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Bioenergy crop greenhouse gas mitigation potential under a range of management practices

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Abstract

Perennial grasses have been proposed as viable bioenergy crops because of their potential to yield harvestable biomass on marginal lands annually without displacing food and to contribute to greenhouse gas (GHG) reduction by storing carbon in soil. Switchgrass, miscanthus, and restored native prairie are among the crops being considered in the corn and agricultural regions of the Midwest and eastern United States. In this study, we used an extensive dataset of site observations for each of these crops to evaluate and improve the DayCent biogeochemical model and make predictions about how both yield and GHG fluxes would respond to different management practices compared to a traditional corn-soy rotation. Using this model-data integration approach, we found 30–75% improvement in our predictions over previous studies and a subsequent evaluation with a synthesis of sites across the region revealed good model-data agreement of harvested yields ($r^2 > 0.62$ for all crops). We found that replacement of corn-soy rotations would result in a net GHG reduction of 0.5, 1.0, and 2.0 Mg C ha^{-1} yr^{-1} with average annual yields of 3.6, 9.2, and 17.2 Mg of dry biomass per year for native prairie, switchgrass, and miscanthus respectively. Both the yield and GHG balance of switchgrass and miscanthus were affected by harvest date with highest yields occurring near onset of senescence and highest GHG reductions occurring in early spring before the new crops emergence. Addition of a moderate length rotation (10–15 years) caused less than a 15% change to yield and GHG balance. For policy incentives aimed at GHG reduction through onsite management practices and improvement of soil quality, post-senescence harvests are a more effective means than maximizing yield potential.

Keywords: bioenergy, feedstocks, GHG, Miscanthus, nitrogen cycling, soil carbon, switchgrass

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Introduction

Atmospheric CO_2 concentrations have risen steadily since the industrial revolution contributing to global climate change. In efforts to provide energy security, bioenergy from corn ethanol has become an important renewable energy source for replacement of fossil fuels, but is of questionable greenhouse gas (GHG) mitigation potential because the associated GHG emissions exceed the potential reductions (Searchinger *et al.*, 2009). Recently, perennial grasses have been suggested as a viable option because of their ability to increase soil carbon storage (Anderson-Teixeira *et al.*, 2009), produce substantial yields with little to no fertilizer inputs (Behnke *et al.*, 2012), and their ability to grow on degraded agricultural or current energy-corn land without displacing food crops (Khanna *et al.*, 2010).

There also has been a wide range of predicted yields depending on the model assumptions about cultivation practices, harvest dates, nitrogen availability, and fertilizer use resulting in large uncertainty about potential yields. Limited field measurements of carbon and nitrogen cycling for perennial grasses such as miscanthus (Miscanthus × *giganteus*) and switchgrass (*Panicum virgatum L.*) have led to poor model representation of nutrient availability and use in relation to production potential (Davis *et al.*, 2010). Modeled estimates of aboveground production in the eastern US vary by 10–20 Mg ha^{-1} yr^{-1} and 3–8 Mg C ha^{-1} yr^{-1} for miscanthus and switchgrass respectively (Davis *et al.*, 2012; Miguez *et al.*, 2012; Mishra *et al.*, 2012). Aboveground net primary production (ANPP) predicted by the DayCent model, assuming symbiotic N fixation (Davis *et al.*, 2012), was considerably

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higher than values predicted by BioCro (Miguez *et al.*, 2012) and MISCANMOD (Mishra *et al.*, 2012), both of which assumed no N limitation to growth. In contrast, predictions of ANPP from DayCent for switchgrass without fertilizer were much lower than estimates from BioCro which again assumed no N limitation.

In addition to the wide range of estimates caused by assumptions about nutrient availability, assumptions about harvest date, harvest losses, and date of senescence have increased the uncertainty in predicted yields. For example, harvest yields in DayCent were simulated for a specific harvest date whereas the other models calculated harvested yield as 66% of projected peak biomass. These results indicate that bioenergy crop yield forecasts are highly dependent on model assumptions including harvest date, harvest loss, fertilizer applications, and N fixation rates.

New data provide an opportunity to evaluate previous projections of yield and GHG mitigation potential as well as improve model calibration and performance across a variety of conditions and management strategies. The EBI energy farm experiment was initiated in 2008 in part to test the changes in GHG or soil organic carbon (SOC) if the land was converted from corn-soy rotation to perennial bioenergy crops miscanthus, switchgrass, and native prairie (Anderson-Teixeira *et al.*, 2013).

Here, we evaluate bioenergy crop management practices by comparing the projected model yields, SOC, and GHG balance following a range of harvest dates spanning peak biomass to complete senescence and a range of cultivation practices (i.e. 5–30 rotation lengths) for miscanthus and switchgrass. First, DayCent was modified to improve projections using data collected at the Energy Farm by calibrating the site and crop submodels. We then compare the previously modeled projections against recent measurements from the Energy Farm where these cropping systems were grown side by side under the same conditions. We evaluated the model using yield data from a synthesis of research sites across the eastern US. Finally, we present new model projections of greenhouse gas emissions and soil carbon sequestration for miscanthus, switchgrass, corn, and mixed-species prairie agro-ecosystems calibrated with the same experimental observations. The specific questions we examine are:

1 How much does model performance improve with incorporation of new observations available from recently published datasets?
2 How does harvest date and rotation length affect the projected yields for miscanthus and switchgrass?
3 How does harvest date and rotation length affect the GHG mitigation benefits for miscanthus and switchgrass?

Materials and methods

Site description

The University of Illinois Energy Farm is located in central Illinois (40.06°N, 88.19°W; Table 1). In 2008, four biofuel feedstocks were planted to examine the potential for bioenergy production and the associated environmental services: miscanthus, switchgrass, restored native prairie, and a corn-corn-soybean rotation. The restored prairie consists of 28 species including species capable of symbiotic N-fixation (Zeri *et al.*, 2011). We chose a hybrid, sterile miscanthus species (*Miscanthus* × *giganteus*) known to have high yield potential in the region (Heaton *et al.*, 2008) and a regionally adapted switchgrass cultivar (*Panicum virgatum* cv. Cave-in-Rock). The corn-corn-soybean rotation is typical for central Illinois, although the study site supported a mixture of alfalfa and the traditional corn-soybean rotation over the last century. Annual precipitation has averaged 104 cm yr^{-1} over the last 30 years, however, the site was considered to be in drought conditions in 2011 (Zeri *et al.*, 2013; 77 cm) and 2012 (75 cm). The soil is a deep and fertile silt loam Flanagan typical of the region with some low lying blocks of Drummer (Smith *et al.*, 2013).

Plots were established in a randomized block design with five replicates consisting of one large plot (4 ha) and three smaller plots (0.7 ha) for each treatment. Measurements at the Energy Farm include above- and belowground live and dead biomass, biomass carbon and nitrogen content, annual harvested carbon and nitrogen removals, annual soil carbon content including carbon isotope signatures, soil texture, nitrous oxide (N_2O) emissions, nitrate leaching (NO_3), and eddy-covariance for net CO_2 exchange between the vegetation and the atmosphere (Anderson-Teixeira *et al.*, 2013; Smith *et al.*, 2013; Zeri *et al.*, 2013). In 2012, new root biomass sampling techniques were used to collect and improve estimates of miscanthus and switchgrass belowground biomass. A total of eight soil pits measuring 1 × 1 m were excavated to 30 cm for each crop. Root biomass was measured at the beginning (Feb 13- Mar 9 2012) and peak (Aug 6–22 2012) of the growing season. After excavation, roots were washed using a 1 mm mesh, then oven dried and weighed.

Model description and simulations

Model simulations of crop yield and soil carbon content were performed using the biogeochemical model DayCent (v. 4.5; Del Grosso *et al.*, 2011), the most recent daily time step version of CENTURY. DayCent simulates the effects of climate and land use change on carbon and nutrient cycling in terrestrial ecosystems and has been validated for use in crop, grassland, and forest ecosystems globally (Parton *et al.*, 1998; Del Grosso *et al.*, 2009). Required inputs for the model include vegetation cover, daily precipitation and temperature, soil texture, and current and historical land use practices. DayCent calculates potential plant growth as a function of water, light, and soil temperature, and limits actual plant growth based on soil nutrient availability. Soil organic carbon is estimated from the turnover of soil organic matter pools, which change with the decomposition rate

Table 1 DayCent simulation site characteristics and model parameter values that remain consistent across crop types and parameter values that vary by crop type

Site level (parameters do not vary by crop type)	
Latitude, Longitude	40.06°N, −88.19°W (Urbana, Illinois USA)
Baseline soil carbon	64 ± 9 Mg C ha^{-1} (plot average for all treatments)
Nitrogen deposition	8 ± 2 kg N ha^{-1} (2008–2011 average)
Soil texture	Sand (16%), Silt (58%), Clay (26%)
Bulk density	1.36
Mean annual precipitation	104 cm yr^{-1} (30 year average)
Mean annual temperature	12.9 °C (30 year average)
Year planted	2008 (randomized block design with 5 replicates)
Site history	Before 1850, Native prairie with grazing and fire; 1850–2007, traditional corn-soy rotation

	Miscanthus	Switchgrass	Prairie	Corn-Soy
Crop level (parameters vary by crop type)				
Symbiotic N-fixation	Yes	No	Yes	No, Yes
Nonsymbiotic N-fixation	Yes	Yes	Yes	Yes, Yes
Maximum C : N (aboveground plant material)	260	220	135	125, 40
Minimum C : N	30	30	30	10, 10
Maximum belowground allocation	30%	30%	40%	30%, 30%
Minimum belowground allocation	20%	20%	30%	10%, 10%
Fertilizer (kg N ha^{-1} yr^{-1})	0	56	0	165– 200, 0

of dead plant material. For this study, DayCent was parameterized to model soil organic carbon dynamics to a depth of 30 cm.

For the DayCent simulations (Table 1), daily climate data were used for the 2008–2012 growing seasons and a longer climate record (1980–2011) was used for historical and future simulations. Data was downloaded from the Daymet database (www.daymet.org; Thornton *et al*., 2012). Historical simulations followed a standard native prairie with a short fire return interval schedule followed by ca. 150 years of agricultural history. Agricultural history included corn-soy rotations, alfalfa, and wheat. Soil carbon stocks were simulated to represent the pre-agricultural native prairie levels with a subsequent decline as the land was cultivated each year for the annual crops. Following the agricultural history, the Energy Farm simulations were run from 2008 to 2012 duplicating the site management. Switchgrass was fertilized with 56 kg N ha^{-1} yr^{-1}. Miscanthus was not fertilized at the Energy Farm as there has been little conclusive empirical evidence that N additions improve productivity (Maughan *et al*., 2012). Finally, while there is also little evidence that miscanthus and switchgrass yields declines over time (Sanderson *et al*., 2006; Christian *et al*., 2008), we assume that farmers will replant as improved cultivars are released. For this reason, future simulations (2009–2038) for miscanthus and switchgrass were varied by rotation length (0, 5, 10, 15, and 30 years) as well as by harvest date (September 1st through March 1st). A baseline corn-corn-soy rotation following the Energy Farm management procedures was simulated for comparison with the cropland converted to bioenergy crops.

Model calibration and improvement

DayCent was calibrated for all crops using new measurements from the Energy Farm including above- and belowground net primary production (NPP) and allocation, biomass carbon and nitrogen content, soils data, daily weather data, greenhouse gas fluxes, N-fixation, N deposition, and litter decomposition rates (Table 1). DayCent was modified to make improved projections for the Energy Farm by the following: (i) altered root dynamics in base DayCent model according to improved empirical data, (ii) crop submodels were calibrated with measured tissue C : N ratios, (iii) symbiotic-N fixation was reduced by 60% in the miscanthus submodel, (iv) retranslocation of plant N at senescence was increased substantially for switchgrass and miscanthus, and (v) a simulated establishment phase of 3 years for switchgrass and 5 years for miscanthus was developed using additional crop submodel definitions.

Following calibration, the model was evaluated against historical data of county mean annual corn and soy productivity available from the National Agricultural and Statistics Service (NASS, 2011), SSURGO soil carbon data (NRCS, 2010), and a synthesis of switchgrass and miscanthus yields from research sites across the eastern US (Arundale *et al*., 2013, Behnke *et al*., 2012; Maughan *et al*., 2012). Simple linear regression statistics and paired t-tests were used to compare the model output with the observations using SigmaPlot v. 12.3 (Systat Software 2011, San Jose, CA, USA).

Results

Model performance following incorporation of site observations

Following calibration with empirical data, modeled estimates (Fig. 1; blue bars) of above- and belowground biomass carbon fell within one SD for each of the perennial crops (Fig. 1; green bars). Aboveground biomass

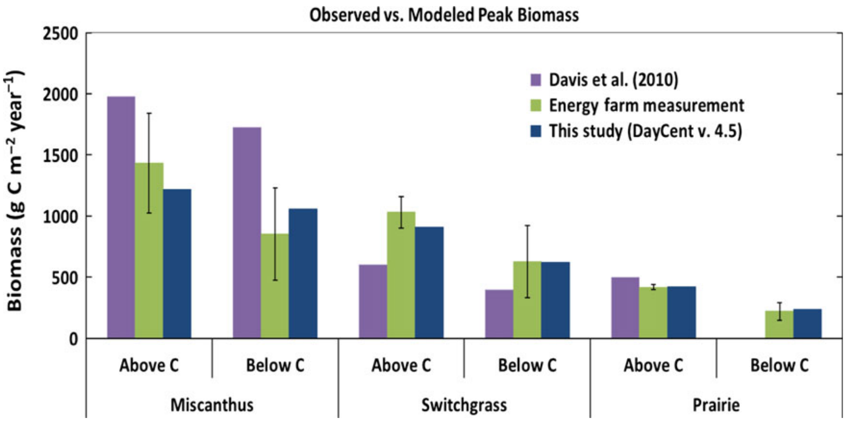

Fig. 1 Observed (green bars) vs. modeled peak biomass for both the previous estimates made at the energy farm (purple bars) and the current estimates using DayCent 4.5 (blue bars). Observation standard deviations are shown (black error bars). Data for previously modeled belowground prairie estimates were not available.

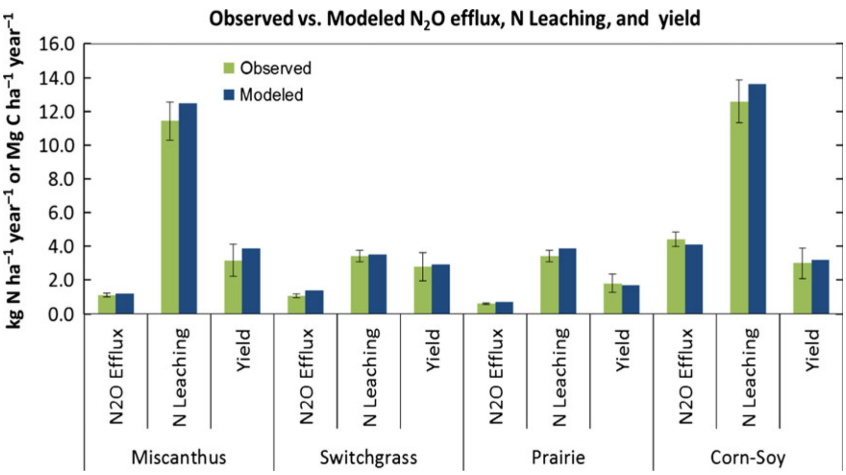

Fig. 2 Observed (green bars) vs. modeled (blue bars) nitrous oxide efflux (N_2O), nitrate leaching, and yield at the Energy Farm. Observation standard deviations are shown by the black error bars. N_20 and N leaching are in units of kg N ha^{-1} yr^{-1} and yield is in Mg C ha^{-1} yr^{-1}.

estimates improved by 18, 27, and 30% for prairie, miscanthus, and switchgrass, respectively, compared with model estimates that were made prior to data availability (Fig. 1; purple bars). Belowground estimates improved by 36% for switchgrass and 76% for miscanthus (prior prairie modeled estimates were not available). When compared with the observation means, the model underestimated miscanthus and switchgrass aboveground biomass by 11% and overestimated miscanthus belowground biomass by 26%. However, because of the large range in observation uncertainty, the differences were not statistically significant (two-sided $P > 0.05$).

Model predictions of nitrous oxide efflux (N_2O), nitrate leaching (NO_3), and yield also compared favorably with measured values (Fig. 2). DayCent overestimated N leaching (2–13%) and N_2O efflux (6–30%) in the perennial grass treatments and N leaching (8%) in the corn-soy treatment. Mean harvested yield was overestimated by 23% for miscanthus, but varied little from the observed means for switchgrass and prairie. Again, although there was both positive and negative model bias, the differences were not statistically significant (two-sided $P > 0.05$).

To evaluate our new calibration spatially, we ran a series of simulations at a network of sites ($n = 10$) across the Eastern US growing both switchgrass and miscanthus (Fig. 3). We compared both the baseline soil carbon estimates and harvested yields with site observations. Modeled baseline soil carbon to a depth

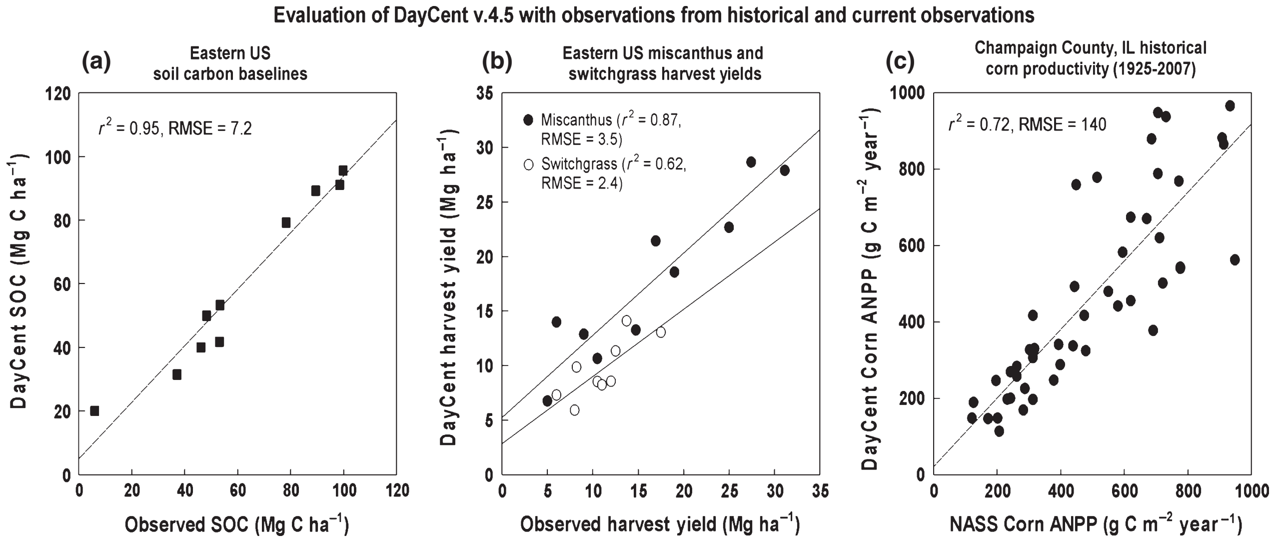

Fig. 3 Model evaluation of (a) soil organic carbon to a depth of 30 cm with NRCS Soil Survey Statistics, (b) miscanthus (solid circles) and switchgrass (open circles) harvested yields and (c) historical corn annual aboveground biomass production from 1925 to 2007. Research sites for miscanthus and switchgrass are located in Nebraska, Illinois, Kentucky, New Jersey, South Dakota, Louisiana, Michigan, Mississippi, Oklahoma, and Georgia. Corn aboveground net primary production (ANPP) was calculated as the total amount of aboveground biomass carbon (stems, leaves, grain, etc.) that was grown each year. Annual NASS data of corn grain bushels per acre were converted to ANPP by assuming a harvest index of 0.50, 13.0% moisture content, and 43.6% carbon content. Using these conversions, 1 bushel of corn grain is equivalent to 19.3 kg C of aboveground net primary production.

of 30 cm correlated remarkably well with site observations (Fig. 3a; $r^2 = 0.95$). Good correlations between modeled harvested aboveground biomass and site observations also were found for miscanthus ($r^2 = 0.87$) and switchgrass ($r^2 = 0.62$). Finally, we compared our historical simulations with county-level NASS data to test the model accuracy during the historical period corn productivity increased over time and found reasonably good agreement (Fig. 3c; $r^2 = 0.72$) as well.

Improved model projections of bioenergy crop yield and GHG reduction benefits

The new model predicted an average yield *at harvest* of 17.2, 9.2, and 3.6 Mg biomass yr^{-1} for miscanthus, switchgrass, and prairie respectively (Table 2). Miscanthus yield was nearly double the switchgrass predictions and four times the restored prairie yields. Compared with prior modeling results, the predicted yields were lower for miscanthus and the restored prairie and higher for switchgrass.

When compared with a continued corn-corn-soy baseline, total GHG reductions summed over the 30 year period were highest for miscanthus, followed by switchgrass and then restored prairie (Table 2). The majority of the GHG mitigation benefits were from changes in soil carbon (Table 2; negative values indicate carbon removed from the atmosphere and stored in the soil). The changes were highest for miscanthus with over 240 metric tons of CO_2-eq. per hectare stored as soil carbon over a 30 year period compared with a corn-corn-soy rotation (ca. 2 Mg C ha^{-1} yr^{-1}). Soil carbon storage was also significant for switchgrass and prairie at rate of about 0.5–1.0 Mg C ha^{-1} yr^{-1}. NO_3 leaching and N_2O efflux were reduced in all three perennial treatments compared to the baseline corn-corn-soy treatment. Leaching reductions were nearly equal for each of the crops; N_2O reductions were similar for miscanthus and prairie and lower for switchgrass. There were no significant changes in methane efflux for any of the treatments.

Effect of harvest date and rotation length on yield

For both miscanthus and switchgrass, fall harvests produced higher yields than spring harvests with maximum yields occurring near the onset of plant senescence (mid-September for switchgrass and mid-October for Miscanthus; Fig. 4). For an early March harvest, yield decreased by over 70% for both crops (Fig. 4; red lines, harvest DOY = 62). If the crops were harvested as recommended (Lewandowski *et al*., 2003; Sanderson *et al*., 2006) in late winter (harvest DOY = 336), the yield loss was reduced to 30% for miscanthus and to 47% for switchgrass.

Table 2 Average harvested yield and net change in soil carbon and GHG fluxes, compared to continuation of a corn-corn-soy baseline. Negative values indicate removals from the atmosphere or C sequestration (positive benefit). Yield is reported as the 30-year average biomass in metric tons (Mg). GHG values summed over the 30 year period and compared to the baseline CCS values. The values represent the total difference between planting CCS or planting the perennial grass. GHG values are in tons of CO_2-equivalents per hectare

Crop	Average Yield (Mg yr^{-1})	N_2O Efflux (Mg CO_2-eq. ha^{-1})	NO_3 Leaching (Mg CO_2-eq. ha^{-1})	CH_4 (Mg CO_2-eq. ha^{-1})	Soil Carbon (Mg CO_2-eq. ha^{-1})	Net GHG (Mg CO_2-eq. ha^{-1})
Miscanthus	17.2	−43.5	−1.1	0.0	−242.1	−286.7
Switchgrass	9.2	−31.4	−1.2	0.0	−99.4	−131.9
Prairie	3.6	−41.6	−1.0	0.0	−57.6	−100.3

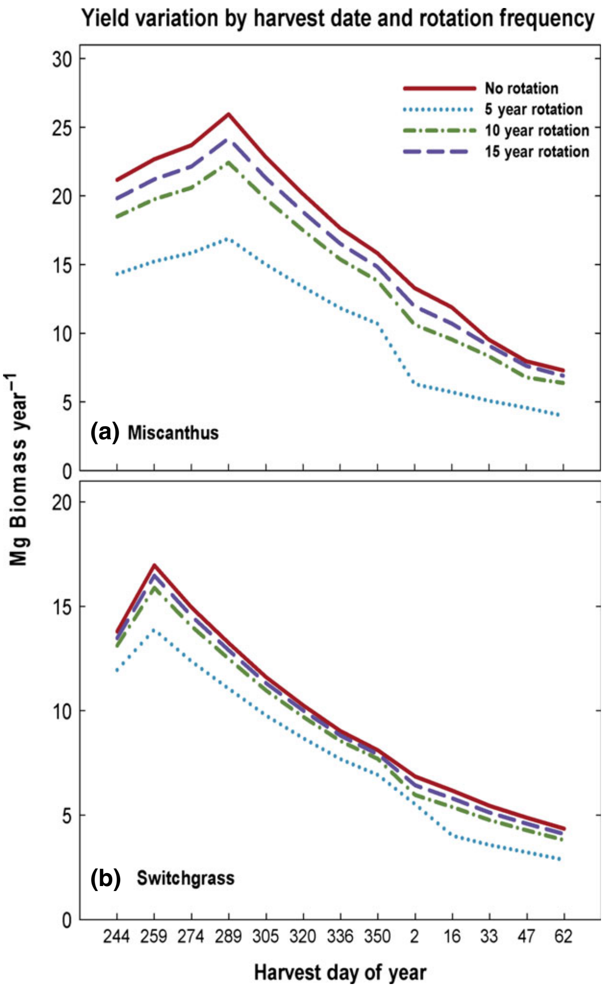

Fig. 4 DayCent simulations of expected harvested yield for different harvest dates (early September – early March) for (a) Miscanthus and (b) Switchgrass. Harvests are shown for both pre- and postsenescence dates for each crop. Yields are in units of biomass per hectare per year (not carbon).

We also tested the yield losses to be expected by adding rotation intervals to each crop. Because, miscanthus typically requires 3–5 years to reach maturity (Miguez *et al.*, 2008) and switchgrass requires at least 2 years (Sanderson *et al.*, 2006), the average yield over 30 years was reduced. We found the yields decreased substantially for a 5 year rotation of both species (Fig. 4; blue lines, 20–35%), and moderately for the 10 year rotations of miscanthus (green lines, 15%), especially in the fall and winter months. The 15 year rotations had little effect on the yields (purple lines, <7%).

Effect of harvest date and rotation length on GHG balance

Harvest date had the opposite effect on GHG reduction than yield with increasing GHG mitigation benefits for spring harvests vs. fall harvests (Fig. 5). Again, the majority of the reduction was because of an increasing soil carbon pool as harvest was delayed postsenescence for both miscanthus (Fig. 5a) and switchgrass (Fig. 5b). However, delaying harvest until early March when the subsequent growing season began caused a slight decrease in the soil carbon change. Changing the rotation length to increasingly shorter intervals reduced SOC storage for both crops with a noticeably higher impact on miscanthus (Fig. 5a; green, red, purple lines). There was a very little discernible change in N_2O efflux either by harvest date or by rotation length, except for a moderate increase in the 5 year rotation of switchgrass and a slight increase for miscanthus.

Discussion

Our findings show significant improvement of model-data agreement by incorporating site-specific data. We were able to accurately simulate the Energy Farm above- and belowground biomass pools, nitrogen dynamics, and harvest yields with and the evaluation using other site data increases our confidence that DayCent can adequately capture carbon and nitrogen dynamics and predict yields across larger regions (Fig. 3). Replacement of corn-corn-soy rotations in central Illinois with perennial crops would result in significant net GHG reductions (100–287 Mg CO_2-eq.) over a 30 year period, primarily because of increases in soil carbon (Table 2). For switchgrass and miscanthus,

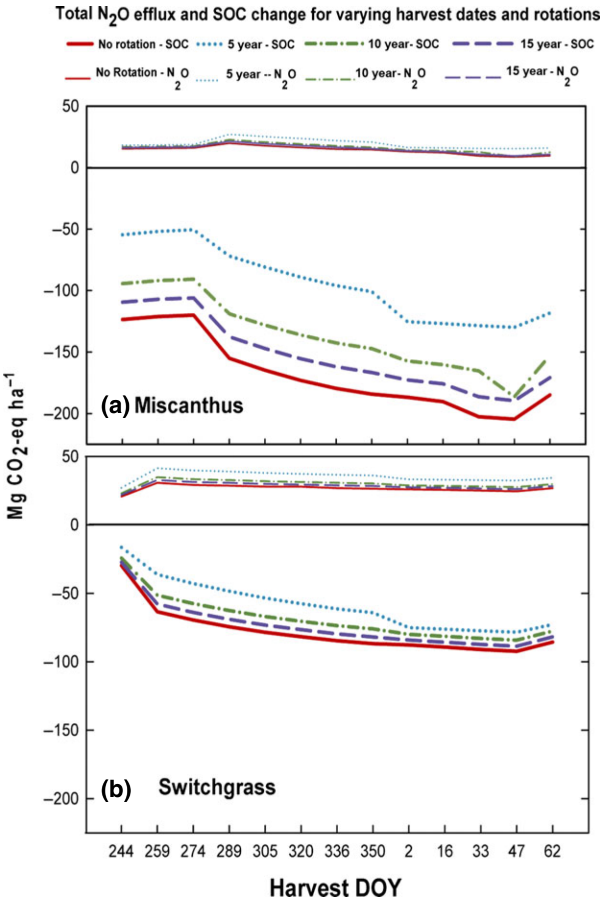

Fig. 5 Total change in nitrous oxide efflux (thin lines) and soil carbon storage (thick lines) over 30 years for different harvest dates (DOY) and rotation frequencies (0–15 years) for (a) Miscanthus and (b) Switchgrass. Negative numbers indicate soil carbon storage (GHG reduction) and positive numbers indicate GHG sources (GHGs added to atmosphere). Values are NOT compared to a corn-soy baseline as in Table 2, but simply show the change in efflux or SOC since conversion to perennial crops.

harvest dates with highest yields occur near onset of senescence and highest GHG reductions occur in early spring before the new crops emergence (Fig. 4). Reduction in yield and GHG balance caused by the addition of a 10–15 year length rotation is minimal (Fig. 5), but may depend on release of higher yielding cultivars. The trade-off between maximizing yield (fall harvest) or GHG reduction (spring harvests) will likely be determined by economic return through land and crop prices, carbon policy incentives, and the price of oil (Jain *et al.*, 2010).

Reduction in model uncertainty was primarily because more data was available to calibrate and evaluate model output. The prior estimates were calibrated against a small set of particularly high-yielding plots (Heaton *et al.*, 2008) and may have overestimated the N-fixing ability of miscanthus. While the enzymes associated with symbiotic N-fixation are present in miscanthus (Davis *et al.*, 2010), field trials at the energy farm have failed to detect appreciable amounts of acetylene reduction, an indicator of N fixation (M. David, pers. comm.). However, model simulations of miscanthus yield were too low when simulated with no symbiotic N-fixation or fertilizer; miscanthus was expressing N-limitation in the model (Davis *et al.*, 2010). Previous work (Heaton *et al.*, 2009) and current farm data indicate a large portion of the miscanthus and switchgrass aboveground plant N (ca. 90% and ca. 70%, respectively) may be retranslocated to the rhizomes at senescence. DayCent allows manipulation of maximum and minimum C : N ratios and maximum retranslocation of nutrients in plant tissues and changing these parameters significantly improved model-data fidelity. However, there is still some underestimation of aboveground biomass (Fig. 1) caused by the apparent N-limitation in the model suggesting the plant is acquiring N from other sources, potentially a mix of fixation and deeper soil layers.

Recent enhancements to the DayCent model include a division of the root biomass pool into juvenile and mature roots allowing for different turnover times (Parton *et al.*, 2010; Del Grosso *et al.*, 2011). The paucity of data available about belowground biomass and processes generally makes modeling experiments difficult to evaluate. For perennial grasses, observed root biomass can be greatly underestimated because rhizome biomass is 'missed' too often with root cores and scaling becomes an issue. We were fortunate to have recent seasonal belowground root biomass and carbon and nitrogen content data and improved sampling techniques (1 m quadrat sampling to 30 cm) that reduced observation uncertainty in the spatial heterogeneity of both the fine roots and, in particular the miscanthus rhizomes.

The new belowground biomass datasets allowed us to determine the correct amount of NPP to allocate to belowground roots, to litter pools, to harvest, and eventually to soil carbon pools resulting in better estimates of belowground C cycling. The amount of carbon entering the soil carbon pool and the release through decomposition determines the rate at which we can expect to see increasing soil carbon storage (Rasse *et al.*, 2005; Schmidt *et al.*, 2011). For the perennial grasses, the model simulations indicate an increasing soil carbon pool at about 0.5–2 Mg C ha yr^{-1} compared with the corn-corn-soy baseline. Part of the increase in SOC can be explained by the lack of cultivation events; the corn-corn-soy baseline system is losing soil carbon as the fields are plowed each year for the next crop (Bernacchi *et al.*, 2005). For the perennial grasses, the largest contribution to soil carbon is from the investment in belowground biomass. Our findings are supported by both biometric estimates of carbon balance (Anderson-Teixeira *et al*., 2009) as well as eddy-covariance data that indicates the perennial grass plots are storing 0.4 – 2.0 Mg C ha^{-1} yr^{-1} after accounting for harvest removals (Zeri *et al*., 2013).

In addition to the positive soil carbon changes, nitrous oxide (a potent GHG) and N leaching were reduced compared with the baseline management. This was expected because of reduced fertilizer use that further enhances the environmental services associated with perennial bioenergy crops. Reductions in N leaching improve water quality and lead to less indirect nitrous oxide emissions. However, the ability to model these GHG fluxes has been limited by the data available to calibrate and evaluate model results. For this study, we have overcome this data limitation and can now make reliable predictions for our study site and could extend our analysis for similar systems across the eastern US (Davis *et al*., 2012; Mishra *et al*., 2012).

DayCent predicted reduced harvested yields of both switchgrass and miscanthus for later harvest dates (i.e. spring) with increasing soil carbon benefits. Harvest yields are known to decrease because of prolonged senescence and crop damage caused by wind and snow for both crops (Lewandowski *et al*., 2003; Adler *et al*., 2006; Fike *et al*., 2006; Christian *et al*., 2008; Miguez *et al*., 2008; Wang *et al*., 2010; Maughan *et al*., 2012). Consequently, more of the aboveground plant biomass is allowed to enter the litter pool which decays and a portion of this pool becomes part of soil carbon. Senesced miscanthus and switchgrass litter is more recalcitrant than corn or soybean litter because of high lignin and low nutrient content (Arundale, 2012), characteristics of low-quality litter for decomposition. This low-quality perennial grass litter has been shown to contribute to soil carbon storage compared to traditional agricultural crops (Luo *et al*., 2010; De Deyn *et al*., 2011; Ziter & Macdougall, 2012).

There is some indication that more nitrate leaching and nitrous oxide emissions occur with spring harvest dates compared to fall harvests (Smith *et al*., 2013), but these are overwhelmingly balanced by the soil carbon increase. Although addition of a 10–15 year rotation reduced average annual yield and GHG benefits, the losses were small and may be minimized had we allowed for simulation of more productive species. It is expected that the rotation length would be based on technological or genetically improved cultivars which may recoup yield losses over time.

This study presents strong evidence for replacement of corn grown for bioenergy with perennial grasses, especially miscanthus and switchgrass, as a means to replace fossil fuels and to reduce GHG emissions associated with corn ethanol production. The decision to maximize harvest yield or GHG mitigation benefits with respect to harvest date and rotation length will largely depend on the GHG policy incentives, the market price of the biomass, and the demand for bioenergy instead of fossil fuels. Here, we show that harvest losses would be a minimum of 30% in the case of miscanthus to realize an 18% increase in *in-situ* GHG reductions with no rotation interval. The GHG reductions shown here do not account for fossil fuel substitutions or subsequent emissions associated with the biomass removal and depending on the efficiency of the biomass conversion, the GHG mitigation potential could change. Also, we recognize there would be displaced corn grain ethanol coproducts if perennial grasses were to replace corn, reducing the positive GHG impacts of the grasses. Full life-cycle assessment is necessary to determine the magnitude of these reductions.

For this study, it is evident that for carbon market incentives aimed at onsite GHG reductions through increased soil carbon storage, the loss in yield by delaying harvest may be acceptable. Finally, soil carbon storage for these simulations has not yet reached the levels measured in native prairie (David *et al*., 2009) and we presume they will continue to increase.

Acknowledgments

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