Soil & Tillage Research 115–116 (2011) 47–55

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

A five-year assessment of corn stover harvest in central Iowa, USA

Douglas L. Karlen [a,*], Stuart J. Birell [b], J. Richard Hess [c]

[a] USDA-Agricultural Research Service, National Laboratory for Agriculture and the Environment (NLAE), 2110 University Boulevard, Ames, IA 50011-3120, United States
[b] Department of Agricultural and Biosystems Engineering, Iowa State University (ISU), 208 Davidson Hall, Ames, IA 50011, United States
[c] Bioenergy Technology Division, Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-2025, United States

ARTICLE INFO

Article history:
Received 15 February 2011
Received in revised form 23 June 2011
Accepted 24 June 2011

Keywords:
Single-pass stover harvest system
Biofuel feedstock
Nutrient removal
Sustainability
Soil Management Assessment Framework (SMAF)
Renewable energy assessment project (REAP)

ABSTRACT

Sustainable feedstock harvest strategies are needed to ensure bioenergy production does not irreversibly degrade soil resources. The objective for this study was to document corn (*Zea mays* L.) grain and stover fraction yields, plant nutrient removal and replacement costs, feedstock quality, soil-test changes, and soil quality indicator response to four stover harvest strategies for continuous corn and a corn–soybean [*Glycine max*. (L.) Merr.] rotation. The treatments included collecting (1) all standing plant material above a stubble height of 10 cm (whole plant), (2) the upper-half by height (ear shank upward), (3) the lower-half by height (from the 10 cm stubble height to just below the earshank), or (4) no removal. Collectable biomass from Treatment 2 averaged 3.9 ($\pm$0.8) Mg ha^{-1} for continuous corn (2005 through 2009), and 4.8 ($\pm$0.4) Mg ha^{-1} for the rotated corn (2005, 2007, and 2009). Compared to harvesting only the grain, collecting stover increased the average N–P–K removal by 29, 3 and 34 kg ha^{-1} for continuous corn and 42, 3, and 34 kg ha^{-1} for rotated corn, respectively. Harvesting the lower-half of the corn plant (Treatment 3) required two passes, resulted in frequent plugging of the combine, and provided a feedstock with low quality for conversion to biofuel. Therefore, Treatment 3 was replaced by a "cobs-only" harvest starting in 2009. Structural sugars glucan and xylan accounted for up to 60% of the chemical composition, while galactan, arabinan, and mannose constituted less than 5% of the harvest fractions collected from 2005 through 2008. Soil-test data from samples collected after the first harvest (2005) revealed low to very low plant-available P and K levels which reduced soybean yield in 2006 after harvesting the whole-plant in 2005. Average continuous corn yields were 21% lower than rotated yields with no significant differences due to stover harvest. Rotated corn yields in 2009 showed some significant differences, presumably because soil-test P was again in the low range. A soil quality analysis using the Soil Management Assessment Framework (SMAF) with six indicators showed that soils at the continuous corn and rotated sites were functioning at an average of 93 and 83% of their inherent potential, respectively. With good crop management practices, including routine soil-testing, adequate fertilization, maintenance of soil organic matter, sustained soil structure, and prevention of wind, water or tillage erosion, a portion of the corn stover being produced in central Iowa, USA can be harvested in a sustainable manner.

1. Introduction

Current U.S. biofuel production is dominated by ethanol made from corn grain or biodiesel made predominantly from soybean oil. On an energy equivalent basis (Btu), corn grain ethanol and soybean biodiesel accounted for 2.1% of the total U.S. liquid transportation fuel in 2007 (EIA, 2007). However, the social, economic, and environmental effects of domestic biofuels have been mixed. Diverting corn, soybean oil, or other food crops to biofuel production has been implicated for inducing competition between food, feed, and fuel, but increases in crop price have also helped revive rural economies (Parcell and Westhoff, 2006). From the perspective of farmers and small rural communities, development of ethanol plants created greater local demand for commodity crops and higher prices for corn and soybean. Local investment and control of ethanol and biodiesel plants has reinvigorated many small Midwestern communities by providing well-paying employment opportunities, but some argue that the number of jobs added to the local economy is overestimated (Low and Isserman, 2009).

Cellulosic biomass, as a biofuel feedstock, has numerous advantages over corn, soybean, and other grains, including its availability from sources that do not compete with food and feed production. Biomass can be reclaimed from municipal solid waste streams and from residual products of certain forestry and farming operations. It can also be grown on idle or abandoned cropland thus minimizing competition with food, feed and fiber production.

* Corresponding author. Tel.: +1 515 294 3336; fax: +1 515 294 8125.
E-mail addresses: Doug.Karlen@ars.usda.gov (D.L. Karlen), sbirrell@iastate.edu (S.J. Birell), jrichard.hess@inl.gov (J.R. Hess).

0167-1987/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2011.06.006

Plant biomass has the potential to play an important role in the global energy future because it can be grown in a sustainable manner and converted into liquid transportation fuels using biochemical, thermochemical or catalytic conversion processes. Biofuels made from renewable feedstocks are an attractive alternative to gasoline because they can decrease the net release of greenhouse gases (GHG) from the transportation sector.

Corn stover, the aboveground material left in fields after corn grain harvest, was identified as a primary biomass source in the Billion Ton Report (Perlack et al., 2005). This raised concern among many soil scientists because harvesting crop residues for biofuel feedstock or any other purpose will decrease annual carbon input and may gradually diminish soil organic carbon (SOC) to a level that threatens the soil's production capacity (Johnson et al., 2006). Concerns were accentuated knowing that for many soils artificial drainage, intensive annual tillage, and less diverse plant communities have already reduced SOC by 30–50% when compared to pre-cultivation levels (Schlesinger, 1985). Returning a portion of crop residues to replenish SOC was deemed essential for sustainability (Lal, 2004a,b; Wilhelm et al., 2007).

Harvesting corn stover as a feedstock for biofuel production could have many benefits, if the process is developed as a complete system that considers all ecosystem services provided by crop residues (Larson, 1979; Karlen et al., 1984; Wilhelm et al., 2010). This includes conserving soil water, reducing surface runoff and evaporation, increasing infiltration rates, controlling soil erosion, recycling plant nutrients, providing habitat and energy for earthworms and other soil macro- and micro-organisms, improving water quality by denaturing and filtering of pollutants, improving soil structure, preserving native habitats, and maintaining biodiversity. Crop residues also help reduce non-point source pollution, decrease sedimentation, minimize risks of anoxia and dead zones in coastal ecosystems, increase agronomic productivity, advance food security, and mitigate flooding by holding water on the land rather than allowing it to run off into streams and rivers (Kimble et al., 2007).

One of the first steps in developing sustainable feedstock harvest programs is to understand the soil resource where the action will be carried out. This is especially true with respect to carbon cycling, since SOC is at least partially responsible for many qualities of productive soils (Kay, 1998; Doran et al., 1998; Doran, 2002; Janzen et al., 1998; Lal et al., 1990; Tisdall and Oades, 1982). Larson et al. (1972) showed that SOC was linearly related to the quantity of residue added, but establishing a direct linkage between stover harvest and subsequent grain yield is difficult. Some studies have shown that residue removal reduces grain and stover yield in subsequent crops (Wilhelm et al., 1986) and further lowers SOC levels (Clapp et al., 2000; Maskina et al., 1993), but others have shown either no effect or even increases in subsequent grain yields (Karlen et al., 2011). Lal (2004a) and Wilhelm et al. (2004, 2007) concluded that returning a portion of the crop residue to soils was crucial for replenishing SOC and that doing so was a fundamental requirement for sustainable soil and crop management.

Soil quality assessment, using tools such as the Soil Management Assessment Framework (SMAF) developed by Andrews et al. (2004), is one approach for evaluating stover harvest effects (Karlen et al., 2011). The SMAF is a useful tool because it is sensitive to various soil quality indicators including SOC and nutrient cycling as well as to crop management practices such as tillage, rotation, or N fertilization (Karlen et al., 2006; Wienhold et al., 2006; Zobeck et al., 2008).

Based on studies by Johnson et al. (2006, 2007, 2009), an approach for balancing the use of crop residues as a feedstock for biofuel or other bioproducts with the need for their ecosystem services is to increase stover yields so that a minimum of 2.2–4.5 Mg ha^{-1} of stover can be collected while still retaining enough crop residue to sustain the soil resource. Technologies such as site-specific management of fertilizer and pesticide inputs (Giles and Slaughter, 1997; Tian et al., 1999; Ferguson et al., 2002; Khosla et al., 2002; Robert, 2002), drain tiles and terraces (Zhang et al., 2002), in-field targeting to address variable source contaminates, field-edge and landscape-scale conservation practices (Berry et al., 2003), rotations and tillage practices within individual fields (Kitchen et al., 2005), and water quality monitoring across watersheds and eco-regions (Hatch et al., 2001) will help achieve those goals. Soil resource management must focus on producing what is needed to make more complex agricultural systems work rather than simply taking what is easily available.

Prior experience with site-specific soil and crop management led to the vision for a single-pass corn harvesting system that would enable producers to harvest grain and stover simultaneously. Properly designed, the machine could harvest corn stover at different rates depending upon landscape position or other factors. By understanding the entire agricultural production system, land-use decisions could be made so that it would be feasible to harvest feedstock for biofuel production without having a long-term negative impact on soil resources.

The objective for this study was to document corn (*Zea mays* L.) grain and stover fraction yields, plant nutrient removal and replacement costs, feedstock quality for subsequent biochemical conversion of the stover to ethanol or other advanced biofuels, soil-test changes, and soil quality indicator response to four stover harvest strategies for continuous corn and a corn–soybean rotation.

2. Methods and materials

2.1. Site selection and general management practices

This study was initiated in the autumn of 2005 in response to a U.S. Department of Energy (DOE) Office of Biomass Programs request for help in determining the feasibility of achieving Billion Ton Report (Perlack et al., 2005) goals. A pilot project (Hoskinson et al., 2007) was conducted and continued for an additional four years. Since the request did not occur until the latter part of the 2005 growing season in U.S. Corn/Soybean Belt, the two fields selected for this study had simply been scheduled for "bulk" crop production. Similar soil and crop management practices were continued through 2009 as documented in Table 1.

2.2. Stover harvest strategies

Corn stover harvest treatments were imposed on 12-row (76 cm row spacing) wide plots with a commercial scale John Deere[1] combine. The treatments were designed to collect (1) all standing plant material (whole plant), (2) the upper-half of the plant (by height) which included cobs, sheath, stalk, and leaves, (3) the lower-half (by height) which was primarily stalk with a few leaves, or (4) no removal. Harvest treatments were accomplished using a row-crop header that harvested six rows with each pass. Stalks were cut at a height of approximately 10 cm for Treatment 1 and just below the ear shank for Treatment 2. Treatment 3 required two passes, the first to collect grain and return the material other than grain (MOG) from the ear shank upward to the soil, and then a second pass to cut the lower portion of the corn plants at a stubble height of approximately 10 cm. Starting in 2009, Treatment 3 was changed to a "cobs only" treatment because that plant fraction

[1] Mention of a trade mark or proprietary product is for information only and does not imply any endorsement of that product to the exclusion of another by the USDA-ARS, DOE, or Iowa State University (ISU).

Table 1
Cultivar and fertilization rates used to produce corn stover harvested as feedstock for potential bioenergy production.

Year	Continuous corn		Rotated corn	
	Cultivar	Fertilization (N–P–K) ($kg\,ha^{-1}$)	Cultivar	Fertilization (N–P–K) ($kg\,ha^{-1}$)
2005	DeKalb 52-45	90–0–0	Fontenell 92M70	196–0–0
2006	Pioneer Brand 35Y61	175–0–0	Merschman Apache 626RR[a]	0–0–0
2007	Agrigold 6395	181–26–100	Pioneer Brand 34A20	204–49–184
2008	DeKalb 61-69	223–0–0	Pioneer Brand 92M11[a]	0–0–0
2009	DeKalb 52-59 VT3	169–20–112	DeKalb 52-59 VT3	185–20–112

[a] Soybean.

provided a better potential feedstock than the lower half of the plant. For the no-removal plots (Treatment 4), a conventional corn head was used so that only the ear, sheath, and a few vegetative plant parts passed through the combine. Each treatment was replicated three times for a continuous corn and corn-soybean cropping system. Plot length was approximately 500 m at the continuous corn site and approximately 900 m at the rotated site. No crop residue was removed following soybean at the rotated site.

2.3. Soil sampling, analyses, and fertilizer recommendations

After the 2005, 2007, and 2009 harvests, composite soil samples were collected to a depth of 15 cm from each plot. The samples were weighed, mixed by hand, and a sub-sample (100 g) was removed and dried at 104 °C to determine soil water content. The field-moist weight was adjusted to a dry weight and divided by the volume represented by the composite sample to provide an estimate of field bulk density (BD). The remaining field-moist soil sample was passed through an 8-mm screen, air-dried, and then crushed to pass a 2 mm screen. For 2005 and 2007, soil samples were analyzed within the NLAE. Soil pH and electrical conductivity (EC) were measured on a subsample using a 1:1 soil to water ratio (Watson and Brown, 1998; Whitney, 1998a). Another sub-sample was extracted using Mehlich III (Mehlich, 1984) solution and analyzed using an inductively coupled plasma-atomic emission spectrograph (ICP-AES) to determine phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) concentrations. A third subsample was extracted with diethylene–triamine–pentaacetic acid (DTPA) as described by Whitney (1998b) and analyzed for extractable copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn). A fourth sub-sample was pulverized before analyzing for total carbon (TC) and total nitrogen (TN) using dry combustion. For samples with pH values greater than 7.3, inorganic C (IC) was also determined (Wagner et al., 1998). The total organic carbon (TOC) values were then calculated as the difference between TC and IC with the latter being zero for samples with pH < 7.3.

The 2009 samples were submitted to a commercial soil-test. Similar analytical procedures were used for pH, EC, and the micronutrients, but P concentrations were measured using a Bray extract (Bray and Kurtz, 1945) and K, Ca, and Mg concentrations were measured after extracting with 1 M ammonium-acetate (NH_4OAc) at pH 7.0 (Warncke and Brown, 1998). The soil-test results for 2005 and 2007 were used to determine P and K fertilizer rates (Table 1) for 2007 through 2009 seasons based on (Sawyer et al., 2006). All N fertilizer applications were made using anhydrous ammonia (NH_3) or urea–ammonium nitrate (UAN) solution as selected by the ISU farm managers.

2.4. Soil quality assessment

The soil data were also used as input for the SMAF which provided a soil quality index for each stover harvest strategy based on six indicators. A SMAF assessment consists of three steps: indicator selection, indicator interpretation, and integration into a soil quality index (Andrews et al., 2004). The indicator selection step uses an expert system of decision rules to recommend indicators for inclusion in the assessment based on the user's stated management goals, location, and current practice. For the indicator interpretation step, observed indicator data are transformed into unitless scores based on clearly defined, site-specific relationships to soil function. The soil functions of interest include crop productivity, nutrient cycling, physical stability, water and solute flow, contaminant filtering and buffering, and biodiversity. The indicator interpretation step uses various factors (*i.e.* organic matter, texture, climate, slope, region, mineralogy, weathering class, crop, sampling time, and analytical method) to adjust threshold values in the scoring curves that are then used to assign a relative value of 0–1 for each type of data being collected. The integration steps allows for the individual indicator scores to be combined into a single index value. This can be done with equal or differential weighting for the various indicators depending upon the relative importance of the soil functions for which they are being measured (Karlen et al., 2008). For this study, soil pH, EC, and soil-test P and K were used to represent the chemical properties; SOC was used to represent biological properties; and BD was used to represent soil physical properties.

2.5. Stover collection and analysis

During harvest, corn grain was separated by the combine and routed to the grain tank. Stover passed through the combine and into a chopper/blower system that deposited the material into a trailing wagon that was equipped with load-cells. Corn grain was transferred from the combine to a weigh-wagon after harvesting each plot. Weights were recorded for both grain and stover and sub-samples were collected to determine the water content. An electronic moisture meter was used for grain, but for stover, the samples were dried at 70 °C in a forced air oven until they reached a constant weight. Stover samples were ground to pass a 2 mm screen before sub-sampling and grinding again to pass a 0.5 mm screen. Carbon (C) and N concentrations were determined by dry combustion using a Carlo-Erba NA1500 NCS elemental analyzer (Haake Buchler Instruments, Paterson, NJ). A second portion of each finely ground sample was sent to a commercial laboratory where the remaining nutrient concentrations were determined.

A second portion of the 2-mm sample was submitted to the Idaho National Laboratory (INL) where the sugar profile was determined in order to calculate minimum ethanol selling price (MESP) based on stover composition. The 2-mm samples were passed through a knife mill with a 1 mm stainless-steel screen. Chemical composition was determined using spectra created on a Foss 6500 NIR instrument that were then fitted with the National Renewable Energy Laboratory (NREL) corn stover calibration model (Hames et al., 2003). The NREL-derived equation: $MESP = 0.7155x^{-09592}$ where x = structural sugars was used to calculate MESP (Ruth and Thomas, 2003).

Nutrient replacement costs were calculated by multiplying nutrient concentrations in the stover by stover yield and fertilizer cost. Statistical analyses were run separately for the continuous corn and rotated site using a General Linear Model (GLM) available with SAS software packages (SAS Institute, 1990).

3. Results and discussion

3.1. Grain and stover yields

Grain and stover yields for each of the treatments are presented in Table 2. Continuous corn grain yields were statistically different ($p \leq 0.05$) in 2007, when the non-removal treatment had lower grain yield than either the whole plant or upper-half treatment. For the three years of rotated corn (2005, 2007, and 2009), grain yields were significantly different only in 2009 when the non-removal and upper-half treatments had higher yields than "whole plant" or "cob only" treatments. This inconsistency among stover harvest treatment effects and the generally non-significant grain yield response is consistent with initial multi-location results that showed no detectable short-term yield response to partial stover harvest at several U.S. locations (Karlen et al., 2011). The most consistent corn grain response was the 21% lower average yield for continuous corn than for rotated corn. This result is consistent with many other studies (e.g. Karlen et al., 1994, 2006). The most unexpected grain yield response occurred at the rotated site in 2006 when soybean yields were lower for all three treatments where corn stover had been harvested in 2005 and especially for the whole plant treatment which had a soybean yield that was 31% lower than for the non-removal treatment. As discussed below, this one-time response was ultimately explained by soil-test data, but one of the most useful outcomes of that experience has been the ability to alert those considering stover harvest to the importance of having good soil-test records and nutrient management information before they initiate any harvest strategy.

As expected, there were statistically significant differences in the amount of stover harvested for the various treatments (Table 2). When averaged for either the three (rotated corn) or five (continuous corn) years, both rotations showed that Treatment 2 (upper half) accounted for 75% of the collectable material. Harvesting the lower half of the plant (by height) required a second pass across the field and often resulted in plugging of the combine because the material would not flow uniformly into the machine. The two lowest stover yields for Treatment 3 (2007 and 2008) were associated with substantial lodging and therefore a lower cutting height was required to get below the ear shank for Treatment 2 (upper half). Also, during those years, stalk rot significantly reduced the mass of the lower stalk fraction. Finally, because of the low stover quality (discussed below), Treatment 3 was changed to "cobs only" in 2009. With regard to the long-term soil carbon balance this harvest management change is not expected to have a detectable impact since the amount of biomass and therefore carbon removal associated with the cob fraction was similar to Treatment 3 during the first two years of this study (Table 2).

3.2. Soil test results

Due to the unexpected soybean yield decrease in 2006, priority was given to analyzing soil samples that had been collected and stored following the 2005 harvest. The soil-test results (Tables 3 and 4) show that Mehlich 3 extractable P and K concentrations at the rotated site were in the low to very low range based on ISU soil-test interpretations (Sawyer et al., 2006). At the continuous corn site, average P and K levels were slightly higher, but the ratings were still in the low to medium categories. The soil analyses also showed a large difference in TOC between the two fields. However, this was expected since the dominant soil series at the continuous site is Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) silty clay loam, while at the rotated site it is Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludolls) loam. The higher bulk density values at the rotated site are attributed to the lower TOC content reflecting the landscape position and presumably greater historical soil erosion because of slope differences. The pH analyses also show the anticipated differences between a calcareous and non-calcareous soil but no

Table 2
Grain and stover harvest yields for continuous and rotated corn near Ames, Iowa USA.

Harvest scenario	2005	2006	2007	2008	2009	Average
Continuous corn – Grain yield (Mg ha^{-1})						
Whole plant	10.4	9.4	12.0	7.8	9.8	9.9
Upper half	10.4	9.5	12.0	8.2	9.5	10.0
Lower half	10.4	9.2	11.8	8.2	9.7[a]	9.8
No removal	10.4	9.0	11.4	8.1	9.6	9.7
$LSD_{(0.05)}$	NS	NS	0.5	NS	NS	NS
Continuous corn – Stover yield (Mg ha^{-1})						
Whole plant	4.70	6.14	5.60	4.20	5.39	5.33
Upper half	2.91	4.98	4.40	3.37	3.65	4.00
Lower half	1.26	1.48	0.70	0.74	1.31[a]	1.18
No removal	–	–	–	–	–	–
$LSD_{(0.05)}$	0.37	0.16	0.45	0.79	0.66	0.20

	2005	2006	2007	2008	2009	Average	
						Corn	Soybean
Rotated corn and soybean – Grain yield (Mg ha^{-1})							
Whole plant	12.7	2.21[a]	13.2	3.44[a]	11.5	12.5	2.83
Upper half	12.4	2.83	12.8	3.66	12.2	12.5	3.25
Lower half	11.7	2.80	13.4	3.41	11.4[a]	12.1	3.11
No removal	12.4	3.20	13.0	3.70	12.3	12.6	3.45
$LSD_{(0.05)}$	NS	0.61	NS	NS	0.7	NS	NS
Rotated corn and soybean – Stover yield (Mg ha^{-1})							
Whole plant	7.11	–	5.67	–	6.84	6.96	–
Upper half	4.58	–	4.93	–	5.08	5.18	–
Lower half	1.48	–	1.56	–	1.72[a]	1.69	–
No removal	–	–	–	–	–	–	–
$LSD_{(0.05)}$	1.78	–	1.79	–	0.48	0.67	–

[a] Cobs only starting in 2009.

Table 3
Post-harvest 0–15 cm soil-test status following the 2005, 2007 and 2009 harvest from a continuous corn site.

Harvest fraction	Bulk density ($g\,cm^{-3}$)	TOC ($g\,kg^{-1}$)	NO_3–N ($mg\,kg^{-1}$)	pH	EC ($\mu s\,cm^{-1}$)	P[a] ($mg\,kg^{-1}$)	K[a] ($mg\,kg^{-1}$)
2005							
Whole plant	1.25	54.4	11	7.7	555	36	145
Upper half	1.28	53.2	9	7.6	543	27	125
Lower half	1.22	54.4	11	7.8	535	28	118
No removal	1.26	52.6	10	7.8	565	35	127
$LSD_{(0.05)}$	NS	NS	NS	NS	NS	NS	NS
2007							
Whole plant	1.07	47.3	12	7.2	453	24	155
Upper half	1.11	43.9	14	7.4	410	20	149
Lower half	1.09	43.2	16	7.5	438	27	176
No removal	1.08	39.6	15	7.5	350	20	139
$LSD_{(0.05)}$	NS	NS	NS	0.2	NS	NS	NS
Harvest fraction	Bulk density ($g\,cm^{-3}$)	TOC ($g\,kg^{-1}$)	NO_3–N ($mg\,kg^{-1}$)	pH	EC ($\mu s\,cm^{-1}$)	P[b] ($mg\,kg^{-1}$)	K[c] ($mg\,kg^{-1}$)
2009							
Whole plant	1.15	29.3	6	7.6	504	12	150[b]
Upper half	1.20	30.3	6	7.6	508	16	158
Lower half	1.13	30.9	6	7.6	516	13	171
No removal	1.22	29.7	7	7.6	501	12	157
$LSD_{(0.05)}$	NS	NS	NS	NS	NS	NS	NS

[a] Mehlich III extractable.
[b] Bray P.
[c] NH_4OAc extractable.

other trends or notable differences. The EC values are low indicating no salinity or soluble salt problems. Post-harvest soil NO_3–N levels were typical for central Iowa soils (Jaynes et al., 2001). Soil-test P and TOC values following the 2009 harvest were lower than following the 2005 and 2007 harvests, but those differences are attributed primarily to the analyses being run in different laboratories and for P using a different extracting solution. With the exception of soil pH for the 2007 sampling at the continuous corn site, none of the soil-test parameters showed significant differences due to the stover harvest strategies imposed for either three (rotated site) or five (continuous corn) years.

3.3. Soil quality assessments

Three separate SMAF analyses were run for each location using average post-harvest soil-test data from 2005, 2007, and 2009 (Table 5). The continuous corn site had a low BD score following the 2005 harvest and a slightly lower score following the 2009 harvest, perhaps because of compaction associated with harvest operations. This was not evident following the 2007 harvest. There was a slight decline in the TOC score between 2005 and 2007 followed by a rather large decline in 2009. This decline could indicate an effect due to less carbon input, but there were no statistical differences in TOC (Table 3) among harvest strategies. It may also reflect the change in laboratories, even though the analytical method (dry combustion) was the same. The K scores increased from 2005 to 2008 (Table 5), reflecting the increased soil-test values in response to higher K fertilization rates (Table 1). The overall SQI for this site indicated that the soil was functioning at 90–97% of its inherent potential following five years of stover harvest. The rotated site had much lower indicator scores for TOC and soil-test K for all three samplings and a slightly lower score for

Table 4
Post-harvest 0–15 cm soil-test status following the 2005, 2007 and 2009 harvest from a rotated corn–soybean site.

Harvest fraction	Bulk density ($g\,cm^{-3}$)	TOC ($g\,kg^{-1}$)	NO_3–N ($mg\,kg^{-1}$)	pH	EC ($\mu s\,cm^{-1}$)	P[a] ($mg\,kg^{-1}$)	K[a] ($mg\,kg^{-1}$)
2005							
Whole plant	1.34	19.2	17	6.6	267	24	100
Upper half	1.37	18.7	16	6.7	241	19	80
Lower half	1.39	19.1	17	6.6	236	26	124
No removal	1.38	19.2	18	6.7	242	24	74
$LSD_{(0.05)}$	NS	NS	NS	NS	22	NS	NS
2007							
Whole plant	1.24	18.6	14	6.3	162	24	112
Upper half	1.17	18.9	11	6.9	188	29	140
Lower half	1.12	20.8	14	6.6	190	20	121
No removal	1.21	16.4	10	6.6	156	24	122
$LSD_{(0.05)}$	NS	NS	NS	NS	NS	NS	NS
Harvest fraction	Bulk density ($g\,cm^{-3}$)	TOC ($g\,kg^{-1}$)	NO_3–N ($mg\,kg^{-1}$)	pH	EC ($\mu s\,cm^{-1}$)	P[b] ($mg\,kg^{-1}$)	K[c] ($mg\,kg^{-1}$)
2009							
Whole plant	1.32	15.0	6	6.6	243	12	100
Upper half	1.33	14.5	6	6.6	252	20	110
Lower half	1.20	15.5	7	6.7	268	13	111
No removal	1.30	15.5	6	6.8	258	15	146
$LSD_{(0.05)}$	NS	NS	NS	NS	NS	NS	NS

[a] Mehlich III extractable.
[b] Bray P.
[c] NH_4OAc extractable.

Table 5
A SMAF analysis using mean post-harvest soil-test values for 2005, 2007, and 2009.

Year	Treatment	Indicator scores						Index
		TOC	BD	pH	EC	P	K	SQI
Continuous corn								
2005	Whole plant	0.99	0.68	0.94	1.00	1.00	0.92	0.92
2005	Upper half	0.99	0.61	0.95	1.00	1.00	0.87	0.90
2005	Lower half	0.99	0.76	0.94	1.00	1.00	0.85	0.92
2005	No removal	0.99	0.66	0.94	1.00	1.00	0.88	0.91
	Average	0.99	0.68	0.94	1.00	1.00	0.88	0.92
2007	Whole plant	0.97	0.99	0.98	1.00	1.00	0.94	0.98
2007	Upper half	0.95	0.96	0.96	1.00	1.00	0.93	0.97
2007	Lower half	0.94	0.98	0.96	1.00	1.00	0.97	0.97
2007	No removal	0.90	0.98	0.96	1.00	1.00	0.91	0.96
	Average	0.94	0.98	0.96	1.00	1.00	0.94	0.97
2009	Whole plant	0.65	0.91	0.95	1.00	1.00	0.93	0.91
2009	Upper half	0.68	0.80	0.95	1.00	1.00	0.95	0.90
2009	Lower half	0.70	0.94	0.95	1.00	1.00	0.97	0.93
2009	No removal	0.66	0.76	0.95	1.00	1.00	0.94	0.89
	Average	0.67	0.85	0.95	1.00	1.00	0.95	0.90
Rotated corn								
2005	Whole plant	0.41	0.93	1.00	1.00	1.00	0.66	0.83
2005	Upper half	0.38	0.88	1.00	1.00	0.98	0.57	0.80
2005	Lower half	0.40	0.84	1.00	1.00	1.00	0.74	0.83
2005	No removal	0.41	0.86	1.00	1.00	1.00	0.54	0.80
	Average	0.40	0.88	1.00	1.00	0.99	0.63	0.82
2007	Whole plant	0.38	0.99	1.00	0.95	1.00	0.70	0.84
2007	Upper half	0.39	0.99	0.99	1.00	1.00	0.79	0.86
2007	Lower half	0.48	0.99	1.00	1.00	0.98	0.73	0.86
2007	No removal	0.24	0.99	1.00	0.92	1.00	0.74	0.82
	Average	0.37	0.99	1.00	0.97	1.00	0.74	0.85
2009	Whole plant	0.24	0.96	1.00	1.00	0.92	0.66	0.80
2009	Upper half	0.22	0.95	1.00	1.00	0.98	0.70	0.81
2009	Lower half	0.26	0.99	1.00	1.00	0.94	0.70	0.81
2009	No removal	0.26	0.97	0.99	1.00	0.96	0.80	0.83
	Average	0.24	0.97	1.00	1.00	0.95	0.71	0.81

soil-test P following the 2009 harvest. The BD score following the 2005 harvest was 10% lower than after the 2007 or 2009 harvest, again presumably reflecting compaction associated with the harvest operation. The overall SQI for the rotated site indicated the soil was functioning at 81–85% of its potential following three stover harvests. The SMAF assessments for both sites were consistent with those reported for other corn stover harvest sites by Karlen et al. (2011).

3.4. Stover nutrient removal

In addition to measuring the quantity of corn stover that could be harvested for each of the treatments (Table 2), the concentrations of several essential plant nutrients were also measured and used to calculate the increase in nutrient removal compared to harvesting only the grain (Table 6). As expected, nutrient removal directly reflected the amount of stover harvested, although plant part did influence the concentrations of nutrients such as K which were higher in the lower half of the plant than in the upper half (data not presented). With regard to feedstock quality for conversion, high K is not desirable and is another reason for leaving the lower portion of the corn plant in the field rather than harvesting it. This also contributed to the decision to convert Treatment 3 to "cobs only" in 2009. Overall, average N–P–K removal was increased by 29, 3, and 34 kg ha^{-1} for continuous corn and 42, 3, and 34 kg ha^{-1} for rotated corn, respectively, when compared to harvesting only the grain. We also quantified the increases, compared to grain-only harvest, in secondary (Ca, Mg, and S) and micronutrient (Cu, Fe, Mn, and Zn) removal for each of the stover harvest scenarios. As expected, all values were proportional to the amount of material removed as the concentrations among plant fractions were relatively consistent (data not presented).

3.5. Fertilizer replacement cost

The increased nutrient removal values were used to help predict the fertilizer costs that might be incurred by implementing the various stover harvest scenarios (Table 7). Obviously, fertilizer price is a major and ever-changing factor that is closely associated with petroleum and transportation costs. Therefore, the estimated nutrient replacement costs have fluctuated a great deal throughout the five years of study and will continue to do so throughout the future. One of the most revealing results, however, was the consistency in total nutrient replacement cost when computed per unit (*i.e.* Mg or metric ton) despite the differences in nutrient concentrations for the various plant fractions (data not shown). Having documented the consistent value of $\$19 \pm \$1$ Mg^{-1}, it is now more feasible to determine a fair market value for both feedstock producers and consumers than when the Billion Ton Report was released.

3.6. Stover quality assessments

In addition to measuring plant nutrient concentrations in the various stover fractions, feedstock quality was evaluated by measuring sugar profiles and using them to calculate a minimum ethanol selling price (MESP). The NIR predictions of compositional chemistry for the harvest scenarios from the first four years indicated differences among plant fractions rotations (Table 8).

Table 6
The average increase in plant nutrient removal for various stover harvest scenarios in central Iowa, USA.

Harvest scenario	Continuous corn				
	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})
Whole plant	29	2.7	34	21	11
Upper half	22	2.1	27	13	7
Lower half	6	0.6	8	4	3
No removal	–	–	–	–	–
LSD$_{(0.05)}$	4	0.6	4	4	2
Harvest scenario	**Continuous corn**				
	S (kg ha^{-1})	Cu (g ha^{-1})	Fe (g ha^{-1})	Mn (g ha^{-1})	Zn (g ha^{-1})
Whole plant	1.8	16	412	131	90
Upper half	1.5	12	277	74	71
Lower half	0.3	2	136	31	18
No removal	–	–	–	–	–
LSD$_{(0.05)}$	0.3	6	171	65	32
Harvest scenario	**Rotated corn and soybean**				
	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})
Whole plant	42	3.3	34	21	18
Upper half	34	3.5	28	13	10
Lower half	10	0.7	10	4	4
No removal	–	–	–	–	–
LSD$_{(0.05)}$	5	1.0	4	4	3
Harvest scenario	**Rotated corn and soybean**				
	S (kg ha^{-1})	Cu (g ha^{-1})	Fe (g ha^{-1})	Mn (g ha^{-1})	Zn (g ha^{-1})
Whole plant	2.3	20	438	113	62
Upper half	2.2	24	204	84	53
Lower half	0.5	4	106	17	12
No removal	–	–	–	–	–
LSD$_{(0.05)}$	0.5	13	110	14	25

Table 7
Stover harvest scenario effect on estimated plant nutrient replacement cost.

Nutrient	Cost[a]	Whole plant	Upper half	Lower half[b]
Continuous corn				
N	\$1.229 kg^{-1}	\$35.64	\$27.04	\$7.37
P	\$6.936 kg^{-1}	\$18.73	\$14.57	\$4.16
K	\$1.108 kg^{-1}	\$37.67	\$29.92	\$8.86
Ca	\$0.0672 kg^{-1}	\$1.41	\$0.87	\$0.27
Mg	\$0.1867 kg^{-1}	\$2.05	\$1.31	\$0.56
S	\$1.542 kg^{-1}	\$2.78	\$2.31	\$0.46
Cu	\$0.0229 g^{-1}	\$0.37	\$0.27	\$0.05
Fe	\$0.0056 g^{-1}	\$2.31	\$1.55	\$0.76
Mn	\$0.0072 g^{-1}	\$0.94	\$0.53	\$0.22
Zn	\$0.0088 g^{-1}	\$0.79	\$0.62	\$0.16
Total value per ha		\$102.69	\$79.00	\$22.88
Total value per Mg		\$19.27	\$19.75	\$19.39
Corn–soybean rotation				
N	\$1.229 kg^{-1}	\$51.62	\$41.79	\$12.29
P	\$6.936 kg^{-1}	\$22.89	\$24.28	\$4.86
K	\$1.108 kg^{-1}	\$37.67	\$31.02	\$11.08
Ca	\$0.0672 kg^{-1}	\$1.41	\$0.87	\$0.27
Mg	\$0.1867 kg^{-1}	\$3.36	\$1.87	\$0.75
S	\$1.542 kg^{-1}	\$3.55	\$3.39	\$0.77
Cu	\$0.0229 g^{-1}	\$0.46	\$0.55	\$0.09
Fe	\$0.0056 g^{-1}	\$2.45	\$1.14	\$0.59
Mn	\$0.0072 g^{-1}	\$0.81	\$0.60	\$0.12
Zn	\$0.0088 g^{-1}	\$0.55	\$0.47	\$0.11
Total value per ha		\$124.77	\$105.98	\$30.93
Total value per Mg		\$17.93	\$20.46	\$18.30

[a] Estimated fertilizer nutrient replacement costs using the most economical sources as provided by Dr. Julian Smith, Brandt Consolidate Ltd., via personal communication (December 2010).
[b] Cobs only starting in 2009.

Harvest fraction significantly affected the compositional estimates, although yearly environmental differences, plant growth differences between sites and corn hybrid differences were also possible underlying factors influencing the stover composition values.

NIR predictions suggest that glucan and xylan, accounted for up to 60% of the chemical composition in the harvested stover, while galactan, arabinan, and mannan accounted for less than 5%. Stover compositional profiles from whole plant and upper half treatments were not significantly different from each other ($p < 0.5$), but they were distinctly different from the lower half treatment in most cases. For example, the whole plant and upper half harvest fractions from both the continuous and rotated sites had lower estimated glucan but higher galactan and arabinan when compared to the lower half harvest fraction. The continuous corn site had significantly higher xylan and lower lignin in whole plant and upper half harvest scenarios compared to the lower half harvest scenario. However, the rotated site saw no significant difference in xylose, mannan, and lignin.

Another feedstock quality observation occurred in 2008 when harvest for one-third of the plots was delayed for approximately six weeks because of weather and machine scheduling conflicts. The NIR spectra indicated that late-harvest plots were different from the other plots, but statistically the differences were not detectable (data not presented).

3.7. Estimating the minimum ethanol selling price (MESP)

The MESP was calculated using the structural sugar data to determine the value of each harvest fraction for ethanol production. Lower MESP values result in more favorable process economics. Calculations for harvest fractions from the continuous corn site show that MESP for the whole plant and upper half fractions were significantly lower in 2007 and 2008

Table 8
Average sugar and lignin concentrations in corn stover collected during 2005 through 2008 using various harvest scenarios in central Iowa, USA.

Harvest scenario	Glucan ($g\,kg^{-1}$)	Xylan ($g\,kg^{-1}$)	Galactan ($g\,kg^{-1}$)	Arabinan ($g\,kg^{-1}$)	Mannan ($g\,kg^{-1}$)	Lignin ($g\,kg^{-1}$)
Continuous corn						
Whole plant	364	223	16.6	31.5	5.2	144
Upper half	358	224	16.9	32.4	5.0	138
Lower half	380	204	13.4	23.5	4.8	165
No removal	–	–	–	–	–	–
$LSD_{(0.05)}$	9	8	2.2	2.7	NS	8
Rotated corn						
Whole plant	355	214	14.9	27.5	4.9	144
Upper half	347	221	15.8	30.4	5.8	134
Lower half	376	187	9.8	18.2	4.7	157
No removal	–	–	–	–	–	–
$LSD_{(0.05)}$	16	NS	2.9	3.9	NS	NS

Table 9
Stover sugar profile effects on minimum ethanol selling price (MESP) for various 2005 through 2008 harvest scenarios in central Iowa, USA.

Harvest scenario	2005 (US $)	2006 (US $)	2007 (US $)	2008 (US $)
Continuous corn				
Whole plant	1.12	1.12	1.09	1.07
Upper half	1.10	1.15	1.08	1.08
Lower half	1.12	1.15	1.10	1.12
No removal	–	–	–	–
$LSD_{(0.05)}$	NS	0.03	0.01	0.01
Rotated corn				
Whole plant	1.14	–	1.10	–
Upper half	1.13	–	1.14	–
Lower half	1.14	–	1.21	–
No removal	–	–	–	–
$LSD_{(0.05)}$	NS	–	NS	–

($LSD_{(0.05)}$ = $0.02) than in 2005 and 2006 (Table 9). The MESP for harvest fractions collected from the rotated site decreased for the whole plant fraction, increased for the bottom half, and increased slightly for the top half. The MESP was the highest for the lower half treatment at both sites. Overall, the whole plant and upper half treatments had the lowest MESP values.

In general, stover harvest fractions from the continuous corn site had higher levels of structural sugars and lower MESP than those from the rotated site. These differences may have been caused by soil resource differences since the continuous site is predominantly Canisteo soil located in a relatively flat area, while the rotated site is on Clarion soil located on hilltop and sideslope positions. The Canisteo site would generally be wetter and have less moisture stress than the Clarion site. Differences in structural sugars and MESP between sites and in harvest years could also reflect differences in corn hybrid. Soil and plant factors have both been shown to influence structural sugar composition (Ruth and Thomas, 2003; Sluiter et al., 2003).

4. Summary and conclusions

This five-year study documented grain and stover yields, nutrient composition and replacement cost, feedstock quality, soil fertility and soil quality effects of four corn stover harvest strategies. Preliminary results by Hoskinson et al. (2007) were confirmed and two long-term stover harvest research sites were developed. The results show that prior to initiating any harvest strategy producers should have good soil-test and nutrient management records for their harvest sites. This will help them avoid unintended nutrient deficiencies and subsequently lower yields. Practices that will enhance the sustainability of stover harvest include replacement of additional plant nutrients removed with the stover, inclusion of annual or perennial cover crops, use of no-tillage, and crop rotation.

Harvesting corn stover increased the average N–P–K removal by 29, 3 and 34 kg ha^{-1} for continuous corn and 42, 3, and 34 kg ha^{-1} for rotated corn, respectively, when compared to harvesting only the grain. The lower half of the corn plant was shown to contribute very little to the total available feedstock biomass because of its high water content. Continued evaluations at these long-term sites will help address several logistical questions associated with stover harvest, storage and transport because of their physical size and management using commercial scale machinery.

Acknowledgement

This research was supported in part by the North Central Regional Sun Grant Center at South Dakota State University through a grant provided by the U.S. Department of Energy Office of Biomass Programs under award number DE-FC36-05GO85041.

References

Andrews, S.S., Karlen, D.L., Cambardella, C.A., 2004. The soil management assessment framework: a quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 68, 1945–1962.
Berry, J.K., Delgado, J.A., Khosla, R., Pierce, F.J., 2003. Precision conservation for environmental sustainability. J. Soil Water Conserv. 58, 332–339.
Bray, R.H., Kurtz, L.T., 1945. Determination of total, organic and available form of phosphorus in soil. Soil Sci. Soc. Am. Proc. 59, 39–45.
Clapp, C.E., Allmaras, R.R., Layese, M.F., Linden, D.L., Dowdy, R.H., 2000. Soil organic carbon and ^{13}C abundance as related to tillage, crop residue, and nitrogen fertilization under continuous corn management in Minnesota. Soil Till. Res. 55, 127–142.
Doran, J.W., 2002. Soil health and global sustainability: translating science into practice. Agric. Ecosys. Environ. 88, 119–127.
Doran, J.W., Elliott, E.T., Paustian, K., 1998. Soil microbial activity, nitrogen cycle, and long-term changes in organic carbon pools as related to fallow tillage management. Soil Till. Res. 49, 3–18.
Energy Information Administration (EIA), 2007. Annual Energy Review. Washington, D.C.
Ferguson, R.B., Hergert, G.W., Schepers, J.S., Gotway, C.A., Cahoon, J.E., Peterson, T.A., 2002. Site-specific management of irrigated maize: yield and soil residual nitrate effects. Soil Sci. Soc. Am. J. 66, 544–553.
Giles, D.K., Slaughter, D.C., 1997. Precision band sprayer with machine-vision guidance and adjustable yaw nozzles. Trans. ASABE 40, 29–36.
Hames, B.R., Thomas, S.R., Sluiter, A.D., Roth, C.J., Templeton, D.W., 2003. Rapid biomass analysis: new tools for compositional analysis of corn stover feedstocks and process intermediates from ethanol production. Appl. Biochem. Biotechnol. 105–108, 5–16.
Hatch, L.K., Mallawatantri, A., Wheeler, D., Gleason, A., Mulla, D., Perry, J., Easter, K.W., Smith, R., Gerlach, L., Brezonik, P., 2001. Land management at the major watershed–agroecoregion intersection. J. Soil Water Conserv. 56, 44–51.
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.
Janzen, H.H., Campbell, C.A., Izaurralde, R.C., Ellert, B.H., Juma, N.G., McGill, W.B., Zentner, R.P., 1998. Management effects on soil C storage on the Canadian prairies. Soil Till. Res. 47, 181–195.

Jaynes, D.B., Colvin, T.S., Karlen, D.L., Cambardella, C.A., Meek, D.W., 2001. Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. J. Environ. Qual. 30, 1305–1314.

Johnson, J.M.F., Allmaras, R.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., Coleman, M.D., Gesch, R., Jaradat, A., Mitchell, R., Reicosky, D., Wilhelm, W.W., 2007. Biomass–bioenergy crops in the United States: a changing paradigm. Am. J. Plant Sci. – Biotechol. 1, 1–28.

Johnson, J.M.F., Papiernik, S.K., Mikha, M.M., Spokas, K., Tomer, M.D., Weyers, S.L., 2009. Soil processes and residue harvest management. In: Lal, R., Steward, B. (Eds.), Carbon Management, Fuels, and Soil Quality. Taylor and Francis, LLC, New York, NY, pp. 1–44.

Karlen, D.L., Hunt, P.G., Campbell, R.B., 1984. Crop residue removal effects on corn yield and fertility of a Norfolk sandy loam. Soil Sci. Soc. Am. J. 48, 868–872.

Karlen, D.L., Varvel, G.E., Bullock, D.G., Cruse, R.M., 1994. Crop rotations for the 21st century. Adv. Agron. 53, 1–45.

Karlen, D.L., Hurley, E.G., Andrews, S.S., Cambardella, C.A., Meek, D.W., Duffy, M.D., Mallarino, A.P., 2006. Crop rotation effects on soil quality at three northern corn/soybean belt locations. Agron. J. 98, 484–495.

Karlen, D.L., Andrews, S.S., Wienhold, B.J., Zobeck, T.M., 2008. Soil quality assessment: past, present and future. J. Integr. Biosci. 6 (1), 3–14.

Karlen, D.L., Varvel, G.E., Johnson, J.M.F., Baker, J.M., Osborne, S.L., Novak, J.M., Adler, P.R., Roth, G.W., Birrell, S.J., 2011. Monitoring Soil quality to assess the sustainability of harvesting corn stover. Agron. J. 103, 288–295.

Kay, B.D., 1998. Soil structure and organic carbon: a review. In: Lal, R., et al. (Eds.), Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, FL, pp. 169–197.

Kimble, J.M., Rice, C.W., Reed, D., Mooney, S., Follett, R.F., Lal, R. (Eds.), 2007. Soil Carbon Management, Economic, Environmental, and Societal Benefits. Taylor and Francis, Boca Raton, FL.

Kitchen, N.R., Sudduth, K.A., Myers, D.B., Massey, R.E., Sadler, E.J., Lerch, R.N., 2005. Development of a conservation-oriented precision agriculture system: crop production assessment and plan implementation. J. Soil Water Conserv. 60, 421–430.

Khosla, R., Fleming, K., Delgado, J.A., Shaver, T.M., Westfall, D.G., 2002. Use of site-specific management zones to improve nitrogen management for precision agriculture. J. Soil Water Conserv. 57, 513–518.

Lal, R., 2004a. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627.

Lal, R., 2004b. Is crop residue a waste? J. Soil Water Conserv. 59, 136–139.

Lal, R., Logan, T.J., Fausey, N.R., 1990. Long-term tillage effects on Mollic Ochraqualf in northwestern Ohio. III. Soil nutrient profile. Soil Till. Res. 15, 371–382.

Larson, W.E., 1979. Crop residues: energy production or erosion control. J. Soil Water Conserv. 34, 74–76.

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.

Low, S.A., Isserman, A.M., 2009. Ethanol and the local economy: industry trends, location factors, economic impacts, and risks. Econ. Dev. Quart. 23 (1), 71–88.

Maskina, M.S., Power, J.F., Doran, J.W., Wilhelm, W.W., 1993. Residual effects on no-till crop residues on corn yield and nitrogen uptake. Soil Sci. Soc. Am. J. 57, 1555–1560.

Mehlich, A., 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15, 1409–1416.

Parcell, J.L., Westhoff, P., 2006. Economic effects of biofuel production on states and rural communities. J. Agric. Appl. Econ. 38 (2), 377–387.

Perlack, R.D., Wright, L.L., Turhollow, A.F., Graham, R.L., Stokes, B.J., Erbach, D.C., 2005. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. DOE/GO-102005-2135 and ORNL/TM-2005/66. Available at: http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf (accessed 20.06.11).

Robert, P.C., 2002. Precision agriculture: a challenge for crop nutrition management. Plant Soil 247, 143–149.

Ruth, M.F., Thomas, S.R., 2003. The effect of corn stover composition on ethanol process economics. In: 25th Symposium on Biotechnology for Fuels and Chemicals. Available at: http://www1.eere.energy.gov/biomass/pdfs/34040.pdf (accessed 20.06.11).

SAS Inst., 1990. SAS/STAT User's Guide. Version 6, 4th ed. SAS Inst., Cary, NC.

Sawyer, J.E., Mallarino, A.P., Killorn, R., Barnhart, S.K., 2006. General guide for crop nutrient recommendations in Iowa. Publication PM-1688 (revised). Iowa State Coop. Ext., Iowa State Univ., Ames.

Schlesinger, W.H., 1985. Changes in soil carbon storage and associated properties with disturbance and recovery. In: Trabalha, J.R., Reichle, D.E. (Eds.), The Changing Carbon Cycle: A Global Analysis. Springer-Verlag, New York, pp. 194–220.

Sluiter, A.D., Hayward, T.K., Jurich, C.K., Newman, M.M., Templeton, D.W., Ruth, M.F., Evans, K.W., Hames, B.R., Thomas, S.R., 2003. Compositional variability among corn stover samples. Available at: http://www1.eere.energy.gov/biomass/pdfs/33925.pdf (accessed 20.06.11).

Tian, L., Reid, L.F., Hummel, J.W., 1999. Development of a precision sprayer for site-specific weed management. Trans. ASABE 42, 893–900.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33, 141–163.

Wagner, S.W., Hanson, J.D., Olness, A., Voorhees, W.B., 1998. A volumetric inorganic carbon analysis system. Soil Sci. Soc. Am. J. 62, 690–693.

Warncke, D., Brown, J.R., 1998. Potassium and other basic cations. In: Brown, J.R. (ed.), Recommended Chemical Soil Test Procedures for the North Central region, NCR Publ. 221 (revised). Missouri Agric. Expt. Stn., Columbia, MO, pp. 31–34.

Watson, M.E., Brown, J.R., 1998. pH and lime requirement. In: Brown, J.R. (ed.), Recommended Chemical Soil Test Procedures for the North Central region, NCR Publ. 221 (revised). Missouri Agric. Expt. Stn., Columbia, MO, pp. 13–16.

Whitney, D.A., 1998a. Soil salinity. In: Brown, J.R. (ed.), Recommended Chemical Soil Test Procedures for the North Central region, NCR Publ. 221 (revised). Missouri Agric. Expt. Stn., Columbia, MO, pp. 59–60.

Whitney, D.A., 1998b. Micronutrients: zinc, iron, manganese and copper. In: Brown, J.R. (ed.), Recommended Chemical Soil Test Procedures for the North Central region, NCR Publ. 221 (revised). Missouri Agric. Expt. Stn., Columbia, MO, pp. 41–44.

Wienhold, B.J., Pikul Jr., J.L., Liebig, M.A., Mikha, M.M., Varvel, G.F., Doran, J.W., Andrews, S.S., 2006. Cropping system effects on soil quality in the Great Plains: synthesis from a regional project. Renewable Agric. Food Sys. 21, 49–59.

Wilhelm, W.W., Doran, J.W., Power, J.F., 1986. Corn and soybean yield response to crop residue management under no-tillage production systems. Agron. J. 78, 184–189.

Wilhelm, W.W., Johnson, J.M.F., Hatfield, J.L., Voorhees, W.B., Linden, D.R., 2004. Crop and soil productivity response to corn residue removal: a literature review. Agron. J. 96, 1–17.

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., Hess, J.R., Karlen, D.L., Johnson, J.M.-F., Muth, D.J., Baker, J.M., Gollany, H.T., Novak, J.M., Stott, D.E., Varvel, G.E., 2010. Balancing limiting factors and economic drivers for sustainable Midwestern US agricultural residue feedstock supplies. Ind. Biotechnol. 6 (5), 271–287.

Zhang, N., Wang, M.M., Wang, N., 2002. Precision agriculture – a worldwide overview. Comput. Electron. Agric. 36, 113–132.

Zobeck, T.M., Halvorson, A.D., Wienhold, B.J., Acosta Martinez, V., Karlen, D.L., 2008. Comparison of two soil quality indexes to evaluate cropping systems in northern Colorado. J. Soil Water Conserv. 63, 329–338.