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Threshold Dynamics in Soil Carbon Storage for Bioenergy Crops

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S *Supporting Information*

ABSTRACT: Because of increasing demands for bioenergy, a considerable amount of land in the midwestern United States could be devoted to the cultivation of second-generation bioenergy crops, such as switchgrass and miscanthus. The foliar carbon/nitrogen ratio (C/N) in these bioenergy crops at harvest is significantly higher than the ratios in replaced crops, such as corn or soybean. We show that there is a critical soil organic matter C/N ratio, where microbial biomass can be impaired as microorganisms become dependent upon net immobilization. The simulation results show that there is a threshold effect in the amount of aboveground litter input in the soil after harvest that will reach a critical organic matter C/N ratio in the soil, triggering a reduction of the soil microbial population, with significant consequences in other microbe-related processes, such as decomposition and mineralization. These thresholds are approximately 25 and 15% of aboveground biomass for switchgrass and miscanthus, respectively. These results suggest that values above these thresholds could result in a significant reduction of decomposition and mineralization, which, in turn, would enhance the sequestration of atmospheric carbon dioxide in the topsoil and reduce inorganic nitrogen losses when compared to a corn−corn−soybean rotation.

INTRODUCTION

Second-generation bioenergy crops, such as *Panicum virgatum* (switchgrass) and *Miscanthus* × *giganteus* (miscanthus), are regarded as potential carbon-neutral energy sources and are an attractive option for mitigating human-induced climatic change.[1] These lignocellulosic feedstocks have potential to further reduce carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions because of relatively higher yields and lower nutrient inputs compared to first-generation crops, such as corn.[1−4] However, the expansion of these crops to meet the bioenergy demand will impact the biogeochemical cycling in the soil. Because the fate of soil carbon and nitrogen over extended time periods is of a global concern,[5,6] we study these dynamics for the bioenergy feedstocks switchgrass and miscanthus.

The dynamics of carbon and nitrogen in the soil are complex and controlled by many variables, such as the microbial population, type of soil, chemical composition and quality of residues, fluxes of water and energy in the soil, field management practices, and harvest treatments.[7−9] In particular, the carbon/nitrogen ratio (C/N) in the soil organic matter is an important variable because it affects the microbial dynamics, which, in turn, is the main controller of processes such as decomposition and mineralization. It is noted that there is a critical soil organic matter C/N ratio, above which microorganisms rely on net nitrogen immobilization.[10] Therefore, above this ratio, there is insufficient nitrogen to sustain microbial growth if the soil inorganic nitrogen is depleted. These conclusions are supported by a previous study where decomposition fluxes were reduced as the organic matter C/N ratio increased.[11]

Land use modifications from corn and soybean rotation to bioenergy crops could impact the soil organic matter C/N ratio. It has been observed that switchgrass and miscanthus show a relatively high aboveground C/N ratio at harvest because of the relocation of nitrogen to rhizomes during the winter.[2] Therefore, the above- and belowground residues from these crops will have different C/N ratios than corn and soybean.[12−14] In turn, this difference will affect the C/N ratio in the soil organic matter in future years. However, the actual

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implications for the C/N ratio in the soil organic matter in future years will be regulated by the amount of above- and belowground residues that are returned to the soil. In particular, in crop systems, aboveground residues play an important role in determining the fate of soil organic matter.[15] It is generally believed that cultivation of switchgrass and miscanthus promotes soil carbon accumulation in the topsoil.[16,17] However, the amount of additional carbon stored in soils varies significantly among studies for these energy crops from 0 to 40% of the initial soil carbon stock.[17] It is worth mentioning that these numbers are also affected by initial conditions of soil organic matter content at the specific sites. Additionally, most previous studies have analyzed the effects of switchgrass and miscanthus cultivation on the retention of carbon[18−22] and reduction of nitrogen[23−26] using fixed amounts of biomass that are returned to the soil after harvest. We explore and analyze how these dynamics are affected by different amounts of aboveground biomass returned to the soil at harvest (harvest litter). In particular, we perform numerical simulations to explore the impact of different crops, namely, corn−corn−soybean rotation, switchgrass, and miscanthus, on the belowground dynamics of carbon and nitrogen.

■ MODELS AND METHODS

Study Site. We use published data for the study site located at the Energy Biosciences Institute (EBI) Experimental Farm at the University of Illinois at Urbana−Champaign, Urbana, IL (40° 3′ 46.209″ N, 88° 11′ 46.021″ W, ∼220 m above sea level). On the basis of records from the Illinois State Water Survey, the mean annual temperature and precipitation are 11 °C and 1051 mm, respectively. Prairie, corn−corn−soybean rotation, switchgrass, and miscanthus have been grown in four quadrants of the facility since 2008 (see Figure S1 of the Supporting Information). Before the experiment, the field was used to cultivate oat in a large plot and corn and soybean in small plots. However, the site historically supported corn−soybean rotation.[14] Severe weather conditions in 2008 and 2009 led to significant mortality of miscanthus. Replanting of this crop was thus performed in 2009 and 2010, delaying the full establishment of miscanthus. On the other hands, switchgrass became well-established and reached its full maturity in 2010.[27] More details about the site can be found in published papers.[14,27,28]

At the field site, water flow and dissolved ammonium and nitrate loads are recorded in tile drains installed to capture the drainage from each quadrant (see Figure S1 of the Supporting Information). Furthermore, the soil organic carbon, nitrogen concentration, particle size, and bulk density to a depth of 1.00 m were measured prior to the start of the experiment in 2008.[14] The nitrogen mineralization and nitrification rates were also measured to a depth of 0.30 m.[14] In addition, litter inputs, aboveground carbon of crops, and leaf area index (LAI) were measured.[27,28] These data were used to test and then validate the numerical models used in this study.

Ecohydrological and Biogeochemical Models. In this study, we implemented the Precision Agricultural Landscape Modeling System (PALMS) to simulate the ecohydrological dynamics. The model has been primarily used in the midwestern United States and simulates plant phenology, surface and subsurface water, and soil heat transport using inputs of soil texture, topography, vegetation type, tile drain map, and weather.[29] This model takes into account ponding and reinfiltration using a two-dimensional surface flow scheme, which is typically not considered in most existing models.[30] This model is therefore able to achieve a more realistic representation of the movement of water in the soil. For this study, there was no need to parametrize corn and soybean phenology because these submodels in PALMS have been previously validated.[30−32] However, for the switchgrass and miscanthus submodels, physiological and phenological parametrizations were required. These were derived from modeling works and experimental data recorded from both the EBI site and sites close to the EBI site in Urbana−Champagn, IL,[2,14,33−37] and from previous publications[38−40] (see Table S1 of the Supporting Information).

We coupled PALMS with a biogeochemical model[41] (see Figure S2 of the Supporting Information), which, in turn, used the developed formulations.[42,43] This multilayer model considers soil carbon and nitrogen dynamics that are controlled by soil microorganisms, land use, climate, vegetation, and field management practices. The model is based on mass balance equations for carbon and nitrogen in the soil. Three pools are used to describe the soil organic matter (litter, humus, and microbial carbon and nitrogen), and two pools are used to describe the soil mineral nitrogen (ammonium and nitrate). The model simulates the microbial dynamics by accounting for the carbon and nitrogen available to sustain the microbial growth at a fixed C/N ratio. In other words, the soil carbon and nitrogen dynamics are directly controlled by soil microorganisms. The explicit consideration of soil microbial dynamics is a key feature for accurate simulations of soil organic carbon (SOC).[46] This important feature is missing in traditional biogeochemical models, such as CLM4cn, DAYCENT, and DNDC.[10,46,47] Therefore, the model is appropriate to explore the consequences that are caused because of limitation of nitrogen in the belowground processes.[10,44,45] Using this biogeochemical model, the impact of hydrological conditions on soil carbon and nitrogen dynamics in a semi-arid climate was tested.[42] A more recent study[41] used this model to examine the influence of hydraulic redistribution on decomposition of soil organic matter in a Mediterranean climate. For this work, we incorporated additional components to the model presented in the previous study[41] to include (1) litterfall and (2) plant nitrogen remobilization. In addition, (3) denitrification, (4) nitrogen flux through the tile drainage, and (5) fertilizer application were included. We also developed (6) a formulation for the fixation of nitrogen by soybean and miscanthus based on previous studies.[22,48,49] These model formulations are described in more detail in section S2 of the Supporting Information. Figure S3 of the Supporting Information shows a schematic representation of the model. The crop and biogeochemical parameters used in this model are described in Tables S2−S6 and Figure S4 of the Supporting Information.

Simulation Scenarios. To capture realistic initial conditions for the carbon and nitrogen states in the soil, we performed numerical simulations for 100 years prior to present using a corn−soybean rotation (Figure 1). We used a spin-up to determine initial concentrations of ammonium, nitrate, and litter C/N ratio, because there were no experimental records of these variables. The spin-up was initialized with available information of SOC[14] and soil microbial biomass (SMB)[50] that were recorded in the study site and an adjacent site at the beginning of 2008. The soil carbon and nitrogen states at the end of this spin-up simulation were used as the initial conditions for a subsequent simulation performed for 50

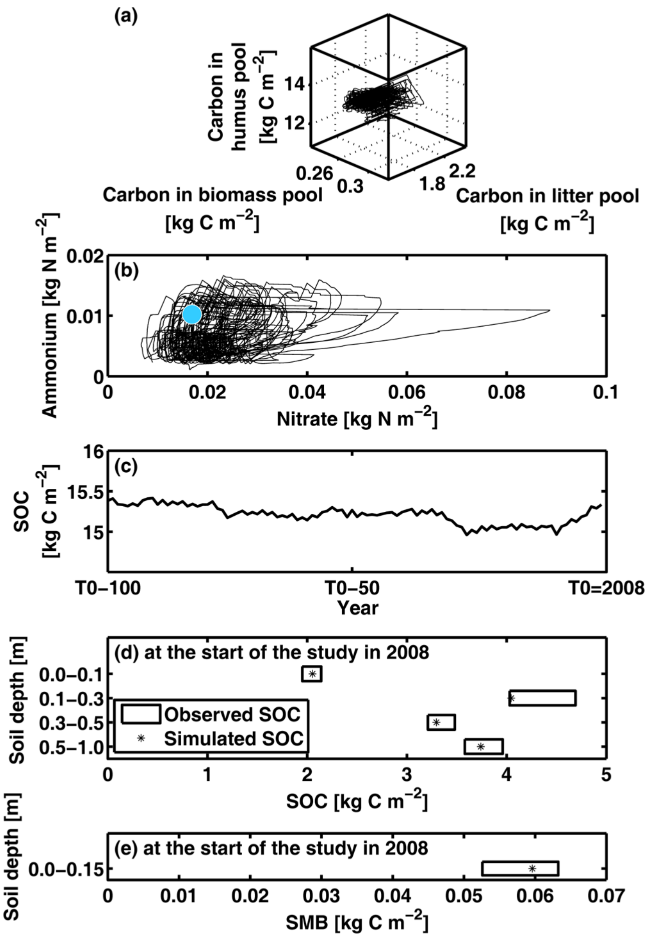

Figure 1. Initial conditions implemented in the simulations were obtained by performing a long-term simulation with corn−soybean rotation until a quasi-steady state was reached. The top two panels display the nonlinear dynamics in the (a) soil carbon pools and (b) soil nitrogen pools for 100 years prior to 2008 (blue dot denotes the final point). The panel in the middle displays the (c) total SOC to a depth of 4.5 m. The bottom two panels show the simulated and observed (d) SOC and (e) SMB in a given depth zone of soil at the beginning of the study in 2008 plotted with each other. Observed data of SOC and that of SMB are from the study site[14] and corn−soybean rotation at an adjacent site in Pana, IL,[50] respectively.

years with the three crops analyzed in this study: corn−corn−soybean rotation, switchgrass, and miscanthus. The atmospheric forcings used in the simulations were generated stochastically using a weather generator.[51] Different variables, such as precipitation, cloud cover, incoming shortwave radiation, air temperature, humidity, wind speed, atmospheric pressure, and vapor pressure were generated at 0.5 h intervals. The stochastic generation was performed with parameters obtained from 10 years of atmospheric data (from 2002 to 2011) recorded at the study site and nearby Willard Airport. Figure S5 of the Supporting Information displays the key meteorological variables that were generated.

To analyze the impact that these crops have on the biogeochemical cycling of carbon and nitrogen in the soil, we considered different scenarios for the amount of biomass that is returned to the soil during harvest. Table 1 lists the scenarios that are considered for each crop.

■ RESULTS

Model Validation. Aboveground carbon and LAI simulated by PALMS presented similar trends to those observed at the study site and at an adjacent site in Bondville, IL, as shown in Figure S6 of the Supporting Information (aboveground carbon, R^2 = 0.86 for corn−corn−soybean rotation, R^2 = 0.73 for switchgrass, and R^2 = 0.88 for miscanthus; LAI, R^2 = 0.83 for corn−corn−soybean rotation, R^2 = 0.95 for switchgrass, and R^2 = 0.80 for miscanthus).

Comparisons of carbon and nitrogen model results against observations of ammonium and nitrate loads in the tile drainage, nitrogen mineralization, nitrification, and litterfall over 3 years showed that model accuracy improved over time (Figure 2). The performance was poor in the 2009 drainage flow in the switchgrass and miscanthus plots that inevitably affects the accuracy of ammonium and nitrate loads. The overestimate in 2009 simulated drainage was probably due partly to the immaturity of the switchgrass and miscanthus and partly to the replantation of the miscanthus in 2009 and 2010. However, the model performance improved considerably for 2011. Despite having the highest evapotranspiration value among all crops because of its longer growing seasons, denser canopy, and deeper root system,[36] miscanthus also showed the highest drainage flow as a result of its location downslope of surface and subsurface lateral flow from the other plots. In addition, to confirm the performance of the model, nitrogen uptakes of the crops considered over the next 50 climatic years of simulation were compared to the normal ranges in nitrogen uptakes from previous studies,[48,52−54] as shown in Figure 3. Simulations of annual total nitrogen uptakes generally fell into these normal ranges.

SOC and SMB. Figure 4 shows the projected total SOC and total SMB to a depth of 4.5 m for different amounts of harvested biomass that is returned to the soil. Following the 2011 harvest practices for corn−corn−soybean rotation, switchgrass, and miscanthus (solid lines, scenario I), the results show that miscanthus accumulates more SOC than the other crops over the next 50 years. Although the averaged total carbon addition into the soil from corn−corn−soybean rotation is even higher than that from switchgrass and miscanthus (Figure 5), the net accumulation in the soil is lower. In other words, the fate of SOC cannot be determined solely by the amount of above- and belowground plant residue inputs. Rather, it is an interplay between the amount of carbon added to the soil, residue C/N ratios, fertilizer input, and soil temperature and moisture. For instance, the average litterfall and dead root C/N ratios for switchgrass and miscanthus are higher than those for corn−corn−soybean rotation (see Tables S2−S5 of the Supporting Information). In addition, the mean soil moisture and temperature are lower in the miscanthus fields because of the much higher LAI (Figure S6 of the Supporting Information). All of these factors and the lack of nitrogen fertilizer inhibit decomposition in miscanthus fields.

Furthermore, results obtained from the 2011 harvest practices (scenario I) indicate that the litter C/N ratio, bioturbation, and fertilizer amount significantly impact SMB. In particular, insufficient soil nitrogen because of a relatively high C/N ratio in the aboveground litterfall and the absence of a fertilizer application restrict the growth of SMB under miscanthus. Although the total amount of SMB to the depth of 4.5 m was not very different among corn−corn−soybean rotation (312 ± 19 g of C m^{-2}), swichgrass (292 ± 49 g of C

Table 1. Harvest Litter Input and Fertilizer Application Scenarios for Driving Soil Carbon and Nitrogen Model Predictions[a]

scenario	percentage of aboveground biomass inputs at harvest (%)	percentage of belowground biomass inputs at harvest (%)[b]	fertilizer[c] (kg of N m^{-2} $year^{-1}$)
		CCS Rotation[d]	
CCS-I[e]	C, 50; S, 100 (185 kg of C m^{-2} $year^{-1}$)	C, 100; S, 100 (191 kg of C m^{-2} $year^{-1}$)	C, 0.0180; S, 0
CCS-II	C, 75; S, 100 (269 kg of C m^{-2} $year^{-1}$)	C, 100; S, 100 (191 kg of C m^{-2} $year^{-1}$)	C, 0.0180; S, 0
CCS-III	C, 100; S, 100 (354 kg of C m^{-2} $year^{-1}$)	C, 100; S, 100 (191 kg of C m^{-2} $year^{-1}$)	C, 0.0180; S, 0
		Switchgrass	
PV-I[e]	2 (17 kg of C m^{-2} $year^{-1}$)	0	0.0056
PV-II	20 (165 kg of C m^{-2} $year^{-1}$)	0	0.0056
PV-III	25 (206 kg of C m^{-2} $year^{-1}$)	0	0.0056
PV-IV	30 (248 kg of C m^{-2} $year^{-1}$)	0	0.0056
		Miscanthus	
MG-I[e]	0	0	0
MG-II	10 (87 kg of C m^{-2} $year^{-1}$)	0	0
MG-III	15 (130 kg of C m^{-2} $year^{-1}$)	0	0
MG-IV	20 (174 kg of C m^{-2} $year^{-1}$)	0	0
MG-V	15 (130 kg of C m^{-2} $year^{-1}$)	0	0.0056[f]

[a]The number in parenthesis represents the mean amount of biomass returned to the soil at harvest over the next 50 years. [b]We assumed that both root and rhizome died after harvest for corn and soybean only. Therefore, harvest practices do not affect root and rhizome biomass for switchgrass and miscanthus. [c]2011 fertilizer applications. The amount of fertilizer applied in the study site was used to drive the model from 2008 to 2011.[14] [d]Grain carbon was subtracted from the aboveground biomass, and only corn was fertilized. [e]2011 harvest litter treatments for corn, switchgrass, and miscanthus and 2010 harvest litter treatments for soybean.[27] [f]The amount of the fertilizer applied to switchgrass was used to analyze the impact of fertilization practices on soil carbon sequestration.

m^{-2}), and miscanthus (280 ± 29 g of C m^{-2}), SMB in the top 0.03 m was very different (13, 6, and 1 g of C m^{-2} on average in corn−corn−soybean rotation, switchgrass, and miscanthus, respectively). Lower SMB in the very top soil layer for switchgrass and miscanthus, which reduces decomposition rates, is the main reason for SOC accumulation.

The simulation results presented in Figure 4 show that higher inputs of litter in the corn−corn−soybean rotation at harvest did not induce considerable variation of SOC. On the other hand, the simulations show important changes in SOC for switchgrass and miscanthus when different amounts of biomass litter are returned to the soil. As expected, accumulation of SOC is enhanced when more biomass is left in the soil. However, a threshold in the fraction of returned biomass was discovered, beyond which the accumulation of SOC was accelerated. From the simulation, we identified that this threshold was around 25 and 15% of aboveground biomass for switchgrass and miscanthus, respectively.

As mentioned above, there are several factors that control the belowground carbon dynamics. However, the most important factor in the accelerated accumulation of SOC in switchgrass and miscanthus is the high aboveground C/N ratio of plant residues returned to the soil. Land use change from row crops to switchgrass and miscanthus with the amounts of litter beyond the thresholds, at harvest, will increase the C/N ratio of organic matter in the topsoil, reaching a point at which an additional input of nitrogen is required for microorganisms (immobilization) to sustain decomposition (see Figure S7 of the Supporting Information). This occurs because nitrogen in the soil organic matter is insufficient to maintain SMB growth at a fixed C/N ratio.

Soil Nitrogen. Figure 6 shows soil inorganic nitrogen (SIN) for corn−corn−soybean rotation, switchgrass, and miscanthus resulting from scenarios I and III over the next 50 years. Switchgrass and miscanthus show considerably lower SIN compared to the corn−corn−soybean rotation. The nitrogen uptakes from the soil by switchgrass and miscanthus were lower than from the corn−corn−soybean rotation. Similarly, the amounts of SIN were also less in the simulations performed for switchgrass and miscanthus. The lower levels of nitrogen uptake and SIN concentration in switchgrass and miscanthus can be explained to a great extent by the lessened net mineralization of nitrogen associated with the reduced decomposition observed in these crops caused by a reduction in SMB in the topsoil, as described above.

As expected, in the corn−corn−soybean rotation, we observed that increased harvest litter enhanced SIN (scenario CCS-III). A 48% increase in the litter input at the time of harvest resulted in a 22% higher SIN. This is explained by higher net mineralization rates attained when more biomass is returned to the soil. Similar patterns were observed for switchgrass and miscanthus below the critical threshold of harvest litter input mentioned above (not shown). However, we observed a reduction in SIN for these crops that was

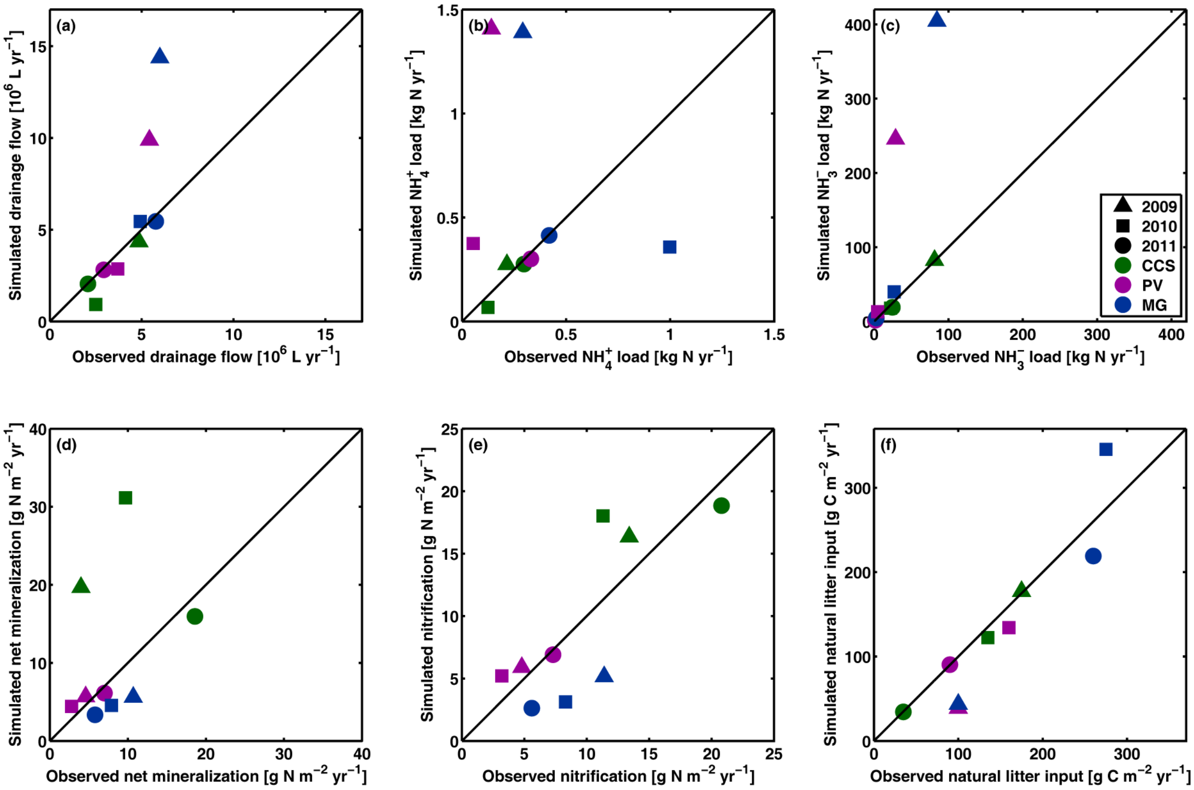

Figure 2. Comparisons of modeled and observed (a) drainage, (b) ammonium and (c) nitrate loads in tile drainge flows, (d) mineralization and (e) nitrification to the depth of 0.3 m, and (f) aboveground natural litter inputs from 2009 to 2011 for corn−corn−soybean rotation (CCS), switchgrass (PV), and miscanthus (MG). The black line is the 1:1 relationship.

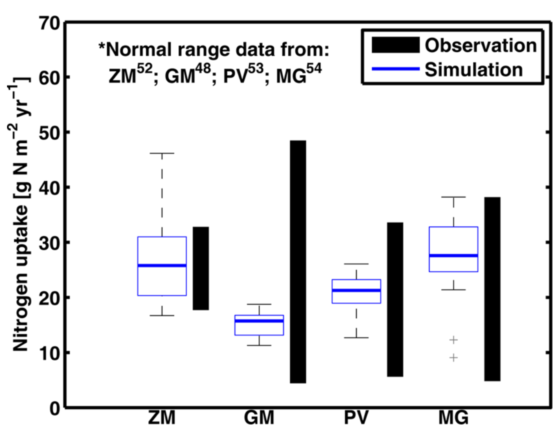

Figure 3. Nitrogen uptakes of corn (ZM), soybean (GM), switchgrass (PV), and miscanthus (MG) over 50 years of simulation with scenario I of harvest litter treatment are shown as boxplots, while the bar plots show the observed normal ranges in nitrogen uptakes from previous studies.[48,52−54]

triggered by a lessening of decomposition and mineralization. Specifically, reductions of 17 and 20% SIN for switchgrass and miscanthus, respectively, occurred in scenarios PV-III and MG-III compared to scenario I.

■ DISCUSSION

The main purpose of this study was to assess the impacts of bioenergy crops on the long-term biogeochemical cycling of carbon and nitrogen. We found that soil carbon and nitrogen dynamics are sensitive to the quantity of harvest litter. Specifically, the results obtained here highlight that there is a threshold effect on the carbon accumulation in the soil, which is dependent upon the biomass that is left after harvest. For switchgrass, it is 25% of the aboveground biomass, and for miscanthus, it is 15% of the aboveground biomass, beyond which the accumulation of carbon in the soil is significantly enhanced and nitrogen leaching is reduced. On the other hand, corn−corn−soybean rotation does not show such threshold effect.

The main factor influencing the accumulation of carbon is a high aboveground C/N ratio in the biomass that is contributed as litter from the switchgrass and miscanthus when harvested. A nitrogen-deficient environment in the topsoil hinders microbial growth and, therefore, decomposition. In addition, a lack of nitrogen fertilizer in miscanthus further enhances the accumulation of carbon in the soil. Thus, adding more than the threshold harvested biomass to the soil, if these crops are grown widely, can result in substantial atmospheric CO_2 sequestration into the soil, mitigating the atmospheric level of CO_2.

Rapid decreases of nitrogen loss in perennial crops have been widely reported.[23,25,55] While consistent with previous findings, our results also indicate that higher accumulations of carbon, according to the thresholds mentioned above, are also associated with lower SIN. In addition, we see that, in switchgrass and miscanthus, SIN was significantly reduced without severely suppressing the crop nitrogen uptake because of their capacity for nitrogen remobilization. Therefore, on the basis of the simulations performed in this study, we believe that switchgrass and miscanthus could further mitigate the leaching of reactive nitrogen out of agricultural watersheds, reducing eutrophication problems downstream.

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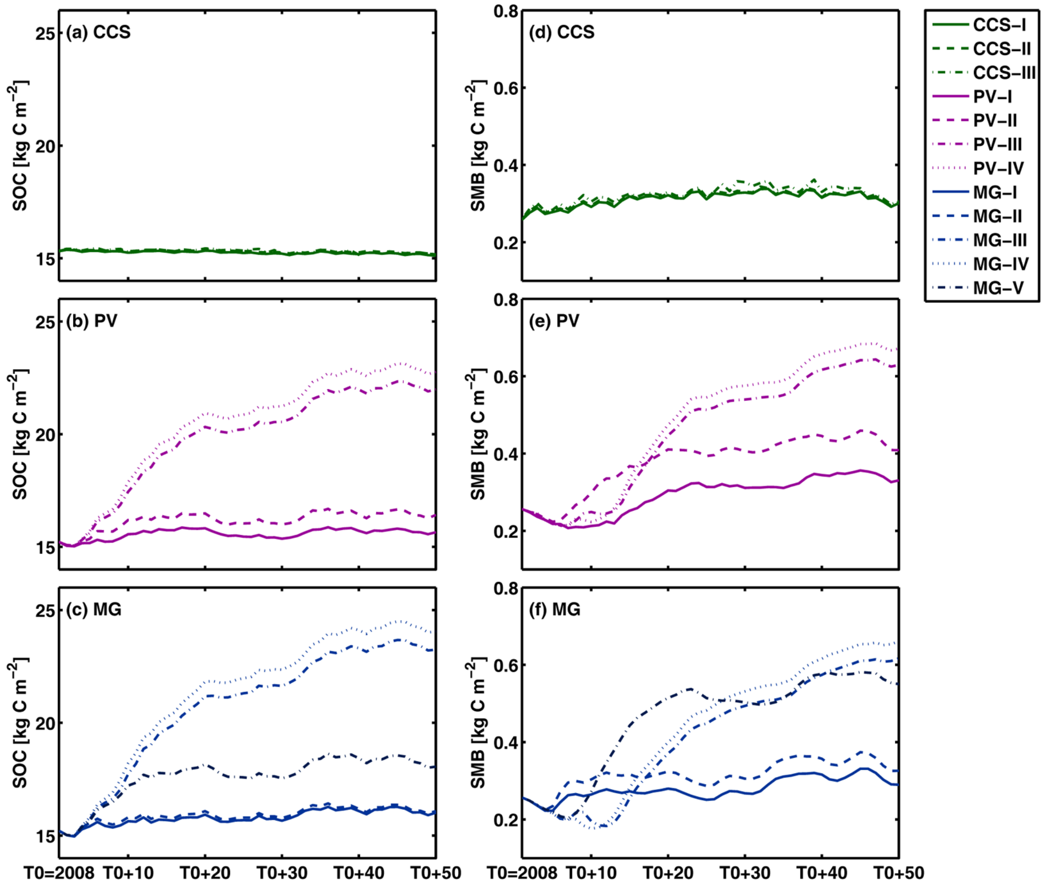

Figure 4. Projected (a–c) SOC and (d–f) SMB for corn–corn–soybean rotation (CCS), switchgrass (PV), and miscanthus (MG) over a 50 year simulation corresponding to different scenarios given in Table 1. The initial condition for all scenarios is the same.

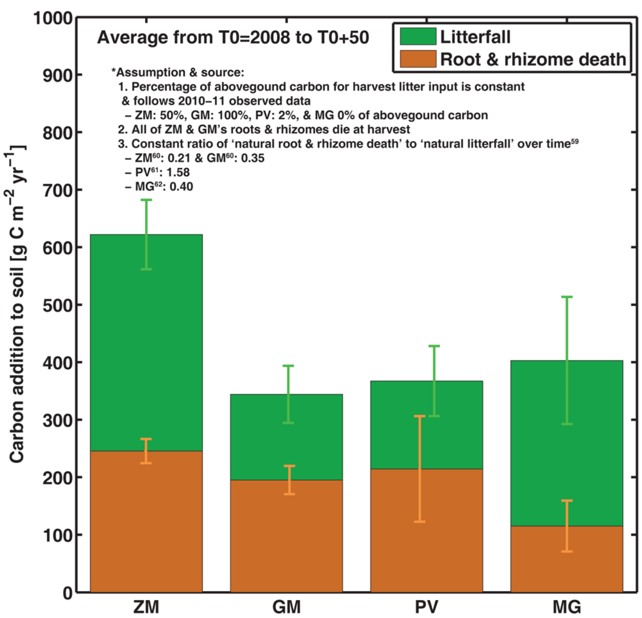

Figure 5. Mean annual values of above- and belowground litter inputs to the soil in corn (ZM), soybean (GM), switchgrass (PV), and miscanthus (MG). The average is computed over a period of 50 years of simulations and performed with scenario I of harvest litter treatments.[59−62] The amount of carbon that is added to the soil contains pre- and direct-harvest organic matter inputs.

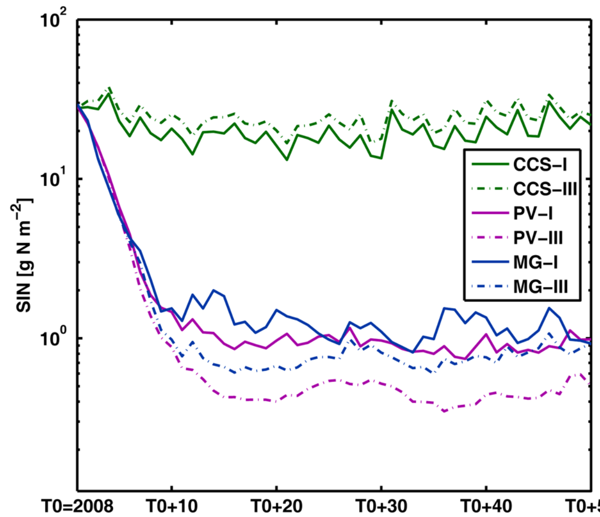

Figure 6. Projected SIN for corn–corn–soybean rotation (CCS), switchgrass (PV), and miscanthus (MG) over a 50 year simulation corresponding to different scenarios given in Table 1. The initial condition for all scenarios is the same.

In our analysis, litterfall and root death are assumed to be the only organic carbon and nitrogen sources for soil organic matter and SMB. Recent studies suggest that root exudates represent an important additional source of soil carbon and nitrogen dynamics, which, in turn, may impact the accumulation of SOC.[56,57] However, sufficient experimental data are not available to quantify the impact and magnitude of root exudates among the crops considered in this study. Therefore, root exudates were not considered in this analysis, and further experimental and numerical investigation should be performed to determine if this additional source enhances or lessens the dynamics observed in this study.

The depletion over time in soil nitrogen would limit crop biomass accumulation because crop nitrogen demands are not likely to be satisfied. The reduced biomass accumulation would consequently decrease SOC accumulation by reduced literfall and belowground crop production. However, the coupled model used in this study does not implement the feedback mechanism to account for the reduced crop biomass because of the soil nitrogen depletion over time, as shown in Figure S2 of the Supporting Information. However, it is worth mentioning that the differences in average nitrogen uptakes by switchgrass and miscanthus observed between scenarios I and IV are not significant (switchgrass, 1.57 g of N m^{-2} $year^{-1}$; miscanthus, 1.66 g of N m^{-2} $year^{-1}$) because of several factors, such as application of fertilizer in switchgrass, the capacity to fix nitrogen in miscanthus, and nitrogen remobilization in both. A detailed evaluation of the impacts of the soil nitrogen depletion feedback mechanism between soil states and plant growth is therefore beyond the scope of this study.

In the context of the rise in the global energy demand and atmospheric carbon dioxide concentration, switchgrass and miscanthus has become more and more important as a renewable source of fuel.[1−4] Our projections suggest that significantly higher SOC accumulation and reduced soil nitrogen loss can be achieved by switchgrass and miscanthus compared to corn−corn−soybean rotation. However, miscanthus and switchgrass transpiration rates are significantly larger than that of corn[36] and have the potential to impact the moisture and runoff rates. This tradeoff has to play an important role in decisions for adoption of suitable practices. The loss of microbial biomass in the topsoil, which is the main driver of the threshold effect, is also an undesirable condition because of its important role in regulating plant productivity and biodiversity.[58] These issues should be assessed together with the benefits of cultivating switchgrass and miscanthus mentioned above for the extensive land use conversion from the annual row crops to the bioenergy crops.

■ ASSOCIATED CONTENT

Supporting Information

Details on parameters and equations and additional figures. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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