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Corn Belt soil carbon and macronutrient budgets with projected sustainable stover harvest

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ABSTRACT

Corn (*Zea mays* L.) stover has been identified as a prime feedstock for biofuel production in the U.S. Corn Belt because of its perceived abundance and availability, but long-term stover harvest effects on regional nutrient budgets have not been evaluated. We defined the minimum stover requirement (MSR) to maintain current soil organic carbon levels and then estimated current and future soil carbon (C), nitrogen (N), phosphorus (P), and potassium (K) budgets for various stover harvest scenarios. Analyses for 2006 through 2010 across the entire Corn Belt indicated that currently, 28 Tg or 1.6 Mg ha^{-1} of stover could be sustainably harvested from 17.95 million hectares (Mha) with N, P, and K removal of 113, 26, and 47 kg ha^{-1}, respectively, and C removal for that period was estimated to be 4.55 Mg C ha^{-1}. Assuming continued yield increases and a planted area of 26.74 Mha in 2050, 77.4 Tg stover (or 2.4 Mg ha^{-1}) could be sustainably harvested with N, P, and K removal of 177, 37, and 72 kg ha^{-1}, respectively, along with C removal of ~6.57 Mg C ha^{-1}. Although there would be significant variation across the region, harvesting only the excess over the MSR under current fertilization rates would result in a small depletion of soil N (-5 ± 27 kg ha^{-1}) and K (-20 ± 31 kg ha^{-1}) and a moderate surplus of P (36 ± 18 kg ha^{-1}). Our 2050 projections based on continuing to keep the MSR, but having higher yields indicate that soil N and K deficits would become larger, thus emphasize the importance of balancing soil nutrient supply with crop residue removal.

1. Introduction

Corn (*Zea mays* L.) stover in the Corn Belt can be a prime feedstock for biofuel production in the United States because of its abundance (Shinners and Binversie, 2007) and the well-developed transportation infrastructure from the field to storage and processing facilities (Moore et al., 2013; Karlen et al., 2014). However, excessive removal of stover could adversely impact soil fertility and productivity (Varvel and Wilhelm, 2008; Tan et al., 2012; Kenney et al., 2013). With an increasing demand for crop residue as biofuel feedstock, balancing residue harvest and nutrient budgets to achieve sustainable crop production and soil fertility is becoming increasingly important. Excessive residue removal will enhance soil erosion, degrade soil physical properties and reduce the soil organic carbon (SOC) pool (Hammerbeck et al., 2012; Khanal et al., 2014). To define how much residue is required to maintain soil fertility, Johnson et al. (2006) proposed the minimum source carbon concept and used it to estimate the minimum amount of crop residue that needed to be retained to sustain soil carbon levels for continuous corn and corn-soybean systems in the U.S. Corn Belt. Wilhelm et al. (2007) also defined the minimum amount of stover retention as a function of soil erodibility, tolerable soil loss, surface slope, tillage method, cropping system, and grain yield. They concluded that the amount of stover required to maintain SOC was even greater than that required to control erosion. By defining the minimum stover requirement (MSR) associated with the baseline SOC level, tillage practice, and crop rotation, Tan et al. (2012) estimated current and future stover production and the harvestable stover amount (HSA) for corn-growing counties across the conterminous United States. More recently, Muth and Bryden (2013) proposed an erosion control integrated model to estimate crop residue removable limits at a state level. The U.S. Department of Energy (2011) documented the potential residue supplies from corn and other grain crops in the U.S. Billion-Ton Update using the POLYSYS model (a policy simulation model of the U.S. agricultural sector) (De La Torre

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Ugarte and Ray, 2000). This model estimates crop residue production by taking the residue as a function of crop yield, moisture, and residue-to-grain ratio. POLYSYS also considers residue production costs and the amount of residue that must remain to keep erosion within tolerable soil loss levels and to maintain SOC levels.

Regardless of the modeling approach, the basic criterion for determining the HSA is still “to maintain SOC level.” Explicitly, the removable rate of corn stover varies with corn grain yield, climatic conditions, and management practices at a specific site (Johnson et al., 2010; Karlen et al., 2014). Karlen et al. (2014) evaluated the effects of corn stover harvest on corn grain yield and nutrient budgets based on multi-location observations across the Midwestern U.S. corn growing states. Their results are site-specific but can be used to verify model simulations and projections of available feedstock as addressed in the revised U.S. Billion-Ton Update.

Macronutrient and SOC budgets are frequently used to evaluate long-term sustainability of farming systems. According to Oenema et al. (2003), overall soil nutrient budgets reflect inputs and outputs, recycling, losses, and changes in soil nutrient pools even though specific losses from leaching, runoff, volatilization, and denitrification are usually uncertain (Oenema and Heinen, 1999).

Many studies have been conducted to estimate nutrient removal with corn grain and stover harvest (Johnson et al., 2010; Khanal et al., 2014; Karlen et al., 2014) and to understand nutrient uptake dynamics under diverse growth conditions (Setiyono et al., 2010; Karlen et al., 2014). Soil nutrient budgets are generally determined by either calculating nutrient removal from harvested crop components and the nutrient concentrations in those components as described by Murrell (2008) and Karlen et al. (2014), or by using a mathematical modeling approach such as a spherical model (Setiyono et al., 2010). The results from both approaches have been determined to be in good agreement for N, P, and K uptake (Tan et al., 2012).

This study was designed to (1) define baseline soil C, N, P, and K pools under predefined minimum stover requirement scenarios; and (2) evaluate the impacts of minimum stover requirement-based harvestable stover amount on soil C, N, P, and K pools for projected current and future stover production at state and regional scales.

2. Materials and methods

2.1. Study area

The U.S. Corn Belt is a region in the middle of the United States where corn is the predominant crop grown on relatively level land with deep, fertile soils. Specific geographic boundaries for the Corn Belt vary, but for this study we defined the area to include Iowa, Illinois, Indiana, Nebraska, Kansas, Ohio, eastern South Dakota, southeastern North Dakota, southern Minnesota, southern Michigan, southern Wisconsin, and northern Missouri (Fig. 1). For 2006 through 2010, corn was planted on an average area of 29.035 million hectares (Mha) and total grain production was 272.60 × 10^{12} g (Tg) (http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS).

2.2. Datasets

The datasets used for this study were: (1) historical county-based corn grain yield statistics for 12 states within the Corn Belt, derived from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) (http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS); (2) minimum

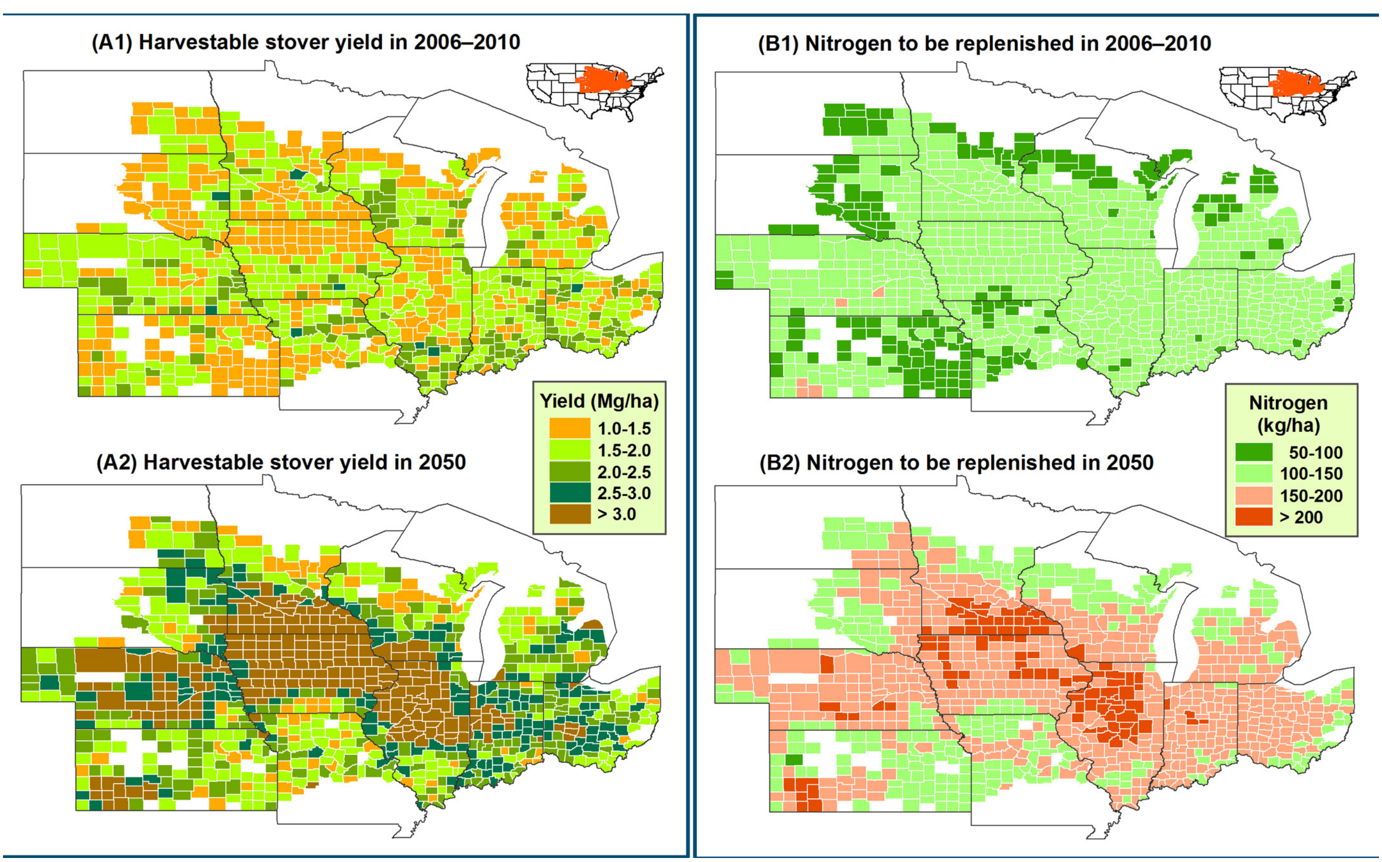

Fig. 1. Spatial distribution of projected harvestable stover yield and extra amount of nitrogen needed with the harvest option II at a county scale across the U.S. Corn Belt.

stover requirement (MSR) to maintain soil fertility for different tillage and crop rotation systems, synthesized from literature reviews (see Tan et al., 2012); and (3) acreage data of tillage practices synthesized from the Crop Residue Management database of the Conservation Technology Information Center (CTIC) (http://www.ctic.purdue.edu/CRM/). The areal proportions of crop rotation systems in the total planted area were calculated from the USDA NASS Cropland Data Layers for 2008–2010 (http://www.nass.usda.gov/research/Cropland/SARS1a.htm).

2.3. Current corn grain yield and its projections from 2011 to 2050

In 2010, corn was harvested from 27.95 million hectares (Mha) in what we defined as the Corn Belt. Based on USDA NASS county statistics, average corn grain yield in this region has increased almost linearly between 1950 and 2010, which is similar to the historical trend reported by Tan et al. (2012) for all corn planted areas in the United States. Therefore, we projected the 2011–2050 corn grain yields based on the historical trend assuming there would be no changes in the harvested area.

2.4. Minimum stover requirement (MSR)

According to Tan et al. (2012), MSR is mainly a function of corn grain yield ($Y_{grn,}$), tillage, crop rotation, and stover harvest option. We synthesized published MSR data reported for all studies in the U.S. Corn Belt and defined the MSR limits for each combination of tillage and crop rotation as presented in Table 1.

How much corn stover can be harvested as biofuel feedstock depends on both stover yield (Y_{stv}) and MSR magnitude as defined above. Y_{stv} (in Mg ha^{-1}) is usually estimated from corn grain yield (Y_{grn}) (Tan et al., 2012) as follows:

$$Y_{stv} = 0.61Y_{grn} + 2.400$$

$$\text{Therefore, } Y_{hs} = Y_{stv} - \text{MSR} = (0.61Y_{grn} + 2.400) - \text{MSR} \quad (1)$$

The Y_{hs}, harvestable stover yield, was estimated with the MSR limits that were related to the baseline SOC levels for each combination of tillage practices and crop rotation systems as listed in Table 1. Three crop rotations [continuous–corn (C–C), corn-soybean (C–S), and corn-other crops (C–O)] and three tillage practices [no-till (NT), reduced-tillage (RT), and conventional tillage (CT)] were evaluated. The average proportion of harvested corn area in each of these systems at the county level during the last 5 years were 0.18, 0.47, and 0.35 for NT, RT, and CT, respectively, and 0.7 and 0.3 for continuous corn and rotation systems, respectively.

2.5. Estimating harvestable stover amount (HSA)

We defined two stover harvest options that show how to collect corn cobs under each MSR scenario because cobs have higher C density and collectability than other components.

Harvest option I: Only the portion of stover yield (including cobs) greater than the MSR limit would be harvested. The annual HSA in a county is:

$$\begin{aligned}\text{HSAc} &= \sum_{i=3}\sum_{j=3}(Y_{hs,c} \times H_{tc} \times \text{Pt}_i,\text{r}_j)\\ &= \sum_{i=3}\sum_{j=3}((Y_{s,c} - \text{MSRt}_i,\text{r}_j) \times \text{Htc} \times \text{Pt}_i,\text{r}_j)\end{aligned}$$

$$\text{giventhat}(Y_{s,c} - \text{MSRt}_i,\text{r}_j) > 0; i = 3; j = 3) \quad (2)$$

where HSAc is annual harvestable stover amount in county c (Mg); $Y_{s,c}$ is the stover yield (Mg ha^{-1}); MSRt$_i$, r$_j$ is the minimum stover requirement (Mg ha^{-1}) under tillage t$_i$ in the cropping system r$_j$; H_{Tc} is the total harvested area (ha) in the county c; and Pt$_i$, r$_j$ is the area proportion under tillage t$_i$ in the cropping system r$_j$. The total HSA for a state was aggregated from all counties within the state.

Harvest option II: All cobs would be harvested first, then only the portion of the total non-cob stover yield that is beyond the MSR limit would be harvested:

$$\text{HSAc} = \sum_{i=3}\sum_{j=3}(((Y_{s,c} - Y_{cob}) - \text{MSRt}_i,\text{r}_j) \times H_{tc} \times \text{Pt}_i,\text{r}_j) + Y_{cob} \times H_{tc}$$

$$\text{giventhat}((Y_{s,c} - Y_{cob}) - \text{MSRt}_i,\text{r}_j) > 0; i = 3; j = 3) \quad (3)$$

where Y_{cob} is cob yield in county c (Mg ha^{-1}). The definitions of all other terms are the same as for Eqs. (1) and (2).

2.6. Calculation of C and required nutrients (N, P, and K)

Average C, N, P, and K contents in corn grain, stover, and cobs (Table 2) were calculated using literature values and used to estimate the amount of each element that would be removed by harvesting corn grain and stover.

Table 2
Fractions of stover components and contents (dry matter) of major elements at grain harvest.

Component of biomass	Fraction of stover	C[d]	N[d]	P[d]	K[d]
		(g kg^{-1})			
Grain	Y[a]	447	13.56	3.02	3.99
Stover (+cob)	*f*(Y): 1.00[b]	435	6.40	0.79	10.06
Non-cob stover[c]	0.32[c]	432	6.77	0.89	10.50
Cob	0.18[c]	452	5.04	0.42	6.78

[a] Grain yield.
[b] Taking all stover mass as 100% (Y_{stv} = 0.61 Y_{grn} + 2.4, Tan et al. (2012)).
[c] Derived from Wilhelm et al. (2011), the stover that excludes cobs.
[d] Values are means synthesized from literature (Johnson et al., 2010; Shinners and Binversie, 2007; Wilhelm et al., 2011).

Table 1
Minimum stover requirement (MSR) for maintaining soil organic carbon in the Corn Belt.

Cropping system[a]	Continuous Corn (C–C)			Corn–Soybean (C–S)			Corn–Other (C–Ot)		
Tillage[b]	NT	RT	CT	NT	RT	CT	NT	RT	CT
MSR[c](Mg ha^{-1})	5.125	6.166	7.206	7.530	7.815	8.100	7.530	7.815	8.100

[a] Average% of C–C, C–S, and C–Ot in the total corn planted area was 31%, 51%, and 18%.
[b] NT: no-till; RT: reduced -tillage; CT: conventional tillage. The value for RT is the average of those for NT and CT.
[c] Average carbon content of dry stover is 43.2%. All values were synthesized from: (Allmaras et al., 2004; Al-Kaisi et al., 2005; Barber, 1979; Clape et al., 2000; Clay et al., 2001; Clay et al., 2006; Crookston et al., 1991; Huggins et al., 1998; Kucharik et al., 2001; Larson et al., 1972; Pikul et al., 2008; Reicosky et al., 2002; Vanotti et al., 1997; Varvel and Wilhelm, 2008; Vitosh et al., 1997).

3. Results

3.1. Current corn grain and stover yields and their projections in the future

Table 3 presents the area-weighted average grain yield which was projected to increase from 7.90 Mg ha^{-1} for 2006–2010 to 11.10 Mg ha^{-1} by 2050. Meanwhile, corn stover yields were projected to increase from 7.00 Mg ha^{-1} to 8.86 Mg ha^{-1}, representing an average increase of 26.7% (ranging from 24.4% in Kansas to 32.5% in North Dakota). This is about 13.6% smaller than the increase in the grain yield due to an increase in grain harvest index over time (Tan et al., 2012). The annual total stover production would increase from 206.34 Tg for 2006–2010 to 262.86 Tg by 2050.

3.2. Harvestable stover amount (HSA)

3.2.1. HSA with harvest option I

HSA magnitudes and harvestable areas with harvest option I (only the portion of stover yield (including cobs) greater than the MSR limit would be harvested) for each state are presented in Table 4. On the annual average for 2006–2010, about 28 Tg of the total stover could be harvested at a rate of 1.57 Mg ha^{-1}. With an increase in grain yield over time, the stover yield is expected to increase and surpass the MSR limit in more harvestable areas at a rate of 2.23 Mg ha^{-1} in 2022 and 2.38 Mg ha^{-1} in 2050, resulting in an annual HSA of 50.2 Tg and 77.4 Tg, respectively. Of the total stover production, the HSA would be only 15.5%, 22.2%, and 29.4% for 2006–2010, 2022, and 2050, respectively.

3.2.2. HSA with harvest option II

The magnitudes of HSA and harvestable acreages with harvest option II (all cobs would be harvested first, then only the portion of the total non-cob stover yield that is beyond the MSR limit would be harvested) are presented in Table 5. Results show that all cobs could be harvested from all corn harvested acreage at an average rate (Mg ha^{-1}) of 1.38, 1.50, and 1.68 for 2006–2010, 2022, and 2050, respectively, which result in an annual cob production of about 38 Tg, 41.1 Tg, and 46.2 Tg, respectively. At the same time, the amount of the harvestable non-cob stover (beyond the MSR limit) could be 11.3 Tg yr^1, 23.9 Tg yr^1, and 35.4 Tg yr^1 at a rate (Mg ha^{-1}) of 1.13, 2.33, and 1.58 for 2006–2010, 2022, and 2050, respectively. The harvestable area for the non-cob stover would account for 31%, 38%, and 74% of the total harvested area for 2006–2010, 2022, and 2050, respectively. As a result, the total amount of both cobs and harvestable non-cob stover could be 49.3 Tg, 65.0 Tg, and 81.6 Tg, respectively. In other words, harvest option II, compared to harvest option I, would lead to more stover (cobs + non-cob stover) feedstock by 21.3 Tg for 2006–2010, 14.8 Tg in 2022, and 4.2 Tg in 2050, but the difference between two harvest options would become small in the future.

3.3. Nutrient requirements and balance with stover harvest scenarios

Table 6 shows that for all of the projected above-ground biomass C, about 54% is contributed by grain, so only 11.4%, 13.4%, and 14% could be sustainably removed from the field in harvestable stover for 2006–2010, 2022, and 2050, respectively. The macronutrients show a similar pattern with a large portion attributed to the grain harvest, especially P, and only a small fraction can be attributed to the removal of harvestable stover. For the three macronutrients, grain harvest accounts for about 71% N, 81% P, and 31% K. Whereas the N, P, and K removal with harvestable stover is only about 6%, 3%, and 12.6%, respectively, for 2006–2010, and 7.3%, 4.0%, and 15.9%, respectively, for 2022, and 7.8%, 4.3%, and 17.4%, respectively, for 2050. After harvesting both grain and harvestable stover, the amounts of nutrients required to replenish for 2006–2010, 2022, and 2050 were 123, 143, and 177 kg N ha^{-1} yr^{-1}, respectively; 26, 30, and 37 kg P ha^{-1} yr^{-1}, respectively; and 47, 58, and 72 kg K ha^{-1} yr^{-1}, respectively. Clearly, the total nutrient requirements and soil nutrient deficits of N, P, or K would increase over time due to an increase in grain yield and harvestable stover yield. Usually, regardless of stover harvest, most of the N, P, and K removed by grain harvest is already accounted for in annual fertilization and nutrient management plans that farmers may have and follow. Therefore, the deficit of each nutrient element mentioned above refers to the extra amount of the nutrient that is needed to replenish if the projected stover harvest takes place. For example, the spatially-explicit extra N requirement following projected stover harvest at a county scale is presented in Fig. 1 (B1 & B2). Aside from fertilization, a substantial portion of required nutrients could be derived from decomposition of the retained stover (see Table 6) and the previous year's below-ground biomass. In view of the budgets just from both the calculated nutrient requirements and the fertilizer-provided nutrients across the whole Corn Belt for 2006–2010 (see Table 7), there could be only a small deficit of N at 5 kg N ha^{-1} yr^{-1} and a relatively high K deficit of 20 kg K ha^{-1} yr^{-1}, but a credible P surplus at a rate of 36 kg P ha^{-1} yr^{-1}. Note that there were large variations in budgets among states. An especially high K deficit was found in every state except

Table 3
Total harvested area, grain and stover yields, and production (oven-dry matter) in the U.S. Corn Belt.

State	Y06–10 Harvested	Y06–10 Grain yield	Y2022	Y2050	Y06–10 Stover yield	Y2022	Y2050	Y06–10 Stover production	Y2022	Y2050
	1000 ha	(Mg ha^{-1})			(Mg ha^{-1})			Tg (10^{12} g)		
Illinois	4884	8.55	9.76	11.98	7.89	8.67	10.10	38.54	42.34	49.31
Indiana	2301	8.18	9.34	11.37	7.56	8.30	9.58	17.40	19.10	22.04
Iowa	5297	8.82	10.12	12.26	7.94	8.74	10.08	42.04	46.29	53.42
Kansas	1521	6.46	7.65	8.96	6.70	7.46	8.33	10.18	11.35	12.67
Michigan	859	6.81	7.86	10.09	6.96	7.68	9.18	5.98	6.60	7.89
Minnesota	2936	7.96	9.25	11.38	7.71	8.56	9.98	22.65	25.12	29.30
Missouri	1171	7.01	7.85	9.97	6.91	7.46	8.82	8.09	8.73	10.33
Nebraska	3498	8.41	9.36	11.32	7.71	8.30	9.54	26.97	29.05	33.36
N. Dakota	790	5.05	6.15	7.77	6.27	7.08	8.31	4.95	5.59	6.56
Ohio	1303	7.91	8.96	10.86	7.45	8.13	9.34	9.71	10.59	12.17
S. Dakota	1699	5.90	7.06	9.11	6.58	7.27	8.69	11.18	12.36	14.76
Wisconsin	1213	7.28	8.27	10.34	7.12	7.76	9.10	8.64	9.42	11.04
Corn Belt	27,474	7.90	9.06	11.10	7.00	7.66	8.86	206.34	226.54	262.86
stdev		1.12	1.19	1.34	0.90	1.02	1.22			

Table 4
MSR-derived harvestable stover production (dry matter) and area in the U.S. Corn Belt with harvest option I.[a]

State	Y06–10 Harvestable stover (+cobs)	Y2022	Y2050	Y06–10	Y2022	Y2050	Y06–10 Harvestable area	Y2022	Y2050
	Tg (10^{12} g)			(Mg ha^{-1})			1000 ha		
Illinois	5.61	10.70	15.64	1.51	2.36	3.21	3708	4524	4875
Indiana	2.12	4.26	6.24	1.66	2.04	2.71	1274	2088	2298
Iowa	6.72	11.58	17.75	1.49	2.25	3.36	4513	5150	5289
Kansas	1.15	2.11	2.87	1.54	2.18	2.43	750	967	1178
Michigan	0.55	1.15	2.00	1.59	2.14	2.36	347	539	848
Minnesota	3.09	5.90	9.20	1.49	2.22	3.17	2079	2662	2901
Missouri	0.78	1.46	2.34	1.71	2.15	2.08	455	680	1123
Nebraska	4.37	6.47	10.33	1.69	2.03	2.97	2588	3183	3476
N. Dakota	0.37	0.79	1.34	1.35	2.14	1.98	273	368	677
Ohio	1.14	2.23	3.25	1.72	2.03	2.50	667	1096	1299
S. Dakota	1.10	1.86	3.67	1.50	1.86	2.28	734	1001	1611
Wisconsin	0.94	1.74	2.81	1.69	2.00	2.41	561	867	1165
Corn Belt	27.95	50.24	77.41	1.57	2.23	2.38	17,950	23,126	26,739
stdev				0.42	0.74	0.81			

MSR: Minimum stover requirement for maintaining soil organic carbon content.
[a] Only the portion of stover yield (including cobs) greater than the MSR limit would be harvested.

Table 5
Corn cob production, harvestable non-cob stover production and area in the Corn Belt with harvest option II.[a]

State	2006–2010 Harvested	2006–2010 Cob yield	2022	2050	2006–2010 Cob production	2022	2050	2006–2010 Harvestable non-cob stover yield	2022	2050	2006–2010 Area of harvestable non-cob stover	2022	2050	2006–2010 Total harvestable stover producion (including cobs)	2022	2050
	1000 ha	(Mg ha^{-1})			Tg (10^{12} g)			(Mg ha^{-1})			1000 ha			Tg (10^{12} g)		
Illinois	4884	1.45	1.56	1.75	7.07	7.63	8.55	1.55	2.61	1.75	1499	1994	4244	9.39	12.84	15.97
Indiana	2301	1.39	1.51	1.69	3.21	3.47	3.88	1.44	2.64	1.52	626	831	1703	4.11	5.67	6.46
Iowa	5297	1.45	1.57	1.75	7.71	8.34	9.27	1.28	2.11	1.74	2132	2415	4962	10.44	13.43	17.91
Kansas	1521	1.23	1.36	1.50	1.87	2.08	2.28	1.01	1.71	1.63	415	582	802	2.29	3.07	3.59
Michigan	859	1.29	1.41	1.63	1.11	1.21	1.40	1.18	2.63	1.55	192	245	502	1.34	1.86	2.18
Minnesota	2936	1.42	1.55	1.73	4.16	4.54	5.09	1.27	2.17	1.73	954	1235	2531	5.37	7.22	9.47
Missouri	1171	1.28	1.38	1.58	1.50	1.61	1.85	1.09	2.49	1.55	285	331	606	1.81	2.43	2.79
Nebraska	3498	1.42	1.51	1.68	4.96	5.28	5.88	1.30	1.85	1.74	1394	1560	2762	6.76	8.17	10.68
N. Dakota	790	1.16	1.31	1.50	0.92	1.03	1.19	0.81	1.80	1.63	155	223	321	1.04	1.43	1.71
Ohio	1303	1.38	1.48	1.66	1.79	1.93	2.16	1.39	2.88	1.54	365	418	846	2.30	3.14	3.46
S. Dakota	1699	1.22	1.34	1.56	2.07	2.28	2.65	0.89	1.36	1.66	412	602	941	2.44	3.10	4.21
Wisconsin	1213	1.32	1.42	1.62	1.60	1.73	1.97	1.20	2.34	1.57	322	389	746	1.99	2.64	3.14
Corn Belt	27,474	1.38	1.50	1.68	37.97	41.14	46.17	1.13	2.33	1.58	8430	10436	20219	49.29	65.01	81.59
stdev		0.10	0.09	0.09				0.44	1.15	0.41						

[a] All cobs would be harvested everywhere and only the portion of the total non-cob stover that is beyond the MSR limit would be harvested.

Table 6
Annual requirements of carbon and major nutrients for grain yield target and nutrient budgets after harvesting grain and projected stover.

Component			Carbon (C) (kg ha^{-1}) 06–10	2022	2050	Nitrogen (N) 06–10	2022	2050	Phosphorus (P) 06–10	2022	2050	Potassium (K) 06–10	2022	2050
Calculated grain + Stover		Mean	7012	7870	9414	162	183	221	31	35	43	109	121	143
		Stdev	646	667	738	16	16	18	3	3	4	9	9	10
Grain		Mean	3745	4283	5252	114	130	159	25	29	35	33	38	47
		Stdev	405	419	463	12	13	14	3	3	3	4	4	4
Stover (+cobs)		Mean	3267	3587	4162	48	53	61	6	7	8	76	83	96
		Stdev	241	248	275	4	4	4	0	0	0	6	6	6
Harvest option I	Collectable stover (+cobs)	Mean	677	756	918	10.0	11.1	13.5	1.2	1.4	1.7	15.7	17.5	21.2
		Stdev	50	113	322	0.7	1.7	4.7	0.1	0.2	0.6	1.2	2.6	7.5
	Retained stover[a]	Mean	2824	2951	3268	41.6	43.4	48.1	5.1	5.4	5.9	65.3	68.2	75.6
	Harvest removal[b]	Mean	4422	5039	6170	124	141	173	27	30	37	49	56	68
Harvest option II	Cob	Mean	625	677	760	7.0	7.5	8.5	0.6	0.6	0.7	9.4	10.2	11.4
	Non-cob stover	Mean	558	953	730	8.8	15	11.4	1.2	2	1.5	13.6	23.2	17.7
	Collectable stover (+cobs)[c]	Mean	803	1052	1316	9.8	13.4	17.2	0.9	1.4	1.9	13.7	19.3	24.9
		Stdev	94	119	175	1.3	1.7	2.6	0.1	0.2	0.3	1.9	2.5	3.9
	Retained stover[a]	Mean	2464	2535	2845	38.3	39.3	44.0	5.0	5.1	5.7	61.9	63.7	71.3
	Harvest removal[b]	Mean	4547	5336	6569	123	143	177	26	30	37	47	58	72

[a] The amount of a nutrient element that theoretically returns to field from retained stover over the whole harvested area.
[b] The amount of nutrients needs to be replenished due to removal by harvesting grain and stover over the whole harvested area.
[c] Average for the entire harvested area even though the collectable area for non-cob stover is part of the total harvested area as shown in Table 5.

Table 7
Annual N, P, and K requirements, their inputs, and budgets in the U.S. Corn Belt averaged for the period from 2006 to 2010.

State	Calculated ($kg\,ha^{-1}$)			NASS applied[a] ($kg\,ha^{-1}$)			Budget[b] ($kg\,ha^{-1}$)		
	N	P	K	N	P	K	N	P	K
Illinois	173	33	115	187	104	119	15	71	4
Indiana	163	32	110	200	77	133	36	46	24
Iowa	174	34	116	159	73	90	−15	39	−26
Kansas	138	27	95	147	41	45	8	15	−51
Michigan	146	28	100	137	36	105	−9	8	6
Minnesota	167	32	112	140	56	71	−27	24	−42
Missouri	145	28	99	141	71	64	−3	43	−35
Nebraska	167	32	112	157	46	29	−10	14	−83
N. Dakota	126	24	88	179	49	37	53	25	−51
Ohio	160	31	108	158	72	102	−2	41	−6
S. Dakota	135	26	94	145	57	33	10	31	−61
Wisconsin	151	29	103	103	49	59	−47	20	−43
Corn Belt	162	31	109	157	67	89	−5	36	−20
stdev	16	3	9	26	19	35	27	18	31

[a] Derived from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS).
[b] The difference between the applied amount and the requirement calculated from N, P, and K contents in above-ground corn components.

Illinois, Indiana, Michigan, and Ohio. Minnesota ($-27\,kg\,N\,ha^{-1}\,yr^{-1}$) and Wisconsin ($-47\,kg\,N\,ha^{-1}\,yr^{-1}$) also had large N deficits.

4. Discussion

4.1. Future corn yield projection

How much stover could be harvested for biofuel production in the future depends not only on the MRS and harvest option, but also on the projection of future corn yield. Although the approach used in this study was thought to be relatively conservative for predicting future corn yield (Tan et al., 2012), there are some factors that could affect future corn production but were not accounted for in the approach. For example, the reliability of USDA NASS county corn yield statistical data (Sadras et al., 2014) which could result in projection uncertainty even though no other better data are available for projecting corn potential production at a regional scale. As well, the positive effect of irrigation on corn yield was observed to be already plateauing in the study region (Grassini et al., 2011) and the historical trend-based prediction could, to some extent, overestimate future corn yield potential, at least for Nebraska where the corn production is mainly irrigated. Additionally, early studies (e.g., Rosenzweig et al., 2002; Izaurralde et al., 2003) demonstrated possible adverse impacts of future climate changes on corn potential productivity. Therefore, some caution on uncertainty may be paid on reading the results presented here.

4.2. Annual harvestable stover supply and its effects on SOC dynamics

The HSA for biofuel production under the MSR scenario would be limited. Of the stover yield, only 13% could be harvested with harvest option I and about 24% with harvest option II. In other words, to keep SOC content at the same level as the baseline would require about 76–87% of stover to be retained in the field. Of all harvested stover with harvest option II (i.e., all cobs would be harvested everywhere), the cobs account for 18.4% and the harvested non-cob stover accounts for only 5.3%, but the proportion of cobs in the total harvestable stover would become smaller over time because of an increase in the yield of the non-cob stover. The rates and magnitudes of our HSA are much smaller than those reported by other authors. Graham et al. (2007) considered the constraints associated with collection equipment, soil moisture, and soil erosion and documented that about 30% of the U.S. stover production could be harvestable around 2000. The same harvestable proportion (30%) was also proposed by Crofcheck and Montross (2004) for collecting only the cobs, leaves, and husks (which have the greatest glucose potential). Gallagher et al. (2003) proposed an average MSR of $1.6\,Mg\,ha^{-1}$ left in the field under mulch tillage and estimated that 50% of the total stover production can be harvested as biofuel feedstock. Hoskinson et al. (2007) suggested that harvesting stover (including cobs) above the 40-cm high stubble would be best for farmers and ethanol producers because of faster harvest speed and higher quality ethanol feedstock. Obviously, our estimates with two harvest options are conservative but are meant to sustain soil fertility and crop productivity.

Iowa is the largest and most concentrated corn producer, and its stover production averag for 2006–2010 accounted for 20.4% of the total production of the Corn Belt (followed by Illinois with 18.7%). Therefore, Muth et al. (2012) used Iowa as an example and developed a residue removal model based on erosion control to assess removable residue limit at a subfield scale. They documented that a removable fraction of the total stover could be 23–89% at three test sites. Muth and Bryden (2013) used the same framework at the state (Iowa) level and reported that about 27% of corn, wheat, and soybean residue in Iowa can be sustainably harvested under current management practices. Because of inclusion of wheat and soybean residue, this number is much higher than our estimate of 12% for the state of Iowa with harvest option I and 19.5% with harvest option II. As discussed above, harvesting an amount of stover based on the MSR limit (regardless of whether cobs are harvested separately) under both current fertilization rates and either harvest options has little adverse impact on soil fertility in view of SOC balance.

In practice, how much crop residue can be sustainably removed at a field scale depends on local climate, soil type, and management practices (Johnson et al., 2006), particularly on the baseline SOC level (Senthilkumar et al., 2009; Tan and Liu, 2013). Long-term cultivation would reduce the SOC content of a soil with a high baseline SOC content because such a soil tends to need more residue retained in the field to sustain the SOC stock than the soil having a lower SOC content (Tan et al., 2012). The MSR values are generally higher in the Corn Belt than other areas. Johnson et al. (2006) documented a range from 5.25 to $12.50\,Mg\,ha^{-1}$ of stover needed to maintain SOC content in the Corn Belt soils. Varvel and Wilhelm (2008) suggested that a stover yield of $6.0\,Mg\,ha^{-1}$ is required to maintain SOC levels in the western Corn Belt.

Kenney et al. (2013) assessed the effects of stover removal at 0, 25, 50, 75, and 100% from continuous corn on water erosion, corn yield, and related soil properties during a 3-year study under various management practices on different soil types in Kansas. They observed that stover removal at rates ≥50% enhanced grain yield but increased risks of water erosion and negatively affected soil water and temperature regimes in this region. Senthilkumar et al. (2009) observed from 20-year experiments that retaining all residue in the field along with either crop cover or conservation tillage on Michigan soils could reduce the rate of SOC loss and enhance soil C sequestration whose baseline SOC levels were less than $9\,g\,C\,kg^{-1}$. However, a higher rate of SOC loss happened to the neighboring never-tilled prairie soils whose baseline SOC was greater than $15\,g\,C\,kg^{-1}$. The SOC content in cultivated croplands tends to be stable over time and finally approaches a level ranging from 8 to $15\,g\,C\,kg^{-1}$ in the plowed layer (Senthilkumar et al., 2009; Liu et al., 2011; Tan and Liu, 2013). Therefore, Tan et al. (2012) assumed that soils with $SOC \geq 12\,g\,C\,kg^{-1}$ are beyond their equilibrium and tend to lose C once the soils are cultivated and that a large part of the reported MSR is attributed to compensating the “impulse loss of SOC,” while the croplands with $SOC < 12\,g\,C\,kg^{-1}$ are closer to C equilibrium status. Furthermore, the magnitudes of MSR should be enough to compensate for the SOC loss induced by cultivation. Therefore, Tan et al. (2012) suggested that the averages of the reported MSR from areas with baseline SOC content less than 12 g C kg^{-1} should be appropriate for estimating both Y_{hs} and HSA in the United States. At this point, a higher harvestable stover amount in the Corn Belt (higher than the estimate presented here) could be available as biofuel feedstock at present and in the future.

4.3. Stover harvest-induced impacts on soil nutrient balance

Soil nutrient budgets depend on how much stover is to be removed or retained besides regular fertilization for securing corn grain production. By analyzing multi-location experimental data in U.S. corn growing states, Johnson et al. (2010) pointed out that the average removed nutrients vary with the magnitude of stover harvested because the content of each nutrient element varies with the component and position of stover (see Table 2). Therefore, the average nutrient removal varies with stover harvest scenarios. To sustain soil fertility in view of nutrient balance, the soil has to be compensated for the output of all nutrients with their input into the system (Lal, 2009).

Synthetic fertilizers have been the primary nutrient sources, especially N, to replenish the nutrient removal by harvesting grain and other biomass. USDA NASS statistics (available at http://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/) show that the fertilization rates (kg ha^{-1} yr^{-1}) of synthetic N, P, and K for corn production increased respectively from 145.5 ± 3.6, 63.7 ± 2.3, and 90.1 ± 2.0 in 1990–1999 to 151.2 ± 4.8, 65.2 ± 1.5, and 93.4 ± 2.8 in 2000–2010. At the same time, the corn grain yield increased from 7742 to 8943 Mg ha^{-1}. A much higher increase rate of corn grain yield (15.5%) than that of fertilization rate (3.9, 2.5, and 3.6% for N, P, and K, respectively) implies a higher fertilizer use efficiency of corn with time due mainly to corn's genetic improvement (Kumudini, 2002).

Generally, N fertilizer use in the United States has increased during the last three decades, with some declines in P and K application. The ratio of N to P_2O_5 and K_2O nearly doubled during that time. Meanwhile, about 11.6% of all corn planted area received 46.2 kg N, 9.0 kg P, and 12.5 kg K per hectare from the applied livestock manure (Tan et al., 2012).

Not all applied nutrients can be taken up by crops. Fixen and Johnston (2002) documented that the amount of N removed in harvested crops averaged for 1998–2000 was equivalent to about 82% of N inputs from N fixation, fertilizer, and recoverable manure application for the leading U.S. corn growing states of the Corn Belt (Illinois, Indiana, Iowa, Minnesota, Nebraska, South Dakota), where P removal exceeded P applied as fertilizer by 30.8%, and the K deficit accounted for 29.4%, but varied from state to state. For example, in Iowa, Illinois, and Indiana for 2007–2008, P deficit was estimated to be 5.5, 10, and 3.5 kg P ha^{-1} yr^{-1}, respectively. However, Iowa had only a small K deficit (<5 kg K ha^{-1} yr^{-1}), Illinois was balanced, and Indiana had some surplus (14 kg K ha^{-1} yr^{-1}).

Our results indicate that a deficit of N occurred in Wisconsin, Iowa, Minnesota, and Nebraska (see Table 7) with no manure application. A moderate P surplus occurred in all corn growing states but a noticeable K deficit took place in all states except Illinois, Indiana, Michigan, and Ohio. If the nutrients from manure application were added to the USDA NASS synthetic NPK statistics, soil NPK budgets following our projected stover harvest options could be fairly balanced for 2006–2010. Additionally, using biofuel end-products as soil amendment can reduce the need for supplemental fertilizers (Murrell et al., 2011). For example, to recycle the stover biofuel process-derived biochar to soil can increase SOC and nutrient contents, especially for soil with low SOC levels (Johnson et al., 2004); because the biochar accounts for 20–30% of the initial stover feedstock and contains about 60% lignin and varying nutrient contents (Yang and Wyman, 2008). Furthermore, crop rotation or winter crop (Pantoja, 2013) can also influence the soil nutrient budget.

5. Conclusions

Assuming an increase in corn grain yield at the historical change trend, the corn stover feedstock in the Corn Belt harvestable for biofuel production could amount up to 77–80 Tg by 2050 from 28 Tg averaged from 2006 to 2010. In other words, only about 13–24% of the stover yield could be harvested in order to maintain SOC level. This estimate is much smaller than the 30% proposed by previous studies. Generally, harvestable stover amount estimated with MSR limits for maintaining SOC level can be sustainable for soil fertility and soil N supply even though there could be some larger deficits of P and K in the future. Because of variations in soil fertility and corn production from field to field and county to county, the information from this study may help policy makers and managers develop sustainable biofuel feedstock systems at a state or regional scale to balance the supply of soil N, P, and K elements with fertilization for specific stover harvest scenarios.

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References

Al-Kaisi, M.M., Yin, X., Licht, M.A., 2005. Soil carbon and nitrogen changes as affected by tillage system and crop biomass in a corn-soybean rotation. Appl. Soil Ecol. 30, 174–191.
Allmaras, R.R., Linden, D.R., Clapp, C.E., 2004. Corn-residue transformations into root and soil carbon as related to nitrogen, tillage, and stover management. Soil Sci. Soc. Am. J. 68, 1366–1375.
Barber, S.A., 1979. Corn residue management and soil organic matter. Agron. J. 71, 624–627.
Clay, D.E., Clay, S.A., Liu, Z., Reese, C., 2001. Spatial variability of C isotopic discrimination in corn. Commun. Soil Sci. Plant Anal. 32, 1813–1827.
Clay, D.E., Carlson, C.G., Clay, S.A., Reese, C., Liu, Z., Chang, J., Ellsbury, M.M., 2006. Theoretical derivation of stable and nonisotopic approaches for assessing soil organic carbon turnover. Agron. J. 98, 443–450.
Crofcheck, C.L., Montross, M.D., 2004. Effect of stover fraction on glucose production using enzymatic hydrolysis. Trans. Am. Soc. Agric. Eng. 47, 841–844.
Crookston, R.K., et al., 1991. Rotational cropping sequence affects yield of corn and soybean. Agron. J. 83, 108–113.
De La Torre Ugarte, D.G., Ray, D.E., 2000. Biomass and bioenergy applications of the POLYSYS modeling framework. Biomass Bioenergy 4 (4), 291–308.
Fixen, P.E., Johnston, A., 2002. Nutrient Budgets in North America. Better Crops 86 (2), 20–22.
Gallagher, P., Dikeman, M., Fritz, J., Wailes, E., Gauther, W., Shapouri, H., 2003. Biomass from Crop Residues: Cost and Supply Estimates. Agricultural Economic Report No. 819. U.S. Department of Agriculture, Office of the Chief Economist, Washington, DC.
Graham, R.L., Nelson, R.G., Sheehan, J.J., Perlack, R.D., Wright, L.L., 2007. Current and potential U.S. corn stover supplies. Agron. J. 99, 1–11.
Grassini, P., Thorburn, J., Burr Cassman, K.G., 2011. High-yield irrigated maize in the Western U.S. Corn Belt I. On-farm yield, yield potential, and impact of agronomic practices. Field Crops Res. 120, 142–150.
Hammerbeck, A.L., Stetson, S.J., Osborne, S.L., Schumacher, T.E., Pikul, J.L., 2012. Corn residue removal impact on soil aggregates in a no-till corn/soybean rotation. Soil Sci. Soc. Am. J. 76, 1390–1398.
Hoskinson, R.L., Karlen, D.L., Birrell, S.J., Radtke, C.W., Wilhelm, W.W., 2007. Engineering, nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios. Biomass Bioenergy 31, 126–136.
Huggins, D.R., Clapp, C.E., Allmaras, R.R., Lamb, J.A., Layese, M.F., 1998. Carbon dynamics in corn-soybean sequences as estimated from natural carbon-13 abundance. Soil Sci. Soc. Am. J. 62, 195–203.

Izaurralde, R.C., Rosenberg, N.J., Brown, R.A., Thomson, A.M., 2003. Integrated assessment of Hadley Center (HadCM2) climate-change impacts on agricultural productivity and irrigation water supply in the conterminous United States Part II. Regional agricultural production in 2030 and 2095. Agric. For. Meteorol. 117, 97–122.
Johnson, J.M.F., Reicosky, D.C., Sharratt, B., Lindstrom, M.J., Voorhees, W.B., Carpenter-Boggs, L., 2004. Characterization of soil amended with the by-product of corn stover fermentation. Soil Sci. Soc. Am. J. 68, 139–147.
Johnson, J.M.F., Allmaras, R., Reicosky, D.C., 2006. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. Agron. J. 98, 622–636.
Johnson, J.M.F., Wilhelm, W.W., Karlen, D.L., Archer, D.W., Wienhold, B., Lightle, D.T., et al., 2010. Nutrient removal as a function of corn stover cutting height and cob harvest. Bioenergy Res. 3, 342–352.
Karlen, D.L., Birrell, R.B., Johnson, J.M.F., Osborne, S.L., Schumacher, T.E., Varvel, G.E., Ferguson, R.B., Novak, J.M., Fredrick, J.R., Baker, J.M., Lamb, J.A., Adler, P.R., Roth, G.W., Nafziger, E.D., 2014. Multilocation corn stover harvest effects on crop yields and nutrient removal. Bioenerg. Res. 7, 528–539.
Kenney, I., Blanco-Canqui, H., Presley, D.R., Rice, C.W., Janssen, K., Olson, B., 2013. Soil and crop response to stover removal from rainfed and irrigated corn. GCB Bioenergy 7, 219–230.
Khanal, S., Anex, R.P., Gelder, B.K., Wolter, C., 2014. Nitrogen balance in Iowa and the implications of corn-stover harvesting. Agric. Ecosyst. Environ. 183, 21–30.
Kucharik, C.J., Brye, K.R., Norman, J.M., Foley, J.A., Gower, S.T., Bundy, L.G., 2001. Measurements and modeling of carbon and nitrogen cycling in agroecosystems of southern Wisconsin: potential for SOC sequestration during the next 50 years. ecosystems 4, 237–258.
Kumudini, S., 2002. Trials and tribulations: a review of the role of assimilate supply in soybean genetic yield improvement. Field Crops Res. 75, 211–222.
Lal, R., 2009. Soil quality impacts of residue removal for bioethanol production. Soil Tillage Res. 102, 233–241.
Larson, W.E., Clapp, C.E., Pierre, W.H., Morachan, Y.B., 1972. Effect of increasing amounts of organic residues on continuous corn: II. Organic carbon, nitrogen, phosphorus, and sulfur. Agron. J. 64, 204–208.
Liu, S., Tan, Z., Li, Z., Zhao, S., Yuan, W., 2011. Are soils of Iowa USA currently a carbon sink or source? Simulated changes in SOC stock from 1972 to 2007. Agric. Ecosyst. Environ. 140, 106–112.
Moore, K.J., Karlen, D.L., Lamkey, K.R., 2013. Future prospects for corn as a biofuel crop. In: Goldman, S.L., Kole, C. (Eds.), Compendium of Bioenergy Plants: Corn. CRC Press, Boca Raton, pp. 331–352.
Murrell, T.S., Fixen, P., Huang, W., Kovar, J., White, P., 2011. Nitrogen, phosphorus, and potassium requirements to support a multi-billion gallon biofuel industry. Soil Water 2011, 160–176.
Murrell, T.S., 2008. Measuring nutrient removal, calculating nutrient budgets. In: Logsdon, S., Clay, D., Moore, D., Tsegaye, T. (Eds.), Soil Science: Step-by-Step Field Analysis. Soil Science Society of America, Madison, WI 53711, USA, pp. 159–182.
Muth Jr, D.J., Bryden, K.M., 2013. An integrated model for assessment of sustainable agricultural residue removal limits for bioenergy systems. Environ. Modell. Software 39, 50–69.
Muth Jr, D.J., McCorkle, D.S., Koch, J.B., Bryden, K.M., 2012. Modeling sustainable agricultural residue removal at the subfield scale. Agron. J. 104, 970–981.
Oenema, O., Heinen, M., 1999. Uncertainties in nutrient budget due to biases and errors. In: Smaling, O., Oenema, E.M.A., Fresco, L.O. (Eds.), Nutrient Disequilibria in Agroecosystems: Concepts and Case Studies. CAB International, Wallingford, UK, pp. 75–97.
Oenema, O., Kros, H., De Vries, W., 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Eur. J. Agron. 20 (1–2), 3–16.
Pantoja, J.L., 2013. Effect of corn stover harvest and winter rye cover crop on corn nitrogen fertilization. Graduate Theses and Dissertations. Iowa State University Paper 13042.
Reicosky, D.C., Evans, S.D., Cambardella, C.A., Allmaras, R.R., Wilts, A.R., Huggins, D. R., 2002. Continuous corn with moldboard tillage: residue and fertility effects on soil carbon. J. Soil Water Conserv. 57, 277–284.
Rosenzweig, C., Tubiellob, F.N., Goldberg, R., Mills, E., Bloomfield, J., 2002. Increased crop damage in the US from excess precipitation under climate change. Global Environ. Change 12, 197–202.
Sadras, V.O., Grassini, P., Costa, R., Cohan, L., Hall, A.J., 2014. How reliable are crop production data? Case studies in USA and Argentina. Food Secur. 6, 447–459.
Senthilkumar, S., Basso, B., Kravchenko, A.N., Robertson, G.P., 2009. Contemporary evidence of soil carbon loss in the U.S. corn belt. Soil Sci. Soc. Am. J. 73, 2078–2086.
Setiyono, T.D., Walters, D.T., Cassman, K.G., Witt, C., Dobermann, A., 2010. Estimating maize nutrient uptake requirements. Field Crops Res. 118 (2), 158–168.
Shinners, K.J., Binversie, B.N., 2007. Fractional yield and moisture of corn stover biomass produced in the Northern US Corn Belt. Biomass Bioenergy 31, 576–584.
Tan, Z., Liu, S., 2013. Baseline-dependent responses of soil carbon dynamics to climate and land disturbances. Appl. Environ. Soil Sci. 2013 206758–7.
Tan, Z., Liu, S., Bliss, N., Tieszen, L.L., 2012. Current and potential sustainable corn stover feedstock for biofuel production in the United States. Biomass Bioenergy 47, 372–386.
U.S. Department of Energy (2011) U.S. billion-ton update: Biomass supply for a bioenergy and bioproducts Industry (Leads Perlack RD, Stokes BJ), ORNL/TM-2011/224. Oak Ridge National Laboratory. Oak Ridge, TN, pp. 227. Available at: http:// www1. eere.energy.gov/biomass/pdfs/billion_ton_update.pdf (Accessed 8 August 2013).
Vanotti, M.B., Bundy, L.G., Peterson, A.E., 1997. Nitrogen fertilizer and legume–cereal rotation effects on soil productivity and organic matter dynamics in Wisconsin. In: Paul, E.A. (Ed.), Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America. CRC Press, Boca Raton, FL, pp. 105–119.
Varvel, G.E., Wilhelm, W.W., 2008. Soil carbon levels in irrigated western corn belt rotations. Agron. J. 100, 1180–1184.
Vitosh, M.L., Lucas, R.E., Silva, G.H., 1997. Long-term effects of fertilizer and manure on corn yield, soil carbon, and other soil chemical properties in Michigan. In: Paul, E.A. (Ed.), Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America. CRC Press, Boca Raton, FL, pp. 129–139.
Wilhelm, W.W., Johnson, J.M.F., Karlen, D.L., Lightle, D.T., 2007. Corn stover to sustain soil organic carbon further constrains biomass supply. Agron. J. 99, 1665–1667.
Wilhelm, W., W, Johnson, J.F.M., Lightle, D.T., Karlen, D.L., Novak, J.M., Barbour, N.W., et al., 2011. Vertical distribution of corn stover dry mass grown at several U. S. locations. BioEnergy Res. 4, 11–21.
Yang, B., Wyman, C.E., 2008. Pretreatment: the key to unlocking low-cost cellulosic ethanol. Biofuels Bioprod. Biorefin. 2, 26–40.