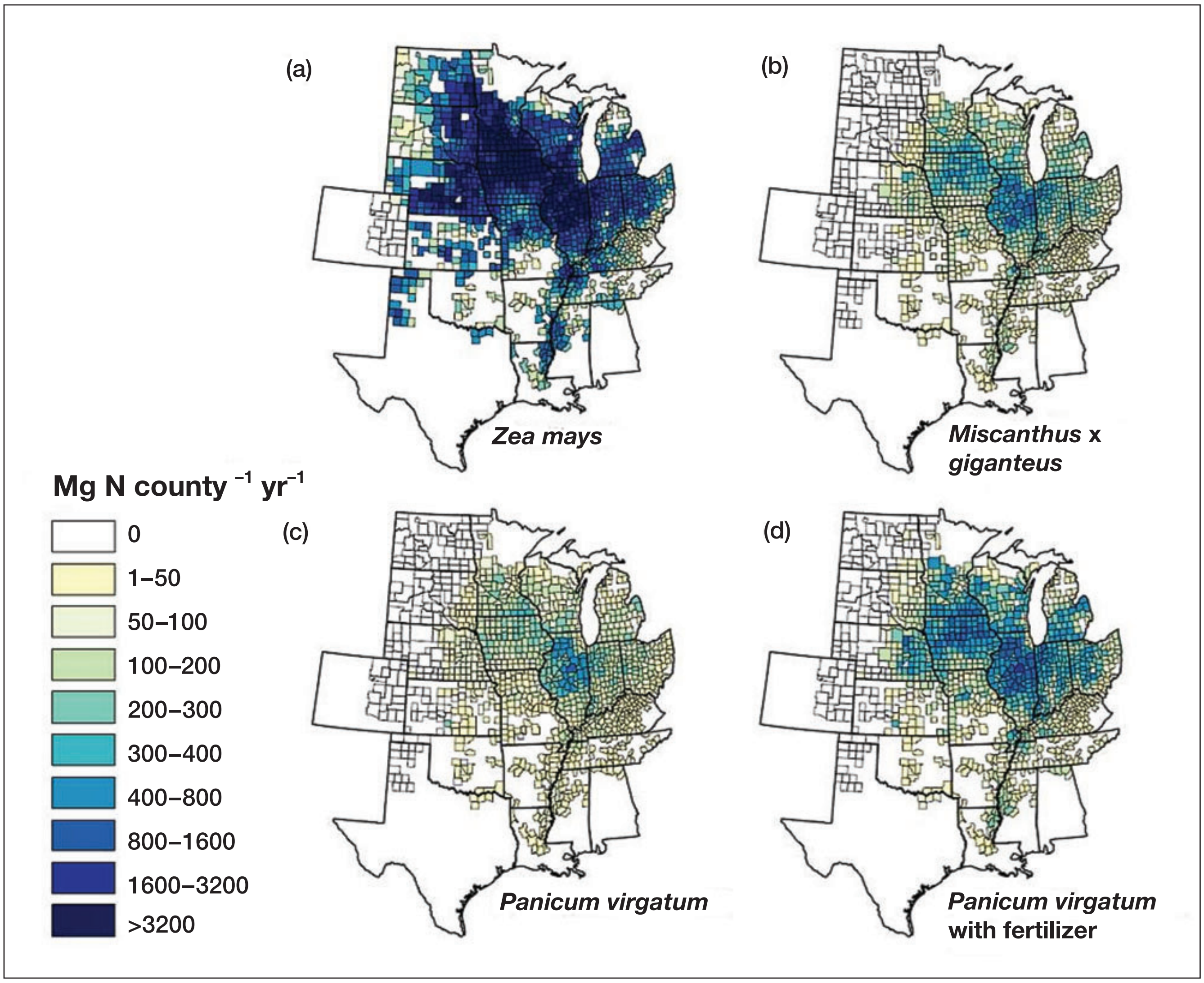
The ILUC estimates reported in the manuscript are based on a very limited analysis that follows the guidelines recently agreed upon by the EPA and the California Air Resources Board. We felt that these were the most relevant to current US policy. There are, however, many other estimates for ILUC that would yield a different response (eg Kline *et al.* 2009; Khanna *et al.* 2010). In some cases, good management could actually lead to "negative" ILUC. This is especially relevant for high-yield, low-input perennial grasses that can actually reduce the land footprint required. We used conservative estimates that directly parallel current policy and demonstrate that, even if we assume ILUC (that may not actually be happening), perennial cellulosic crops are still a net sink of greenhouse gases. In other words, even with the most conservative assumptions, the benefits outweigh the costs and are very different for corn ethanol impacts.



WebFigure 1. *County-resolution estimates of modeled soil carbon projected for the beginning of 2020 for (a)* Zea mays, *(b)* Miscanthus × giganteus, *(c)* Panicum virgatum *without fertilizer, and (d)* P virgatum *with fertilizer, if grown on* Z mays *cropland in the central US.*



WebFigure 2. *Flow of carbon modeled in four alternate bioenergy feedstock crops. (a) The legend defines the mean annual fluxes that are quantified in Tg C for (b)* Zea mays, *(c)* Miscanthus × giganteus, *(d)* Panicum virgatum, *and (e) fertilized* P virgatum. *Quantities represent 10-year averages of county estimates summed for the total central US region, where each crop was simulated on* Z mays *cropland. Not all pools and fluxes of carbon are represented (eg no dissolved organic carbon is included) and the numbers do not represent a closed cycle.*



WebFigure 3. *County-resolution estimates of mean modeled annual nitrogen leaching (2011–2020) for (a)* Zea mays, *(b)* Miscanthus × giganteus, *(c)* Panicum virgatum *without fertilizer, and (d)* P virgatum *with fertilizer, if grown on* Z mays *cropland in the central US.*

WebTable 1. Farm machinery emissions estimates*

Crop	*Cultivation stage*	*Practice*	*CO_2 (kg C ha^{-1})*
Corn	tillage	plow	17.01
		disk	4.65
		seedbed preparation	4.37
		cultivation	4.34
	planting	fertilizer	3.94
	management	pesticide	1.34
		liming	2.23
			1.34
	harvest	grain	28.15
	Annual total		**67.37**
Switchgrass	mowing	seed year	5.63
		established	7.34
	baling	seed year	7.27
		established	9.83
	Annual total seed year		**12.9**
	Annual total after establishment		**17.17**
Reed canarygrass	mowing	seed year	4.49
		established	4.16
	baling	seed year	4.66
		established	2.98
	Annual total seed year		**9.15**
	Annual total after establishment		**7.14**

Notes: *Source: Adler *et al.* (2007).

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