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Energy sorghum biomass harvest thresholds and tillage effects on soil organic carbon and bulk density

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ABSTRACT

Bioenergy feedstock production systems face many challenges, among which is the lack of guidelines on sustainable biomass harvest thresholds and tillage cropping systems that maintain soil quality and productivity. We used the ALMANAC crop model to evaluate four biomass removal rates, 0%, 50%, 75% and 100%, and four tillage cropping systems, continuous No Till (NT), and Conventional Till (CT), and periodically plowed or subsoiled NT lands at Shorter, AL, for a Lynchburg loamy sand soil, over 51 yr of actual weather data: 1960–2010. Farmers periodically plow or subsoil NT lands to alleviate problems of drainage, pests, and soil compaction. Given the importance of soil organic carbon (SOC) as a soil quality indicator, we premised sustainability upon the maintenance of SOC at or above the initial SOC levels. As expected, NT had the highest SOC and lowest bulk density (BD) across the four biomass removal rates and gained the highest percent SOC over the 51-yr simulation period. For this study, the 75% biomass removal rate was applied sustainably on NT energy sorghum production systems, giving an annual harvestable biomass yield of 18.0 ± 0.9, residue biomass, 6.2 ± 0.3, and a root biomass of 7.2 ± 0.4 Mg ha^{-1}. However, the 75% removal rate also significantly increased soil bulk density, a critical indicator of soil compaction, by 30%. Compared to conventional tillage, subsoil tillage maintained SOC and better alleviated soil compaction in NT systems, but at the reduced biomass removal threshold of 50%. Long-term biomass removal resulted in reduced total biomass yields over time due to nutrient depletion as reflected by increased N stress days on subsequent crops. We attributed the N stress to N immobilization by the decomposing residues, reduced mineralization and N losses. Additional inputs will be needed to avoid increased N uptake from the soil which could result in soil mining.

1. Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] grown as a biomass feedstock crop, and often referred to as energy or biomass sorghum, could be the ideal feedstock for the cellulosic ethanol industry because of its robust establishment, broad adaptability and drought tolerance, water and nutrient use efficiency, and high annual biomass yields (Rooney et al., 2007; Venuto and Kindiger, 2008). Energy sorghum varieties are capable of producing high biomass yields because they are photoperiod sensitive, and can continue to grow vegetatively for more than 200 days in subtropical regions (Marsalis and Bean, 2011). Best management practices (BMPs) for energy sorghum production are relatively well documented, with some practices based on interpolations from forage, grain and sweet sorghum production guidelines (Blade Energy Crops, 2010; Mask et al., 1988; Marsalis and Bean, 2011). Of concern however, is the lack of published data on biomass harvest thresholds, tillage cropping system effects, and the subsequent impacts of reduced soil biomass inputs on soil organic carbon (SOC) storage and bulk density (BD). Reviews of the limited studies that have been conducted to determine permissible corn stover removal thresholds indicate that 30–50% of harvestable biomass can be removed without adverse effects on soil quality and the environment (Blanco-Canqui and Lal, 2007; Graham et al., 2007; Kim and Dale, 2004; Nelson, 2002). Assuming 53% of total aboveground biomass for corn is harvested as grain (Johnson et al., 2006a) then permissible corn biomass (grain + stover) removal thresholds would range from 67% to 74%. However, most of the above studies base sustainability

Abbreviations: ALMANAC, Agricultural Land Management and Numerical Assessment Criteria; NT, No Till; CT, Conventional Till; SS, Subsoiling.

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of stover removal thresholds on the need to control soil erosion, and not maintenance of SOC (Graham et al., 2007). According to Wilhelm et al. (2007), stover needed to maintain SOC, and thus productivity, are a greater constraint to environmentally sustainable cellulosic feedstock harvest than that needed to control water and wind erosion. Using biomass for bioenegy demands that we have accurate estimates of minimum source carbon (MSC) inputs to sustain long-term soil productivity, including biomass cover for erosion control (Johnson et al., 2006a).

Given the many positive attributes of conservation tillage and retention of crop residues; increased SOC storage, decreased net greenhouse gas (GHG) emissions and global warming, improved soil moisture retention, reduced sediment and nutrient losses by runoff, and decreased soil compaction (USDA NRCS, 2006), it is expected that sustainable energy sorghum cropping systems ought to include some form of conservation tillage, and that site-specific biomass harvest thresholds should maintain and not deplete SOC.

Indiscriminate biomass harvests could result in reduced residue biomass returns to the soil, which when coupled with repeated passes by traffic collecting and transporting the biomass off the field, could increase soil BD or compaction (Hakansson and Reeder, 1994; Raper, 2005). Studies by Voorhees (1983) in Minnesota suggest that even normal wheel traffic can result in soil compaction in No Till (NT) systems. Soil compaction reduces crop yields due to restricted root growth (Taylor et al., 1996), poor root zone aeration (Unger and Kaspar, 1994), restricted water infiltration (Potter et al., 1995), nutrient losses through increased water runoff and erosion (Kaspar et al., 2001; Young and Voorhees, 1982), and enhanced nitrogen (N) losses from denitrification (Johnson et al., 1986).

Subsoiling or deep tillage to below depths of 35 cm is commonly applied to alleviate the effects of soil compaction (Raper et al., 2005; Saveson and Lund, 1958). Subsoiling can however, be expensive and time consuming (Raper, 2005), necessitating alternative tillage methods. Moldboard plowing was very effective in ameliorating surface compaction in Minnesota (Voorhees et al., 1986). Although farmers periodically plow-back their conservation-tilled lands to alleviate problems of drainage, pests, and soil compaction (Causarano et al., 2008), not much is known about the potential impact of applying these tillage changes to conservation-tilled lands, especially as regards soil productivity and environmental integrity.

Crop simulation models provide researchers with an efficient way of obtaining realistic assessments of the effectiveness of new farm management strategies. To this end, we applied the Agricultural Land Management and Numerical Assessment Criteria (ALMANAC) biophysical model (Kiniry et al., 1992) to (i) evaluate sustainable energy sorghum feedstock harvest thresholds, based on the maintenance of SOC stocks and (ii) assess the effects of periodic moldboard plowing (MB), and subsoiling (SS) of conservation-tilled (No Till – NT) energy sorghum production systems on SOC storage and bulk density.

We chose the ALMANAC model because it has been used extensively to analyze plant community dynamics, phenology, water use efficiency, radiation use efficiency, crop grain and bioenergy feedstock yields (Engel et al., 2010; King et al., 1998; Kiniry et al., 2005, 2008; Persson et al., 2011). In addition, the model can be tailored to evaluate novel bioenergy feedstock crops such as energy sorghum, energy cane, etc. which have distinct growth habits but yet poorly understood crop traits or parameters.

2. Materials and methods

2.1. Description of the ALMANAC model

The ALMANAC model uses a daily time step to simulate various biophysical processes including crop growth and competition of plant communities, weather, hydrology, erosion, soil organic carbon, nutrient cycling (N&P), pesticide fate, and management practices. Four key databases are needed to run the model: Crop management; this includes information on land preparation, fertilizer application, planting, irrigation and harvesting, Weather data; can be generated within the model or downloaded from weather websites, such as the National Oceanic and Atmospheric Administration (NOAA), Soils data; can be downloaded from soils websites, such as the Soil Survey Geographic (SSURGO) database produced and distributed by the USDA Natural Resources Conservation Service (NRCS). The ALMANAC model has an inbuilt Crops parameter database which was developed from extensive field studies, the literature, and expert judgment. For all databases, default parameter values can be modified within set limits to describe new management, soils, crop, and weather scenarios.

The crop growth model component is particularly important to this study as it simulates light interception, energy conversion to total biomass, grain yield, partitioning into aboveground (shoots) and belowground (roots) biomass, key components in modeling SOC dynamics. In the model, crop growth is based on radiation interception and radiation-use efficiency (RUE). RUE is a function of the vapor pressure deficit and atmospheric CO_2, while radiation interception is defined by a preset curve of leaf area index evolution and an extinction coefficient (K_c) for photosynthetically active radiation (PAR). LAI evolution is simulated with a daily heat unit system that correlates plant growth with temperature. Actual crop growth is restricted by various stresses that include temperature, soil moisture, plant nutrients (N&P), aeration, salinity, pH, and soil strength. Included in this study is a discussion on the impact of biomass harvest on N stress. The N stress factor (like the P stress factor) is based on the ratio of simulated plant N contents to the optimal value. According to Jones (1983) the N stress factor varies non-linearly from 1.0 at optimal N contents to 0.0 when N is half the optimal level. The ALMANAC model counts the days on which N stress occurs and reduces potential crop yield by a fixed amount.

2.2. ALMANAC model calibration and evaluation

We calibrated and evaluated the ALMANAC model's ability to accurately simulate energy sorghum biomass yields by comparing simulated with measured yields from rainfed and irrigated energy sorghum field studies conducted at the USDA-ARS Dale Bumpers Small Farms Research Center, Booneville (93°:59′35″W, 35°:5′10″N), AR, the Gulf Coast Experiment Station, Fairhope (87°:52′55″W, 30°:32′56″N), AL, and the E.V. Smith Research Station, Shorter (85°:53′50″W, 32°:25′22″N), AL, USA, during the years: 2008–2010, by Snider et al. (2011) and Rocateli et al. (2012). The photoperiod-sensitive energy sorghum cultivar, *1990* was used in all the studies. The soil at Booneville, was a Leadvale silt loam (fine-silty, siliceous, semiactive, thermic Typic Fragiudult), Fairhope, a Malbis fine sandy loam (fine-loamy, siliceous, subactive, thermic Plinthic Paleudults), and Shorter, a Lynchburg loamy sand (fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults). The 2008 trial at Shorter, AL, consisted of four experiments which compared two tillage systems; moldboard plowing vs. subsoiling, under either rainfed or irrigated production (Table 1).

For model calibration and fine-tuning, we used the 2008 dataset for Shorter, AL (Table 1), because the study represented a typical biomass production scenario comparing rainfed and irrigated production. Furthermore, the study utilized the commercially recommended seeding rates of 407,700 seeds ha^{-1} for the 1990 cultivar (Rocateli et al., 2012). Using data from the literature, we created a 'new' crop of energy sorghum by modifying the ALMANAC inbuilt grain sorghum crop parameter template. We then compiled simulations to model the four trials at Shorter, AL, as described in Table 1. Simulations were run, using actual 2008 weather and

Table 1
Simulated tillage cropping systems, field management operations and inputs, and yield datasets for Shorter, AL, 2008. A total of four experiments were conducted; two tillage systems, moldboard vs. subsoiling, under either rainfed or irrigated production. N.B. The rainfed systems were similar to the irrigated, except for the irrigation inputs.

Tillage system	Field operation	Date	Depth/amount	Biomass yield (Mg ha^{-1})
[a]Moldboard plowing (CT)	Fertilizer (N)	4/18/2008	14 kg ha^{-1}	
	Fertilizer (P)	4/18/2008	4 kg ha^{-1}	
	Moldboard plow[a]	2/21/2008	20–30 cm	
	Irrigated	4/21/2008	12 mm	
	Plant	2/21/2008		
	Fertilizer (N)	5/15/2008	110 kg ha^{-1}	
	Irrigated	5/7/2008	8 mm	
	Irrigated	6/9/2008	24 mm	
	Irrigated	6/22/2008	32 mm	
	Irrigated	7/6/2008	30 mm	
	Irrigated	7/20/2008	25 mm	
	Harvest – irrigated	10/9/2008		27.18
	Harvest – rainfed	10/9/2008		22.14
Subsoiling (SS)	Fertilizer (N)	4/18/2008	14 kg ha^{-1}	
	Fertilizer (P)	4/18/2008	4 kg ha^{-1}	
	In-row subsoiler	2/21/2008	35–40 cm	
	Irrigated	4/21/2008	12 mm	
	Plant	2/21/2008		
	Fertilizer (N)	5/15/2008	110 kg ha^{-1}	
	Irrigated	5/7/2008	8 mm	
	Irrigated	6/9/2008	24 mm	
	Irrigated	6/22/2008	32 mm	
	Irrigated	7/6/2008	30 mm	
	Irrigated	7/20/2008	25 mm	
	Harvest – irrigated	10/9/2008		28.39
	Harvest – rainfed	10/9/2008		21.32

[a] Moldboard plowing (MB) represents conventional tillage (CT) in the ALMANAC model.

the USDA NRCS SSURGO soils data. We systematically adjusted the ALMANAC inbuilt default crop parameters based on data from the literature and by following the parameter estimation method of Hunt et al. (1993); the crop parameters are estimated iteratively by running the appropriate model with approximate parameters, comparing the simulated model output (e.g. dry biomass yields) to actual data, and then altering the crop parameter until the predicted and measured values match. The 'new' crop parameters represented the energy sorghum crop in the model. To achieve the best-fit relationship, we also adjusted the residual N for the Lynchburg loamy sand soil on which the study was conducted, by an equivalent of 75 kg N ha^{-1}, which in the model had reflected an N stress of approximately 45 days.

We then tested the calibrated ALMANAC model for its accuracy and versatility to simulate energy sorghum biomass yields, with data from a rainfed experiment by Snider et al. (2011) which evaluated the effects of row spacing on energy sorghum biomass yields (Table 2). For each site-year, we simulated three inter-row spacings, 19 cm, 38 cm and 76 cm (high, medium and low plant population, respectively), by assigning an appropriate light extinction coefficient (K_c value) to each inter-row spacing based on linear regression extrapolations of K_c against row spacing as implied in Flénet et al.

Table 2
Simulated energy sorghum inter-row spacings, estimated K_c values, tillage cropping systems and field management operations, inputs and amounts, and yield datasets for Booneville, AR, 2010, and Fairhope, AL, 2009–2010.

Location	Year	Row spacing[a]	Estimated K_c[b]	Field operation	Date of operation	Depth/amount	Biomass yield (Mg ha^{-1})
Booneville, AR	2010	76 cm	0.24	No Till	–		15.43
		38 cm	0.48	Fertilizer (N)	6/2/2010	72 kg ha^{-1}	17.72
		19 cm	0.60	Fertilizer (P)	6/2/2010	72 kg ha^{-1}	32.88
				Plant	6/3/2010		
				Fertilizer (N)	6/30/2010	78 kg ha^{-1}	
				Harvest	10/25/2010		
Fairhope, AL	2010	76 cm	0.24	Moldboard plow	3/15/2010	20–30 cm	16.9
		38 cm	0.48	Fertilizer (N)	4/28/2010	27 kg ha^{-1}	28.33
		19 cm	0.60	Fertilizer (P)	4/28/2010	67 kg ha^{-1}	61.14
				Tandem disk	5/4/2010	8–15 cm	
				Plant	5/5/2010		
				Fertilizer (N)	5/27/2010	135 kg ha^{-1}	
				Harvest	10/6/2010		
Shorter, AL	2009	76 cm	0.24	Tandem disk	4/28/2009	15–20 cm	18.23
		38 cm	0.48	Field cultivator	2/28/2009	15–20 cm	31.52
		19 cm	0.60	Fertilizer (N)	4/28/2009	45 kg ha^{-1}	31.91
				Fertilizer (P)	4/28/2009	46 kg ha^{-1}	
				Plant	4/30/2009		
				Fertilizer (N)	5/29/2009	123 kg ha^{-1}	
				Harvest	11/6/2009		

[a] Inter-row spacing: 19 cm – high, 38 cm – medium, 76 cm – low plant population.
[b] Estimates based on linear regression extrapolations of K_c against row spacing as implied in Flénet et al. (1996).

Table 3
Initial soil conditions for a few selected soil variables for the simulated Lynchburg loamy sand at Shorter, AL. The soil properties were compiled from the USDA NRCS SSURGO database.

	Soil layer number									
	1	2	3	4	5	6	7	8	9	10
Depth (m)	0.01	0.10	0.19	0.29	0.38	0.53	0.67	0.96	1.55	2.03
Porosity (mm)	0.45	0.45	0.45	0.45	0.45	0.47	0.47	0.47	0.47	0.48
Field capacity (mm)	0.19	0.19	0.19	0.19	0.19	0.24	0.24	0.24	0.24	0.27
Wilting point (mm)	0.10	0.10	0.10	0.10	0.10	0.16	0.16	0.16	0.16	0.20
Soil water (mm)	0.17	0.17	0.17	0.17	0.17	0.22	0.22	0.22	0.22	0.25
Saturated conductivity (mm/h)	100.80	100.80	100.80	100.80	100.80	32.40	32.40	32.40	32.40	32.40
BD 33kPA (t m^{-3})	1.45	1.45	1.45	1.45	1.45	1.40	1.40	1.40	1.40	1.38
BDD oven dry soil (t m^{-3})	1.52	1.52	1.52	1.52	1.52	1.47	1.47	1.47	1.47	1.44
Sand (%)	67.30	67.30	67.30	67.30	67.30	55.40	55.40	55.40	55.40	51.50
Silt (%)	20.20	20.20	20.20	20.20	20.20	17.60	17.60	17.60	17.60	13.50
Clay (%)	12.50	12.50	12.50	12.50	12.50	27.00	27.00	27.00	27.00	35.00
Rock (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
pH	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60
Soil organic carbon (%)	0.74	0.74	0.74	0.74	0.74	0.15	0.15	0.15	0.15	0.15

(1996). The ALMANAC model accounts for the effect of row spacing through the potential LAI and light interception. LAI normally increases with increasing planting density or when row spacing is reduced. Light intercepted by a crop canopy (IPAR) is calculated from Beer's Law equation: IPAR = PAR × [1 − exp (−k × LAI)], where k is the light extinction coefficient (K_c value). For most crops, the effect of row spacing on k is described by a linear regression (Flénet et al., 1996). Similarly, we adjusted the residual N for the Malbis fine sandy loam at Fairhope, AL, and the Leadvale silt loam at Booneville, AR, by 75 kg N ha^{-1} in order to achieve the best-fit relationship between measured and simulated energy sorghum biomass yields.

2.3. Model simulations

We used the calibrated and tested ALMANAC model to evaluate energy sorghum feedstock harvest thresholds, and tillage cropping systems effects on SOC and BD for a Lynchburg loamy sand (Table 3). Although the natural fertility and SOC content are low, crops generally respond well to recommended applications of fertilizer and lime.

Model simulations were conducted for Shorter, AL, for combinations of four biomass removal rates; 0%, 50%, 75% and 100%, for rainfed NT systems that were conventionally tilled (NTCT) or subsoiled (NTSS) after every 4 yr (Table 4) over a 51-yr time series of actual weather data; 1960–2010. The 0% and 100% biomass removal rates were included for impact evaluation purposes. According to Meki et al. (2011), harvesting less than 40% of crop residue is not likely to be economical, given cost of the equipment operation, whereas collection of more than 80% is nearly impossible without some specialized equipment. In the model we simulated harvestable biomass removal using a forage harvester with a harvest recovery efficiency of 0.95. For purposes of this study, we assigned the three rates of biomass removal of 50%, 75%, and 100%, to represent the biomass that is recovered at harvest, as a proportion of the total aboveground biomass yield with no biomass removal at all (0% biomass removal rate). In the model the residue biomass was either left lying on the soil surface (NT) or incorporated into the soil by moldboard plowing (CT) or subsoiling (SS). We also simulated continuous NT (NTNT) and CT (CTCT) systems as baselines for comparison.

Designing sustainable biomass feedstock production systems requires accurate estimates of residual and root biomass for soil erosion control and maintenance of SOC. There is little published data that can be used to fully understand the role and contribution of root biomass to SOC. An accurate accounting of total root C sources is critical for assessing the overall plant-derived C inputs into the soil (Johnson et al., 2006b). Through simulation modeling, it is possible to estimate the contribution of root biomass to SOC. The fraction of total biomass partitioned to the root system normally decreases from 0.3 to 0.5 in the seedling to 0.05–0.2 at maturity (Jones, 1985). In the ALMANAC model, as is also the case in the sister model, EPIC (Williams, 1995), this partitioning is simulated by decreasing the fraction linearly from emergence to maturity, while rooting depth is simulated as a function of heat units and potential root zone depth. The change in root weight through the root zone is simulated as a function of plant water use and root weight in a given soil layer.

2.4. Data analysis

We applied mean separation statistics – confidence limits, standard deviations, and standard errors for the mean at $P \leq 0.05$ and 0.001 probability levels (Snedecor and Cochran, 1989), and regression analysis using the PROC REG procedure in SAS (SAS Institute, 2007) to determine biomass harvest rates and tillage cropping systems effects on simulated harvested biomass yields, residue biomass, root biomass, SOC storage and bulk density. We used Fisher's Paired t test to assess differences between measured and simulated dry biomass yields.

Table 4
Simulated tillage cropping systems field management operations for conventionally tilled (CT) continuous No Till (NTCT) or subsoiled (SS) No Till (NTSS) energy sorghum cropping systems. The long-term impacts were assessed over a 51 year time series: 1960–2010.

Years	FOS[a]	NTCT[b]/NTSS[c]
One → Four	1	Herbicide application
	2	Fertilizer application
	3	Planting
	4	Pesticide application
	5	Herbicide application
	6	Harvesting
Five → Five	1	Herbicide application
	2	[d]Subsoiling OR moldboard plowing
	3	Fertilizer application
	4	Planting
	5	Pesticide application
	6	Herbicide application
	8	Harvesting

[a] Field operation sequence.
[b] Continuous No Till (NT) for 4 yr, with Conventional Tillage (Moldboard plowing) in fifth yr.
[c] Continuous No Till (NT) for 4 yr, with Subsoiling (SS) in fifth yr.
[d] Subsoiling is tillage below 35 cm soil depth (ASAE, 1999) whereas Conventional Tillage is usually <35 cm soil depth.

Table 5
Calibration of the ALMANAC model. Adjusted grain sorghum parameters (default values) for simulation of energy sorghum (adjusted values) at Shorter, AL, USA (85°53′50″W, 32°25′22″N).

Parameter	Comment	Default value	Adjusted value
Biomass-energy ratio (Mg ha^{-1} MJ^{-1} m^{-2})	Potential growth rate per unit of intercepted PAR	37.2	50.0
Leaf Area Index (LAI)	LAI adjusted to reflect more PAR interception	3.5	6.0
Harvest index	HI for grain sorghum adjusted to fit biomass harvests	0.45	0.90
Plant height (m)	Photoperiod sensitivity allows energy sorghum to continue to grow vegetatively.	1.40	3.00
Light extinction coefficient (K_c)	Energy sorghum has a bigger light intercepting canopy compared to grain sorghum	0.47	6.00

3. Results and discussion

3.1. ALMANAC model calibration and evaluation

We identified five main crop parameters in the grain sorghum crop parameter template that needed adjusting, in order to accurately simulate the measured biomass yields of the 'new' Energy sorghum crop; biomass energy ratio, leaf area index (LAI), harvest index (HI), plant height, and the light extinction coefficient (K_c) (Table 5). The maximum radiation-use efficiency used for energy sorghum was 6.0 g biomass MJ^{-1} PAR, whereas the default value in the model's inbuilt grain sorghum crop parameter template was 3.7 g biomass MJ^{-1} PAR. We adjusted the default LAI value of 3.5–6.0 which implies more PAR interception and hence high biomass accumulation in energy sorghum compared to grain sorghum. Energy sorghum can grow up to more than 3 meters. The HI was adjusted to reflect biomass harvest as opposed to grain. The higher K_c value reflects more light interception by a more robust energy sorghum canopy.

Simulated and measured energy sorghum dry biomass yields were highly correlated, $R^2 = 0.95$, $P \leq 0.05$ (Fig. 1). In addition, the calculated Paired t test statistic of 0.29, with 11 degrees of freedom (Table 6), shows that there were no significant differences ($P \leq 0.05$) between simulated and measured yields. Overall, the ALMANAC model was able to predict biomass yields with acceptable accuracy with a mean simulation percent error of <1 (0.72%). Both the slope and intercept of the regression line shown in Fig. 1 were not significantly different from 1 and 0, respectively. The model managed to provide a good representation of biomass yields under different water availability scenarios as shown by the accurate biomass yield predictions under both rainfed and irrigated production, and across the three planting populations (Fig. 1). Furthermore, we demonstrated the versatility of the ALMANAC model by accurately simulating the effect of the three inter-row spacings, 19, 38, and 76 cm, on biomass yields by assigning the appropriate light extinction coefficient (K_c value) (Table 2) based on linear regression extrapolations of K_c against row spacing as implied in Flénet et al. (1996).

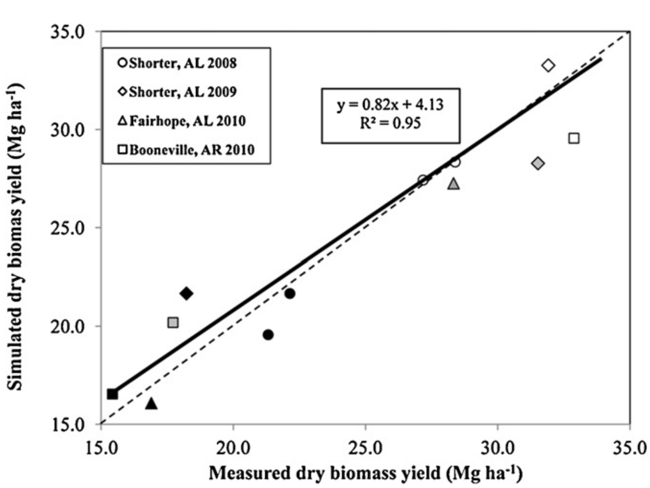

Fig. 1. ALMANAC model calibration and validation: simulated and measured energy sorghum dry biomass yields in rainfed (●) and irrigated (○) systems, and at three planting populations: low – black infill, medium – gray infill, and high – no infill. The dark line represents the regression line and the dashed line is the 1:1 line through the origin.

3.2. Harvested dry biomass, residues, root biomass, and total soil biomass inputs

Statistically, there was no tillage cropping system effect on any of the variables (Table 7). Averaged across tillage cropping systems, the 50%, 75% and 100% biomass removal rates yielded 14.3, 18.2, and 25.1 Mg biomass ha^{-1}, respectively. For this study, our simulated biomass yields at the 100% rate of removal were consistent with rainfed energy sorghum yields reported elsewhere; 20.0–29.0 Mg ha^{-1} (Habyarimana et al., 2004), 26.8 Mg ha^{-1} (Propheter et al., 2010), 26.0–30.1 Mg ha^{-1} (Rocateli et al., 2012), and 25.3 Mg ha^{-1} (Ra et al., 2012). Similarly, our average estimate of root biomass with no residue removal of 10.7 Mg ha^{-1} is within the range of values reported for forage crops (6.8–14.4 Mg ha^{-1}) by Bolinder et al. (2002). Despite the importance of root biomass in SOC dynamics, it is often overlooked because it is difficult to measure under field conditions. Simulation modeling provides a tool by which realistic estimates can be obtained. On average, root biomass respectively contributed 24%, 37%, 54%, and 95% of total soil biomass inputs when biomass was removed at 0%, 50%, 75%, and 100%. Literature reviewed by Wilhelm et al. (2004) shows that roots contribute more than half the soil C inputs. Furthermore, studies by Angers et al. (1995), Barber and Martin (1976), and Flessa et al. (2000) show that only 11% of aboveground biomass residues are returned as SOC, whereas 37% of root biomass is returned as SOC. The higher lignin content of roots means they have a slower rate of decomposition relative to shoots, resulting in a longer residence time of root derived C in the soil (Balesdent and Balabane, 1996; Huggins et al., 1998).

Over time, there is a decline in biomass productivity if the energy sorghum production system is not augmented with external inputs, such as increased fertilizer, cattle or poultry manure, or cover crops (Fig. 2). From Fig. 2, it would appear that total biomass declines faster than the more stable root biomass as described by the fitted quadratic functions (Table 8), results which are consistent with observations by Huggins et al. (1998) and Balesdent and Balabane (1996) mentioned above. The biomass removal rates of 50%, 75% and 100% reduced overall biomass yields and soil biomass inputs (residue biomass + roots) over the 51-yr simulation period

Table 6
Comparison of measured and simulated energy sorghum dry biomass yields (Mg ha^{-1}).

Statistic	Dry biomass yields
Mean error (measured – simulated)	0.17
Standard deviation of error	2.07
Paired t statistic	0.29
Degrees of freedom	11
Pr > |t|	0.78

Table 7
Simulated tillage cropping system and biomass removal rate effect on energy sorghum harvested dry biomass, residues, root, and total soil biomass inputs. Data values are annual averages based on a 51-yr simulation time series: 1960–2010. ± Mean confidence limits at $p \leq 0.05$.

Tillage system	Biomass				
	Removal rate	Harvested Mg ha^{-1}	Residue Mg ha^{-1}	Roots Mg ha^{-1}	Soil inputs Mg ha^{-1}
NTNT[a]	0%	0 ± 0.0	35.8 ± 1.0	10.6 ± 0.3	46.4 ± 1.4
	50%	14.3 ± 0.5	14.8 ± 0.5	8.6 ± 0.3	23.5 ± 0.8
	75%	18.0 ± 0.9	6.2 ± 0.3	7.2 ± 0.4	13.4 ± 0.6
	100%	26.4 ± 1.7	0.5 ± 0.0	8.0 ± 0.5	8.5 ± 0.6
CTCT[b]	0%	0 ± 0.0	36.2 ± 1.0	10.7 ± 0.3	46.9 ± 1.4
	50%	14.3 ± 0.5	14.8 ± 0.5	8.7 ± 0.3	23.5 ± 0.8
	75%	18.3 ± 0.8	6.3 ± 0.3	7.3 ± 0.3	13.6 ± 0.6
	100%	23.2 ± 1.5	0.4 ± 0.0	7.0 ± 0.4	7.4 ± 0.4
4 yr NT + 1 yr CT (NTCT[c])	0%	0 ± 0.0	36.1 ± 1.0	10.7 ± 0.3	46.8 ± 1.4
	50%	14.3 ± 0.5	14.8 ± 0.5	8.6 ± 0.3	23.4 ± 0.8
	75%	18.3 ± 0.7	6.3 ± 0.2	7.3 ± 0.3	13.6 ± 0.5
	100%	25.4 ± 1.7	0.4 ± 0.0	7.7 ± 0.5	8.1 ± 0.5
4 yr NT + 1 yr SS (NTSS[d])	0%	0 ± 0.0	36.1 ± 1.0	10.7 ± 0.3	46.8 ± 1.4
	50%	14.3 ± 0.5	14.8 ± 0.5	8.7 ± 0.3	23.5 ± 0.8
	75%	18.2 ± 0.7	6.3 ± 0.3	7.3 ± 0.3	13.6 ± 0.5
	100%	25.3 ± 1.6	0.4 ± 0.0	7.6 ± 0.5	8.0 ± 0.5

[a] Continuous No Till.
[b] Continuous Conventional Till.
[c] Continuous No Till (NT) for 4 yr, with Conventional Till (Moldboard plowing) in fifth yr.
[d] Continuous No Till (NT) for 4 yr, with Subsoiling (SS) in fifth yr.

Table 8
Regression statistics and fitted regression equations describing the long-term impacts of biomass removal on total and root biomass. Both the quadratic and linear terms are significant at <0.0001.

Variable	Regression statistics				
	Parameter	Estimate	Standard error	*t* Value	Pr > |*t*|
Total biomass (Tb)	Intercept	59.29	1.11	53.40	<.0001
	Br[a]	−14.51	1.01	−14.33	<.0001
	Br*Br	1.91	0.20	9.58	<.0001
	Fitted equation	$Tb = 1.91Br^2 - 14.51Br + 59.29$			
Root biomass (Rb)	Intercept	13.56	0.26	52.12	<.0001
	Br	−3.32	0.24	−13.97	<.0001
	Br*Br	0.44	0.05	9.34	<.0001
	Fitted equation	$Rb = 0.44Br^2 - 3.32Br + 13.56$			

[a] Biomass removal rate.

by 17%, 28%, 31%, and 49%, 70%, 82%, respectively. Higher biomass removal rates can drastically reduce the pool of nutrients available for crop nutrient uptake and cycling, resulting in reduced plant growth, overall biomass yields, and the total amount of biomass that is returned to the soil over time (Fig. 2 and Table 7). Similar results were reported by Blanco-Canqui and Lal (2009); corn residue removal at 50% and 100% reduced grain yield by 1.8 and 3.3 Mg ha^{-1} yr^{-1}, respectively.

In this study, soil N nutrient pool depletion was reflected in the average annual N stress days suffered by the crop (Fig. 3). Tillage cropping system (NTNT vs. CTCT) and climatic factors influenced the number of N stress days experienced by the simulated energy sorghum crop, and this is also reflected in the huge inter-annual variation in N stress days at the different biomass removal rates. High residue biomass retention can result in N immobilization (Table 9), which could also cause N stress. For this study, however,

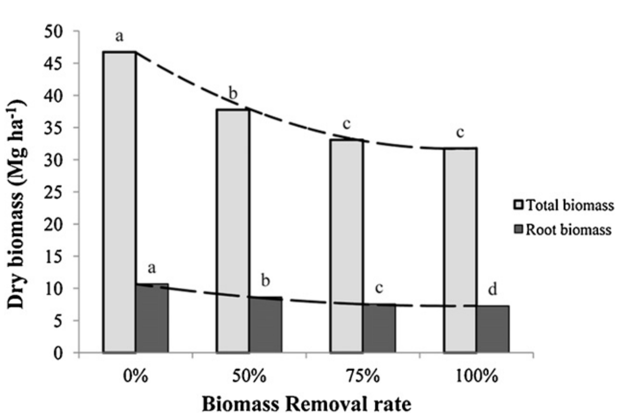

Fig. 2. Long-term impacts of biomass removal on energy sorghum total biomass (aboveground + roots) and root biomass. Data values are annual averages based on a 51-yr simulation period: 1960–2010. For each variable, data values with the same letter are not significantly different at $P \leq 0.05$.

Table 9
Effects of biomass removal on nitrogen (N) mineralization, immobilization, uptake and net balance. ± Standard deviations at $P \leq 0.001$.

	Biomass removal rate (kg ha^{-1})			
	0%	50%	75%	100%
Applied N	199	199	199	199
Mineralized N	672 ± 8	243 ± 2	83 ± 1	−2 ± 2
Immobilized N	341 ± 4	174 ± 2	85 ± 2	72 ± 3
N uptake	412 ± 3	274 ± 1	224 ± 2	204 ± 5
Net N balance[a]	0 ± 0	0 ± 0	−67 ± 3	−3460 ± 3

[a] The net N Balance takes into account total N losses (data not shown, but accounted for in the model simulation outputs) from the cropping systems.

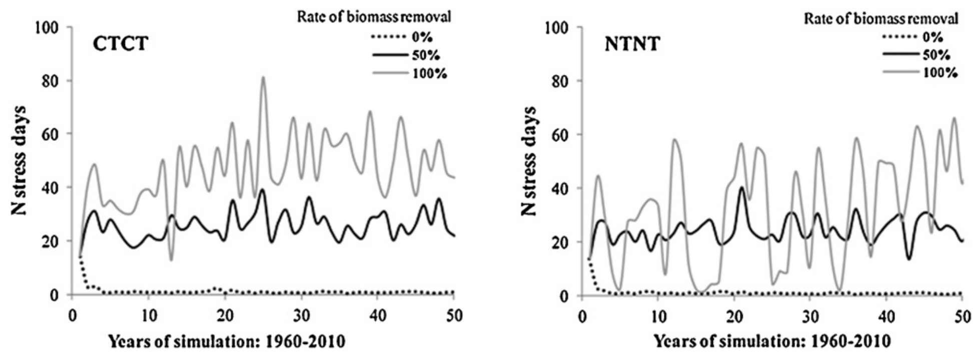

Fig. 3. Average annual number of nitrogen stress days by tillage system: No Till (NT) and Conventional Till (CT), and energy sorghum biomass removal rate: 0%, 50%, and 100%.

retention of all biomass (0% removal rate) shows almost no N stress at all under both NTNT and CTCT (Fig. 3). On average, the 50% and 100% biomass removal rates increased N stress for NTNT and CTCT by 24 and 33 days, and by 26 and 47 days, respectively. The difference between tillage systems was due to the interacting effect of other stresses other than N, such as water and temperature stress which were generally higher under CTCT compared to NTNT (data not shown). Overall, increasing biomass removal reduced both N immobilization and mineralization (Table 9), and when N uptake and N losses were also accounted for (data not shown), resulted in negative N balances at the 75% and 100% removal rates. According to Power and Doran (1988), increasing residue return to the soil, increases total N immobilization, implying that higher N additions are needed to avoid soil mining for residue decomposition. A study by Beri et al. (1995) showed reduced wheat and rice yields due to low plant available N&P, induced by N&P immobilization during residue decomposition.

The impacts of biomass removal on soil nutrient depletion have been widely documented (Blanco-Canqui and Lal, 2009; Fixen, 2007; Karlen et al., 1994; Larson et al., 1972). According to the USDA (1978), crop residues contain valuable nutrients that represent 40, 10, and 80% of the N, P and K, respectively, of the fertilizer applied to all crops in the US. Fixen (2007) estimated that removal of corn residues at 40% would reduce the soil N content by 20%, P by 14%, and K by 110% in the US Corn Belt region. Furthermore, biomass residue removal removes more nutrients from the agroecosystem than grain harvest alone (Andrews, 2006). This reduction in nutrient pools with biomass removal has been directly correlated with long-term reduction in crop yields (Blanco-Canqui and Lal, 2009). Some beneficial tradeoffs from harvesting biomass have also been noted. According to Meki et al. (2011) biomass removal reduced the pool of nutrients available for loss resulting in decreased non-point-source nutrient losses, while Pantoja et al. (2011) observed increased corn yields and reduced N stress when corn residues were removed, and attributed this to reduced N immobilization associated with decomposition of high C:N ratio corn residues.

3.3. Soil organic carbon

3.3.1. Tillage cropping system effects

Soil organic carbon storage was hugely impacted by both tillage cropping system and rate of biomass removal (Fig. 4). As expected, SOC storage under NTNT (4a) was on average higher than that under CTCT (4b). Differences were significant and most pronounced in the top 40 cm of the soil profile, which when averaged across biomass removal rates, NTNT had a 21% higher SOC storage than CTCT. Our simulated results are similar to those reported by Follet (2001), West and Post (2002), and several others in the literature. Differences in SOC storage are the result of disturbance of the soil through plowing (or subsoiling) which in the model increases organic matter decomposition rates, and tillage-induced SOC losses in sediment erosion (data not shown). Six et al. (2000) proposed a model to explain the differences in SOC storage under NT and CT. In summary, under NT, SOC is protected from microbial decomposition through formation of stable microaggregates, whereas CT disrupts microaggregate formation, and increases SOC exposure to microbial decomposition. For this study, SOC storage differences between tillage cropping systems seem to disappear at soil depths greater than ~50 cm. As expected, SOC storage in the top 20 cm of the soil profile is higher in continuous NT, with no biomass removal (Fig. 4a), when compared to NTSS (Fig. 4d), whereas the reverse is true when considering the 20–50 cm depth. Subsoiling relocates SOC to deeper depths.

Although environmental concerns and economic incentives induce farmers to adopt NT practices, farmers often rotate tillage systems to optimize yields and alleviate pests and soil problems such as compaction, and drainage. Fig 4c and d illustrates the effects of periodically plowing back (NTCT), and subsoiling (NTSS) NT lands. Compared to NTNT, NTCT and NTSS tillage systems resulted in pronounced decreases in SOC storage in the top 20 cm of the soil profile of 29% and 18%, respectively. However, both tillage systems had higher total percent SOC than CTCT. Furthermore, both NTCT and NTSS maintained total SOC storage above the initial levels over the 51-yr simulation period. Similar reductions in SOC with one-time tillage of NT land were reported by Stockfisch et al. (1999). VandenBygaart and Kay (2004) conducted an experiment to determine the change in SOC when long-term (22 yr) NT lands in southern Ontario, Canada were moldboard-plowed once. Out of four soil textural classes, they noted a loss of about 3 Mg C ha^{-1} in the 15–30 cm depths of a sandy loam soil after only 18 mo. Plowing resulted in a redistribution of SOC in the top soil profile with no significant change in SOC when the whole profile was considered. This is consistent with the results of Pierce et al. (1994) and Kettler et al. (2000) who also observed no significant changes in SOC (after 4 yr and 5 yr, respectively), after a single plow of NT lands. Six et al. (2002) suggest that a single CT event is not sufficient to cause significant breakdown of SOC locked up in soil aggregates. Unfortunately, most reported field data on SOC dynamics are based on short term studies and in most cases only consider the top 30–40 cm of the soil profile.

3.3.2. Effects of biomass removal rate

The long-term impacts of energy sorghum biomass removal on SOC storage under the four tillage cropping systems are shown in Fig. 4. Overall, differences in SOC storage were most apparent in the top 50 cm of the soil profile and were directly proportional to the soil biomass inputs. Averaged across tillage cropping systems, SOC storage gains of 49% and 7% were observed with no biomass

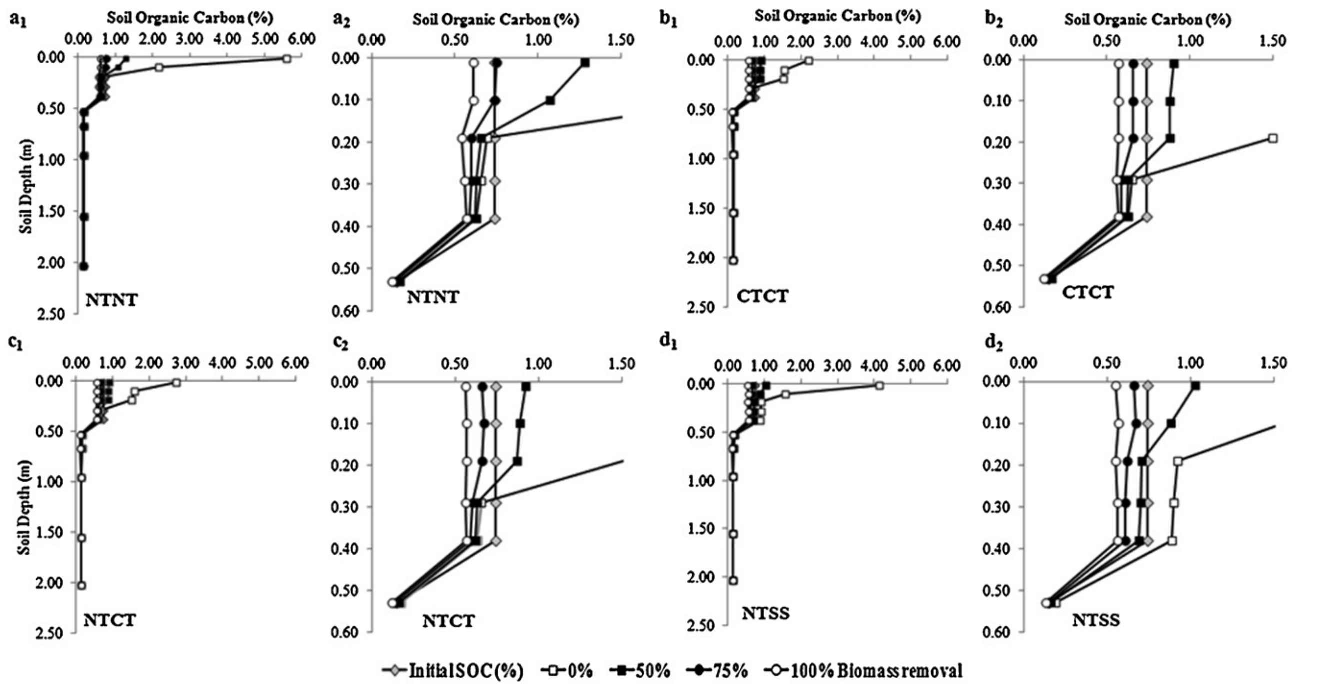

Fig. 4. Simulated long-term (51 yr) impacts of energy sorghum biomass removal on SOC storage under continuous No Till (NTNT), continuous Conventional Till (CTCT), and NTCT: four years of NT followed by one year of Conventional Till (CT), and NTSS: four years of NT followed by one year of subsoiling (SS). The second set of figures (a_2, b_2, c_2 and d_2) is included to clearly visualize responses in the congested parts of the primary figures (a_1, b_1, c_1 and d_1).

removal and at the 50% removal rate, respectively, whereas losses of 15% and 28% were obtained at the 75% and 100% biomass removal rates, respectively. These gains and losses were relative to the initial SOC assuming no energy sorghum cropping. For NTNT, the 0% and 50% biomass removal rates increased SOC levels above the initial SOC levels in the top 20 cm of the soil profile, while SOC levels for the 75% removal rate were similar to initial levels, but only in the top 10 cm of the soil profile. At the 100% biomass removal rate, SOC losses were obtained throughout the whole soil profile. As for CTCT, NTCT, and NTSS, only the 0% and 50% biomass harvest rates maintained SOC storage above the initial SOC levels, but only in the top ~25 cm of the soil profile. The 75% and 100% biomass removal rates had SOC levels below the initial SOC levels. To minimize SOC loss due to plowing and subsoiling NT lands, farmers will have to consider applying various strategies, such as lowering the biomass removal threshold, applying cattle or poultry manure, or incorporating cover crops in the cropping system. The use of winter cover crops in corn-soybean rotations enhanced SOC concentration, reduced soil compaction, increased aggregate stability, improved soil water retention and nutrient pools (Villamil et al., 2006).

Our simulated permissible biomass removal threshold range of 50–75% (i.e. based on no adverse effects on SOC storage) for the four tillage cropping systems compares reasonably well with perceived corn total aboveground biomass (grain + stover) removal thresholds for the U.S. Corn Belt region of between 67% and 74%, assuming a corn HI of 0.53 (Johnson et al., 2006b). For the current study, the 75% biomass removal rate can sustainably be applied on continuous NT energy sorghum production systems, assuming an annual harvestable biomass yield of 18.0 ± 0.9, residue biomass, 6.2 ± 0.3, and a root biomass of 7.2 ± 0.4 Mg ha^{-1} (Table 7). For this system, the total biomass inputs to the soil of 13.4 ± 0.4 Mg ha^{-1} are equivalent to 5.4 ± 0.2 Mg C ha^{-1} yr^{-1} [assuming soil organic matter (SOM) is 40% C by mass (Stevenson, 1994)]. A study by Johnson et al. (2006b) estimated the minimum aboveground source C inputs required to maintain SOC (MSC) for a number of crops at 2.5 ± 1.0 Mg C ha^{-1} yr^{-1}. Their estimates of the total aboveground + root source C inputs to the soil were at least twice MSC, which compares reasonably well with the value of 5.4 ± 0.2 Mg C ha^{-1} yr^{-1} obtained in this study. Similarly, our simulated minimum biomass residues needed to maintain and/or increase SOC, and hence protect soil quality and productivity (6.2–14.8 Mg ha^{-1}) are consistent with reviewed estimates of 0.8–14 Mg biomass ha^{-1} by Wilhelm et al. (2004). Biomass removal thresholds are however subject to many site-specific factors, such as land type, topography, soil texture-hydrologic group interactions, agroclimate, management practice, and socioeconomics, and hence cannot be based on a "*one size fits all*", but will most likely be met through a range of biomass removal rates (Meki et al., 2011).

3.4. Soil bulk density

Although the ALMANAC model cannot directly simulate the potential cumulative effects of repeated wheel traffic and harvesting equipment-induced soil compaction, the model managed to capture the effects of both tillage and biomass removal on soil bulk density (Table 10 and Fig. 5a), a critical indicator of soil compaction. Averaged across tillage systems, biomass removal significantly ($P \leq 0.05$) increased soil compaction as measured by the increase in BD (surface 0–10 cm soil depth) with increasing biomass removal rate. The 50%, 75% and 100% biomass removal rates increased BD (relative to the 0% removal rate) by 0.27, 0.32, and 0.34 Mg m^{-3}, respectively. There was a very high correlation between BD and SOC across tillage systems and biomass removal rates (Fig. 5b). Bulk density increased linearly with decrease in percent SOC.

As expected, the NTNT system had the lowest BD across the four biomass removal rates and gained the highest percent SOC over the 51-yr simulation period. Subsoiling at biomass removal rates lower than 50% provided a better method of alleviating compaction than NTCT (as shown by the lower BD of the NTSS system relative to NTCT). However, there were no differences in BD at the 75% and 100% biomass removal rates.

Table 10
Percent soil organic carbon (SOC) and bulk density (BD) at the end of the 51-yr simulation period (surface 0–10 cm soil depth). Initial percent SOC = 0.74, initial BD = 1.45 Mg m^{-3}.

Cropping system	Biomass removal rate							
	0%		50%		75%		100%[b]	
	SOC	BD	SOC	BD	SOC	BD	SOC	BD
NTNT[a]	5.59	0.95	1.28	1.33	0.75	1.40	0.61	1.42
CTCT[b]	2.44	1.20	0.89	1.38	0.65	1.41	0.56	1.43
NTCT[c]	2.74	1.17	0.92	1.38	0.66	1.41	0.56	1.43
NTSS[d]	4.14	1.04	1.03	1.36	0.66	1.41	0.55	1.43
Mean	3.73	1.09	1.03	1.36	0.68	1.41	0.57	1.43
SE	0.72	0.06	0.09	0.01	0.02	0.00	0.01	0.00

[a] Continuous No Till.
[b] Continuous Conventional Till.
[c] Continuous No Till (NT) for 4 yr, with Conventional Till (Moldboard plowing) in fifth yr.
[d] Continuous No Till (NT) for 4 yr, with Subsoiling (SS) in fifth yr.

Overall, our results are consistent with data reported elsewhere in the literature; Blanco-Canqui and Lal (2007), Bordovsky et al. (1999), Clapp et al. (2000), Karlen et al. (1994), Pierce et al. (1994), and Wilhelm et al. (2004). A 50% stover removal rate increased soil bulk density by 0.15 Mg m^{-3} in NT silt loams in Ohio after one and three years of stover removal (Blanco-Canqui and Lal, 2007), while complete removal of sorghum residues for a two-year period increased cone index from 0.5 to 1.0 MPa in a NT clay loam (Sow et al., 1997). The magnitude of impacts of crop residue removal on soil compaction however, varies with soil, tillage, residue type and cropping system (Blanco-Canqui and Lal, 2009). Overall, crop residue removal enhances compaction because residues cushion the soil from the compactive effects of heavy farm machinery or repeated agricultural traffic.

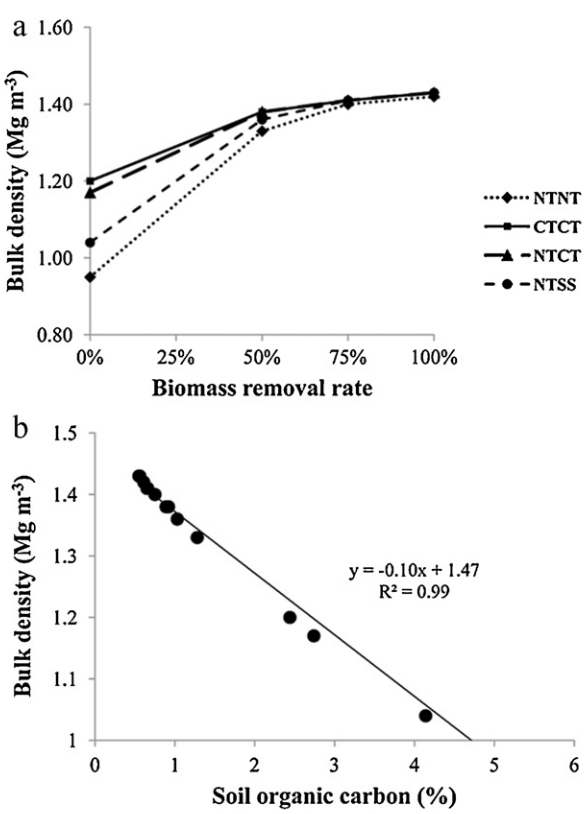

Fig. 5. Effects of biomass removal on soil bulk density – (a) and relationship between soil organic carbon and bulk density (surface 0–10 cm soil depth) – (b). Data values are annual averages of four tillage cropping systems, NTNT, CTCT, NTCT, and NTSS over a 51-yr simulation period: 1960–2010.

4. Conclusion

Given the importance of SOC as a soil quality indicator in agroecosystems, that also include biomass feedstock production systems (Karlen et al., 2011), biomass removal can only be justified if it does not deplete the SOC pool. It is assumed that if SOC is maintained, then there will also be sufficient residues to control erosion. Accurate estimates of how different energy sorghum biomass removal rates and soil management practices impact total soil biomass inputs, and hence SOC, are urgently needed to design biomass feedstock production systems that sustain productivity and environmental integrity. For this study, 75% of energy sorghum biomass can be removed from a continuous NT system without any detrimental effects on SOC storage. This level of biomass removal however, significantly increased soil bulk density, a critical indicator of soil compaction, not only in the continuous NT system, but in all the tillage systems that we evaluated. Compared to conventional tillage, subsoil tillage was more effective in alleviating soil compaction on NT systems, but at a reduced biomass removal threshold of 50%. Long-term biomass removal resulted in reduced total biomass yields over time due to nutrient depletion (N stress) which could be attributed to reduced N mineralization, N losses, and perhaps N immobilization. Additional inputs will be needed to avoid increased N uptake from the soil which could result in soil mining. To maximize harvest thresholds, alleviate soil compaction, control erosion, maintain SOC and nutrient cycles, there is need for harvest technologies that minimize field traffic passes, coupled with application of additional conservation practices that incorporate cover crops, cattle and poultry manure in the production system. According to the USDA NRCS (2006), periodic checks and monitoring of SOC should be conducted to ensure that soil quality is not sacrificed in the name of renewable biomass energy. Although for this study we simulated energy sorghum continuously for a 51-yr cycle, this is unrealistic under real agroecosystems, where rotating crops would be an advantageous BMP. How these rotations affect SOC storage in the long-term is yet to be evaluated. Although the results of this study need further validation with measured field data, they underscore the importance of applying tillage cropping and biomass harvesting systems that optimize feedstock production while ensuring adequate residue and root biomass that sustainably maintain SOC, minimize compaction, and hence soil quality and productivity.

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