Corn Stover Harvest Strategy Effects on Grain Yield and Soil Quality Indicators

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Recibido: 22/10/12 Aceptado: 15/10/13

Summary

Developing strategies to collect and use cellulosic biomass for bioenergy production is important because those materials are not used as human food sources. This study compared corn (*Zea mays* L.) stover harvest strategies on a 50 ha Clarion-Nicollet-Webster soil Association site near Emmetsburg, Iowa, USA. Surface soil samples (0 to 15 cm) were analyzed after each harvest to monitor soil organic carbon (SOC), pH, phosphorus (P) and potassium (K) changes. Grain yields in 2008, before the stover harvest treatments were imposed, averaged 11.4 Mg ha^{-1}. In 2009, 2010, and 2011 grain yields averaged 10.1, 9.7, and 9.5 Mg ha^{-1}, respectively. Although grain yields after stover harvest strategies imposed were lower than in 2008, there were no significant differences among the treatments. Four-year average stover collection rates ranged 1.0 to 5.2 Mg ha^{-1} which was 12 to 60% of the above-ground biomass. SOC showed a slight decrease during the study, but the change was not related to any specific stover harvest treatment. Instead, we attribute the SOC decline to the tillage intensity and lower than expected crop yields. Overall, these results are consistent with other Midwestern USA studies that indicate corn stover should not be harvested if average grain yields are less than 11 Mg ha^{-1}.

Keywords: bioenergy, biomass, sustainable feedstock, soil management, soil quality

Resumen

Efecto de distintas estrategias de cosecha de rastrojo de maíz sobre el rendimiento en grano e indicadores de la calidad del suelo

El desarrollo de estrategias para utilizar biomasa celulósica para la producción de bioenergía permitiría utilizar recursos que no son fuente de alimento para el ser humano. Este estudio comparó estrategias de cosecha de rastrojo de maíz (*Zea mays* L.) en 50 ha ubicadas sobre la Asociación de suelos Clarion-Nicollet-Webster cerca de Emmetsburg, Iowa, Estados Unidos. Se analizaron muestras de suelo superficial (0 a 15 cm) después de cada cosecha para monitorear los cambios en el carbono orgánico del suelo (COS), pH, fósforo (P) y potasio (K). Los rendimientos de grano en 2008, antes de que se impusieran los tratamientos de cosecha de rastrojo, promediaron 11,4 Mg ha^{-1}. En 2009, 2010 y 2011 los rendimientos de grano promediaron 10,1, 9,7 y 9,5 Mg ha^{-1}, respectivamente. Aunque los rendimientos de grano después de impuestos los tratamientos fueron inferiores a los del 2008, no se encontraron diferencias significativas entre los tratamientos. Las tasas promedio de cuatro años de cosecha de rastrojo variaron entre 1,0 y 5,2 Mg ha^{-1}, lo que representó del 12 al 60% de la biomasa por encima del suelo. El COS mostró una leve disminución durante el estudio, pero el cambio no estuvo relacionado con los tratamientos de cosecha de rastrojo, sino con la intensidad de labranza y los menores rendimientos del cultivo. En general los resultados son consistentes con otros estudios obtenidos en el medio oeste de Estados Unidos, indicando que el rastrojo del maíz no debe cosecharse si los rendimientos medios de grano son menores a 11 Mg ha^{-1}.

Palabras clave: bioenergía, biomasa, materia prima sustentable, manejo de suelo, calidad de suelo

Introduction

The US EPA (United States Environmental Protection Agency) identified corn stover, the aboveground material left in fields after grain harvest, as the most economical agricultural feedstock … to meet the 16 billion gallon cellulosic biofuel requirement (Schroeder, 2011). They estimated that 7.8 billion gallons of ethanol would come from 82 million tons of corn stover by 2022, which is consistent with conclusions reached by the US Department of Energy (2011). A major reason that corn stover was identified as an important feedstock because of the vast area upon which corn is grown in the Midwestern USA. However, corn stover has many other functions within the soil. Therefore, if (1) yields are low, (2) an excessive amount is harvested for any use, or (3) tillage intensities are too aggressive, harvesting stover may decrease the amount of carbon (C) returned to the soil to a level that will not be sufficient to sustain soil organic carbon (SOC), soil aggregation, or other soil quality indicators.

To help resolve the emerging questions regarding the sustainability of stover harvest, a private-public research project involving POET-DSM Advanced Biofuels, Iowa State University (ISU), and the USDA-Agricultural Research Service (ARS) was initiated in 2008. Seven stover harvest strategies were evaluated, even though none were an exact match to what POET-DSM ultimately decided to ask their residue suppliers to follow. Fortunately, treatments 4 and 6 bracket the recommended practice of simply turning off the residue chopper/spreader and then baling the windrow that is created.

The two most frequent questions being asked about stover harvest for any use, including bioenergy, bio-products, animal feed or bedding, are: (1) will it reduce subsequent crop yields, and (2) will it degrade soil quality by increasing erosion, decreasing soil organic matter, depleting soil fertility, or having any other adverse environmental effects? Our objective is to summarize the first four years of collaborative research conducted by Agricultural Research Service (ARS), Iowa State University, and POET-DSM partners to answer these questions.

Methods and materials

A 50 ha field study located at Longitude -94º 39’ 13.97" W and Latitude 43º 04’ 59.30" N was designed and initiated in 2008 to complement on-going work by POET-DSM with farmers, researchers, and equipment dealers on harvest, transportation and storage logistics associated with corn stover harvest for their new lignocellulosic bioenergy investment known as «Project Liberty.» Seven treatments: conventional– no stover harvest (Treatment 1); cob only (Treatment 2); plant material other than grain (MOG) collected directly (Treatment 3) or by direct-baling (Treatment 4); a two-pass rake and bale operation (Treatment 5), and a high-cut (just below the ear – Treatment 6) or low-cut (10-cm stubble height – Treatment 7) were established following grain harvest in 2008. Each stover harvest treatment was replicated three times in 2 ha blocks. Treatments 3, 6, and 7 were imposed using a «row-crop» head attached to a single-pass, dual stream biomass harvester developed at ISU using a John Deere 9750 STS combine. The same combine, but equipped with a «conventional» grain head was used for Treatments 1, 2, and 5. For Treatment 1, cobs and any other non-grain plant material were allowed to pass through the combine and were distributed on the soil surface. For Treatment 2, light-weight leaf and upper plant parts were again allowed to pass through the combine, but the heavier cobs were routed into the chopper/blower where they were partially ground and blown into a trailing wagon. For Treatment 5, all above-ground, non-grain plant parts were allowed to pass through the combine and drop to the ground before raking and baling the stover in a separate operation. Treatment 4 was imposed using an experimental AGCO combine with an attached baler that captured and baled all plant material other than grain (MOG) passing through the combine in a single-pass operation.

Field management was carried out by POET-DSM employees using soil and crop management guidelines provided by the research team. Table 1 summarizes the tillage practices, fertilizer rates, planting and harvest dates, and corn hybrids used for 2008 through 2011. Productivity assessments were based on annual grain and stover yields. To assess plant nutritional response, 10 whole plant samples were collected at V6 growth stage and leaf samples from opposite and below the primary ear were collected at anthesis. Plant samples were dried at 40 °C, ground to pass a 1 mm screen and submitted to a commercial laboratory for P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn analyses. Total carbon (TC) and total N (TN) concentrations were determined within the ARS National Laboratory for Agriculture and the Environment (NLAE) analytical laboratory by dry combustion using a Carlo-Erba NA1500 NCS elemental analyzer (Haake Buchler Instruments, Paterson, NJ).

Hand samples were collected from 1.5 m^2 areas within each plot during the three-week period between physiologic maturity and combine harvest to obtain an estimate of the potential above-ground stover production and the harvest index for each year. Samples were fractionated into five components: (1) ear shank upward; (2) below the ear leaving a stubble height of 10 cm; (3) dropped leaves, tassels, and stalk components; (4) cobs; and (5) grain. Weights for the non-grain components were summed to estimate the above-ground biomass. The grain weight was divided by the sum of all five fractions to estimate the harvest index (HI).

Corn grain was transferred from the combine to a weigh-wagon after harvesting each plot. Weights were recorded for both grain and stover. 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 ºC in a forced air oven until they reached a constant weight. Grain yield is reported at a constant water content of 155 g kg^{-1}, while stover yields are reported at a water content of 0 g kg^{-1}. For Treatment 4, several bales from each plot were sampled to create a composite sample that was submitted for moisture and compositional analysis. Stover samples were ground to pass a 2 mm screen before sub-sampling and grinding again to pass a 0.5 mm screen. They were also analyzed for TC and TN within the NLAE and by a commercial laboratory for the other elements listed for the V6 and leaf samples.

Surface (0 to 15 cm) soil cores were collected following harvest but before chisel plowing each year. Ten, 119 cm^3 soil cores were collected randomly and composited for each 2 ha plot. Samples were dried, crushed, and passed through a 2 mm screen and analyzed by a commercial laboratory for pH, P, K, Ca, Mg, B, Cu, Fe, Mn, and Zn concentrations. A subsample was also analyzed by the NLAE analytical laboratory for TN and TC concentrations. For samples with pH values greater than 7.3, inorganic C (IC) was also determined (Wagner *et al.*, 1998). Total organic carbon (TOC) values were then calculated as the difference between TC and IC with the latter being considered zero for samples with pH <7.3. In the Spring of 2009, deep soil cores were collected to a depth of 1.2 m to characterize initial soil profile conditions for each plot. The cores were divided into five segments: 0 to 15 cm, 15 to 30 cm, 30 to 60 cm, 60 to 90 cm, and 90 to 120 cm. Each segment from every core was analyzed for bulk density (BD), total carbon (TC), inorganic carbon (IC), organic carbon by difference (*i.e.*, TC – IC), total N, nitrate-N (NO3-N), ammonium-N (NH3-N), pH, electrical conductivity (EC), Bray extractable P, ammonium-acetate exchangeable K, Ca, and Mg, and DTPA extractable Cu, Fe, Mn, and Zn concentrations.

Yield, plant analysis, and soil-test data were analyzed using a General Linear Model with SAS Version 9.2 software. Seasonal (Year), treatment, and treatment by year effects were evaluated. Least Significant Difference (LSD) values were used to separate mean values for factors with statistically significant F values at $P \leq 0.1$.

Results and discussion

There were no significant stover harvest treatment differences in dry matter accumulation by any of the plant fractions collected prior to combine harvest (Table 2), but there were significant differences for all plant fractions and for the HI among years. The very high HI for 2008 reflects the failure to obtain an estimate of dry matter for fallen leaves. Using an average of the dropped leaves for the other three years (*i.e.*, 1.0 Mg ha^{-1}) reduces the HI to 0.56 which is still high but not unrealistic for a corn crop yielding more than 11 Mg ha^{-1}.

Grain yield measured with combines in 2008 averaged 11.4 ± 0.3 Mg ha^{-1} for the 21, 2 ha plots where the stover harvest treatments were imposed during or following harvest. Subsequent grain harvests showed significant ($P \leq 0.04$) seasonal effects with yields averaging 10.1, 9.7, and 9.5 Mg ha^{-1} in 2009, 2010, and 2011, respectively. This was consistent with the trends observed with the small hand samples (Table 2). Also, as noted for the hand samples, there were no significant differences among the stover harvest treatments and furthermore, the treatment by year interaction was not significant at $P \leq 0.1$ (Table 3).

Several factors undoubtedly contributed to the gradual decline in yield including the well-established yield penalty (Karlen *et al.*, 1994) associated with continuous corn production. This site was planted to soybean [*Glycine max* (L.) Merr.] in 2006, so by 2011, grain yields reflected a fifth consecutive year of corn production. Other potential factors contributing to a gradual yield decline include a combination of highly variable soil-test values across the field (data not presented) for which uniform fertilization (Table 1) was inadequate, excessive early-season rainfall in 2010 which flooded and killed plants in low-lying topographic positions known as «potholes», and severe wind damage in August 2011 that resulted in a substantial amount of lodging and reduced the overall yield potential.

Measured amounts of harvested stover and the fraction of above-ground material collected are presented in Table 4. The initial business model for POET-DSM had been to use only the cob fraction as feedstock for cellulosic bioenergy, but that plant fraction accounted for only 12% of the above-ground biomass. Twelve percent was lower than expected but in the range reported by Halvorson and Johnson (2009)

Table 1. Preplant tillage, fertilizer application rates, corn hybrid, planting dates, and harvest dates used for the stover harvest evaluations near Emmetsburg, Iowa, USA.

Year	Stover Harvest Rate†	Preplant Tillage	Fertilizer Application Rates (kg ha^{-1})			Hybrid	Planting Date	Harvest Dates
			N	P_2O_5	K_2O			
2008	All	Fall disk/rip; Spring disk & field cultivate	226	78	56	DeKalb 50-44 VT3 Agrigold 6325 VT3 NK‡ 3616 VT3	May 4th	November 4-8
2009	Low removal	Fall disk/rip; Spring disk	202	67	22	NC+‡ 1775 VT3	May 9th	November 5-9
2009	High removal	& field cultivate	202	67	45			
2009	Starter fertilizer		2	9	0			
2010	Low removal	Fall disk/rip; Spring disk	224	73	34	NC+ 197-84 STX	May 5th	October 6-11
2010	High removal	& field cultivate	247	73	56			
2010	Starter fertilizer		2	10	2			
2011	Low removal	Fall disk/rip; Spring disk	224	73	73	NC+ 202-32 STX	May 5th	October 6-20
2011	High removal	& field cultivate	247	73	90			
2011	Starter fertilizer		2	10	7			

† Low removal treatments = conventional (Treatment 1); cobs only (Treatment 2); MOG (Treatment 3), Direct Bale (Treatment 4)
High removal treatments = two-pass baling (Treatment 5); high cut (Treatment 6); low cut (Treatment 7)

‡ NK = Northrup King; NC+ = Channel Bio Corp. (a subsidiary of Monsanto Inc.).

Table 2. Average stover harvest treatment and seasonal effects on plant fraction dry matter and the harvest index computed from 1.5 m^2 hand samples collected in 2008, 2009, 2010, and 2011 near Emmetsburg, Iowa, USA.

Stover Harvest Treatment	Top	Bottom	Cob	Dropped	Grain	Total	Harvest Index
				------------------------ Mg ha^{-1} ------------------------			
Conventional – no removal	2.46	3.90	1.47	0.98	10.30	8.57	0.54
Cobs only	2.51	3.76	1.60	0.87	10.18	8.52	0.54
MOG bulk collection	2.62	3.69	1.57	1.06	10.12	8.68	0.53
MOG direct bale	2.45	3.60	1.56	1.00	9.64	8.62	0.53
Rake and bale	2.61	3.88	1.55	1.04	10.36	8.81	0.54
STS high-cut	2.62	3.82	1.56	1.03	9.72	8.77	0.52
STS low-cut	2.73	3.92	1.58	1.04	10.55	9.01	0.54
LSD$_{(0.1)}$	NS	NS	NS	NS	NS	NS	NS

Year	Top	Bottom	Cob	Dropped	Grain	Total	Harvest Index
				------------------------ Mg ha^{-1} ------------------------			
2008	2.89	3.91	1.60	---	12.28	8.40	0.59
2009	2.04	4.13	2.12	1.60	9.07	9.89	0.48
2010	3.06	3.50	1.16	0.24	9.18	7.96	0.53
2011	2.36	3.69	1.35	1.17	10.34	8.56	0.54
LSD$_{(0.1)}$	0.18	0.29	0.26	0.12	0.79	0.52	0.02

Table 3. Stover harvest treatment by seasonal interaction and the three-year average corn grain yields for a bioenergy feedstock study with POET-DSM near Emmetsburg, Iowa, USA.

Treatment	2009	2010	2011	3-Year Average
		------------------- Mg ha^{-1} -------------------		
Conventional – no removal	9.8	9.5	9.9	9.7
Cobs only	9.6	9.5	9.9	9.7
MOG bulk collection	9.6	9.6	9.8	9.7
MOG direct bale	10.2	9.7	8.3	9.4
Rake and bale	10.5	9.8	9.3	9.9
STS high-cut	10.7	8.8	9.4	9.6
STS low-cut	10.6	11.1	9.6	10.4
$LSD_{(0.1)}$		NS		NS

Table 4. Seasonal and four-year average corn stover yield as well as the average percent collected using the seven different harvest strategies near Emmetsburg, Iowa, USA.

Treatment	2008	2009	2010	2011	4-Year Mean	Average Collection†
		------------ Mg ha^{-1} ------------				%
Conventional – no removal	0	0	0	0	0	0
Cobs only	1.04	1.47	1.12	0.44	1.02	12
MOG bulk collection	1.50	2.02	1.31	1.47	1.57	19
MOG direct bale	---	1.95	1.78	2.02	1.92	24
Rake and bale	5.05	3.36	3.24	5.06	4.18	50
STS high-cut	4.70	4.14	3.74	3.84	4.10	50
STS low-cut	5.00	5.61	5.49	4.83	5.23	60
$LSD_{(0.1)}$		0.17			0.20	0.04

† The average stover collection was computed by dividing the 4-year mean machine harvest values by estimates of total above-ground biomass computed from the 1.5 m^2 hand samples (Table 2).

and Wienhold *et al.* (2011). The potential amount of above-ground stover, estimated from the hand samples collected from each plot, averaged 9.9, 8.4, 8.0, and 7.6 Mg ha^{-1} in 2008, 2009, 2010, and 2011, respectively. Subtracting the 5.24 Mg ha^{-1} of corn stover estimated by Wilhelm *et al.* (2007) as the amount needed to sustain soil organic carbon levels, the sustainable amount harvestable stover averaged 2.1, 1.4, 1.2, and 1.0 Mg ha^{-1} for 2008, 2009, 2010, and 2011, respectively. This indicated that an average of only 17% of the above-ground biomass could be sustainably removed from this site. Fortunately, this is consistent with current POET-DSM guidelines that ask their residue providers to collect an average of approximately 1 Mg ha^{-1} by simply turning off the residue spreader on their combines and then baling the windrow that is formed.

Figure 1 provides a visual reference for what the soil surface looked like after the various stover harvest treatments were imposed. Clearly, there was insufficient surface cover to protect the soil from wind and water erosion following the more aggressive harvest strategies. This situation was made even worse by the aggressive fall tillage associated with a disk/ripper implement (Table 1).

Obviously, the most critical factor to ensure an adequate stover supply for maintaining or enhancing soil quality and providing feedstock for bioenergy or bio-product industries is to achieve high crop yields. Several soil and crop

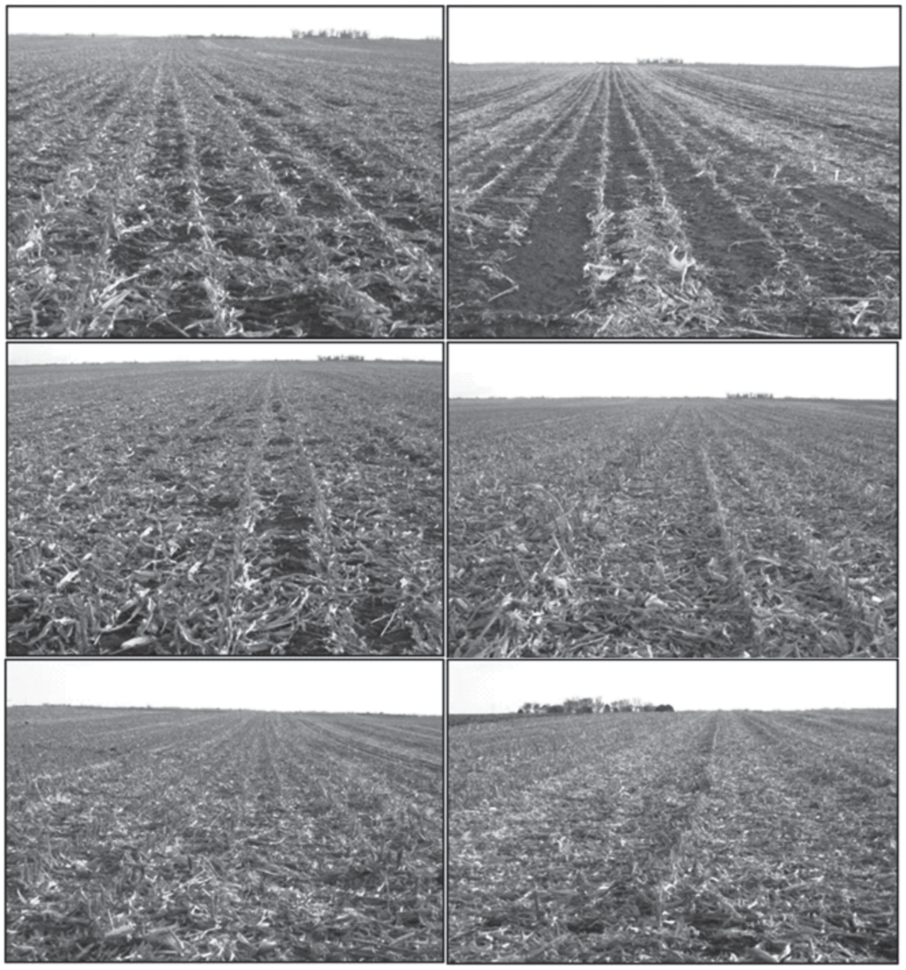

Figure 1. Post-harvest images of «low cut» Treatment 7 (top left), «rake and bale» Treatment 5 (top right), «high cut» Treatment 6 (middle left), «MOG» Treatments 3 and 4 (middle right), «cob only» Treatment 2 (lower left) and «conventional grain harvest» Treatment 1 (lower right).

management practices can be used to achieve higher grain yields and thus increase the amount of stover available for both bioenergy production and sustaining critical ecosystem services. First, there was substantial variation in soil fertility across the 50 ha research site, as evidenced by highly significant ($F \leq 0.0001$) replicate effects (data not presented). This variation presumably influenced the 4-year mean soil-test P and K values (Figure 2), since K removal, which averaged 6.5 kg Mg^{-1}, showed no significant differences among the stover harvest treatments. To effectively address significant soil-test variability at the field scale, producers should use soil- testing, plant analysis, nutrient management plans, and perhaps differential fertilization strategies to create a soil condition or quality that will support both grain production and crop residue harvest operations. Also, as the excessive rainfall event of 2010 confirmed, this field would very likely benefit from an improved surface or tile drainage system designed to prevent crop loss in areas where rainfall and runoff water accumulate. A more intensive nutrient management program may also help increase crop yields as evidenced by the three-year average nutrient concentrations at anthesis for four critical plant nutrients (Table 5). There were no significant leaf N concentration differences among the stover harvest treatments, but since the N fertilization rates (Table 1) would be considered more than sufficient, it was surprising that leaf tissue N concentrations at anthesis were below the critical level established for that nutrient. In addition, leaf S concentrations were just barely above the critical value established for that nutrient.

Soil profile analyses for samples collected to a depth of 1.2 m during the Spring of 2009 (Table 6) showed no significant differences among the stover harvest treatements

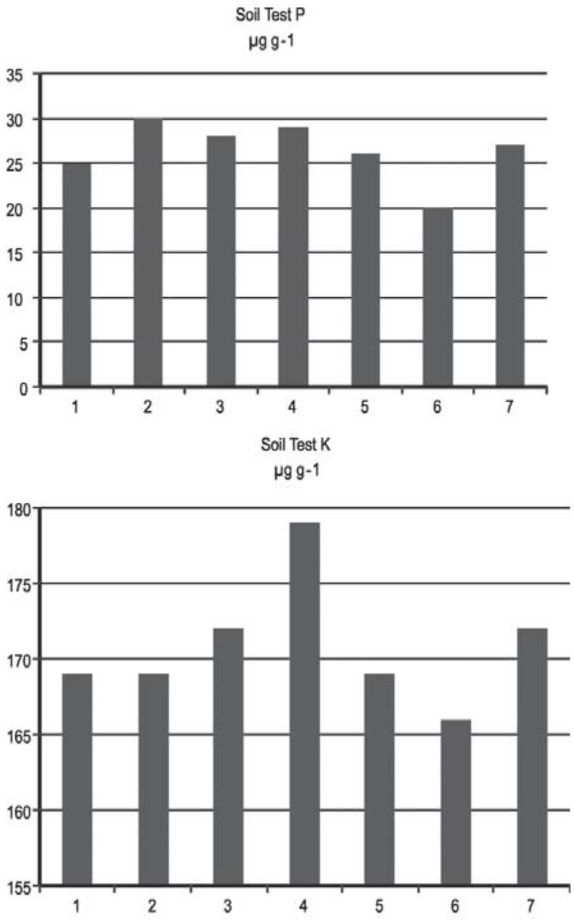

Figure 2. Four-year mean soil-test P and K values for seven stover harvest treatments (none, cobs only, MOG, single-pass bale, two-pass bale, STS-high, and STS-low) evaluated near Emmetsburg, Iowa, USA.

imposed the previous autumn. Bulk density (BD) values showed no root limiting zones and concentrations of the other parameters were similar to those measured at other Iowa USA locations having similar topographic features and soil types (*e.g.* Karlen *et al.*, 2013). Once again, soil-test K levels at lower soil profile depth increments were quite low and since leaf K concentrations at anthesis (Table 4) were just slightly above the critical level, this study supports the previous recommendations that further studies are needed to understand the role and effects that subsoil K concentrations are having on overall crop growth, development and yield on glacial till soils such as these.

Soil organic carbon (SOC) content was also monitored because of its importance in sustaining soil resources and the potential impact that harvesting crop residues could have on that indicator of resource sustainability (Johnson *et al.*, 2009; Wilhelm *et al.*, 2007). There were no significant stover harvest effects, but seasonal and replicate effects where highly significant (F < 0.0001) and the Least Significant Difference (LSD) value for the data shown in Figure 3 was 2.0.

Once again, we suggest that tillage intensity (Table 1) coupled with crop yields that were lower than expected for several reasons were undoubtedly the primary factors contributing to the gradual decline in surface SOC levels (Figure 3). These measurements reinforce the need for improved soil and crop management practices to ensure crop yields are sufficient to support sustainable grain and stover harvest from soils such as these. Practices that we would recommend to increase productivity at this location include the use of split fertilizer applications, fertilizer application

Table 5. Three-year average (2009-2011) ear leaf nutrient concentrations for the various stover harvest treatments near Emmetsburg, Iowa, USA.

Treatment	**N**	**P**	**K**	**S**
		--------------- Mg kg^{-1} ---------------		
Critical Value	**27.0**	**2.50**	**17.0**	**1.50**
Conventional – no removal	23.6	2.80	18.5	1.60
Cobs only	25.2	2.50	19.1	1.60
MOG bulk collection	24.8	2.80	19.2	1.60
MOG direct bale	24.0	2.80	18.9	1.60
Rake and bale	25.9	2.80	18.7	1.60
STS high-cut	24.4	2.70	18.8	1.60
STS low-cut	24.8	2.60	18.5	1.60
LSD$_{(0.1)}$	NS	NS	NS	NS

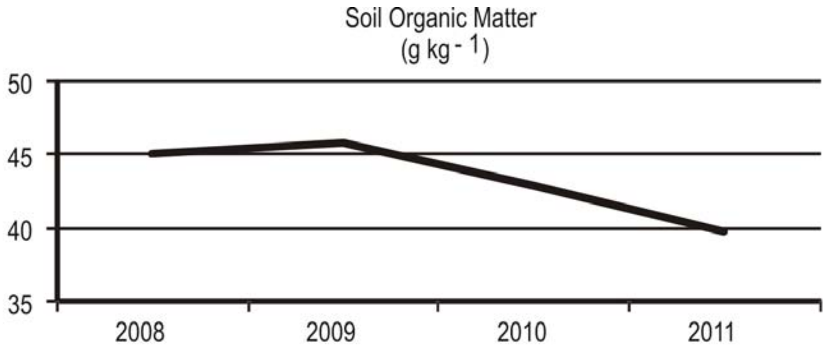

Figure 3. Soil organic matter trends at a research site used to evaluate various stover harvest treatments near Emmetsburg, Iowa, U.S.A.

Table 6. Soil profile analysis in Spring 2009 at the POET-DSM research site near Emmetsburg, IA, USA.

Treatment	**0 to 15 cm**								
	BD†	**TC**	**IC**	**OC**	**TN**	**NO$_3$-N**	**NH$_4$-N**	**pH**	**EC**
	g cm^{-3}	**--------------- g kg^{-1} ---------------**				**-------- Mg kg^{-1} --------**			**µs cm^{-1}**
Conventional – no removal	1.21	35.0	3.1	31.8	2.77	8.5	0.1	6.7	345
Cobs only	1.11	33.8	2.4	31.5	2.62	14.0	0.2	6.8	291
MOG bulk collection	1.26	32.4	1.5	30.9	2.62	9.4	0.1	6.8	335
MOG direct bale	1.31	33.5	2.2	31.4	2.74	8.1	0.1	7.1	335
Rake and bale	1.30	32.0	1.5	30.5	2.62	9.2	0.1	6.8	358
STS high-cut	1.28	34.2	3.9	30.3	2.7	10.4	0.1	7.2	366
STS low-cut	1.19	35.1	2.8	32.3	2.84	10.1	0.1	7.4	368
LSD(0.1)	NS	NS	NS	NS	NS	NS	NS	NS	NS

	P	**K**	**Ca**	**Mg**	**Cu**	**Fe**	**Mn**	**Zn**
	---------------------------- Mg kg^{-1} ----------------------------							
Conventional – no removal	22	156	5825	538	1.6	52	29	0.9
Cobs only	24	163	4779	462	1.6	54	26	0.9
MOG bulk collection	24	172	4423	447	1.6	51	31	1
MOG direct bale	24	185	5383	504	1.4	28	25	1
Rake and bale	22	164	5858	512	1.6	41	24	1
STS high-cut	12	134	6904	540	1.5	28	21	0.9
STS low-cut	22	171	5580	412	1.5	35	20	0.7
LSD(0.1)	NS	NS	NS	NS	NS	NS	NS	NS

Continues on page 139.

Table 6, continuation.

Treatment	15 to 30 cm								
	BD	TC	IC	OC	TN	NO_3-N	NH_4-N	pH	EC
	g cm^{-3}	-------------- g kg^{-1} --------------				-------- Mg kg^{-1} --------			μs cm^{-1}
Conventional – no removal	1.41	27.2	3.8	23.4	1.98	5.8	0.06	7.0	340
Cobs only	1.40	26.8	2.8	24.0	2.05	5.0	0.13	7.0	288
MOG bulk collection	1.37	28.8	1.8	27.0	2.28	6.1	0.10	6.8	294
MOG direct bale	1.39	26.6	3.1	23.6	2.08	5.7	0.06	7.2	310
Rake and bale	1.41	26.0	3.0	23.0	2.09	6.0	0.08	7.0	320
STS high-cut	1.41	26.6	5.6	21.0	1.89	5.0	0.09	7.3	334
STS low-cut	1.40	29.0	4.4	24. 6	2.21	5.8	0.07	7.7	331
LSD(0.1)	NS	NS	NS	NS	NS	NS	NS	0.5	NS

	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	-------------------------- Mg kg^{-1} --------------------------							
Conventional – no removal	6.9	97	7433	598	1.6	30	14	0.4
Cobs only	7.2	97	5136	525	1.7	36	14	0.5
MOG bulk collection	10.2	103	5106	466	1.4	42	23	0.6
MOG direct bale	8.3	101	6553	523	1.4	19	16	0.5
Rake and bale	7.2	99	10584	605	1.5	39	12	0.7
STS high-cut	6.6	109	7187	551	1.6	18	11	0.5
STS low-cut	7.4	96	6582	448	1.5	25	12	0.4
LSD(0.1)	NS	NS	NS	98	NS	NS	7.00	NS

Treatment	30 to 60 cm								
	BD	TC	IC	OC	TN	NO_3-N	NH_4-N	pH	EC
	g cm^{-3}	--------------- g kg^{-1} ---------------				-------- Mg kg^{-1} --------			μs cm^{-1}
Conventional – no removal	1.47	18.4	6.4	11.9	1.12	4.0	0.06	7.3	340
Cobs only	1.45	14.7	3.9	10.8	1.02	2.9	0.07	7.2	284
MOG bulk collection	1.43	16.6	4.3	12.4	1.18	3.9	0.08	7.2	284
MOG direct bale	1.49	20.5	7.8	12.7	1.18	2.8	0.07	7.5	303
Rake and bale	1.48	16.2	6.0	10.2	1.03	4.0	0.09	7.3	298
STS high-cut	1.51	16.1	7.3	8.8	0.93	3.4	0.09	7.7	327
STS low-cut	1.42	20.9	9.2	11.8	1.17	2.7	0.06	7.8	314
LSD(0.1)	NS	NS	NS	NS	NS	NS	NS	0.4	NS

	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	----------------------------Mg kg^{-1} ----------------------------							
Conventional – no removal	2.6	79	7822	648	1.8	17	8	0.3
Cobs only	3.5	91	5098	654	1.8	20	7	0.3
MOG bulk collection	2.8	78	5299	514	1.6	17	13	0.3
MOG direct bale	2.9	76	7042	558	1.7	12	9	0.3
Rake and bale	3.3	87	7198	580	1.9	18	7	0.4
STS high-cut	4.7	105	6704	538	1.7	11	6	0.3
STS low-cut	1.9	82	8335	568	1.7	14	8	0.4
LSD(0.1)	NS	NS	NS	NS	NS	NS	NS	0.10

rates that result in a gradual increase in soil-test levels, planting cover crops, reducing tillage intensity, and using crop rotations. Implementing a suite of these practices would very likely increase the amount of stover that could be harvested in a sustainable manner. For other locations with even greater in-field variability in slope and soil type, producers may want to implement site-specific landscape management practices (Muth, 2012) that integrate multiple feedstock sources.

Conclusions

This report summarizes four years of public-private research collaboration designed to evaluate different corn stover harvest strategies in North Central Iowa, USA. The results are consistent with other studies indicating that to sustain soil resources in the US Corn/Soybean Belt stover harvest should not exceed 1 Mg ha^{-1} unless average grain yields are greater than 11 Mg ha^{-1}. This conclusion is consistent with current POET-DSM guidelines being given to their residue providers.

The seven stover harvest strategies showed no significant differences in their effect on soil organic carbon (SOC), presumably because the factors having the greatest impact on SOC were the intensive pre-plant tillage practices and lower than anticipated crop yields. Annual soil-test sampling and analysis of the surface 0 to 15 cm layer appears sufficient for assessing soil fertility changes, making annual fertilizer recommendations, and monitoring short-term SOC changes. However, in addition to measuring total carbon (TC) and inorganic carbon (IC) before calculating organic carbon (OC) by difference, short-term carbon and nitrogen cycling should also be assessed using particulate organic matter (POM) or other labile organic carbon measurements.

Deep (1.2 m) soil cores collected when the study was initiated confirmed there were no significant differences among the sites chosen for the various stover harvest treatments. The profile analysis did support previous concerns regarding the role and importance of subsoil K levels for crop production on soils derived from glacial till within this region. This information will also provide a valuable reference for long-term evaluation of soil management effects on the soil profile at this site.

Finally, to increase crop production and thus increase available stover supplies for both bioenergy production and maintenance of critical ecosystem services, a new research design comparing three stover harvest strategies (no removal, the POET-DSM method, and a two-pass rake and bale operation) within either a two-year (corn-soybean) or four-year (corn-corn-corn-soybean) rotation was implemented in 2012. Furthermore, a grid-based soil testing and fertilization program was initiated in 2013 to reduce spatial variability effects within this 50 ha research site.

References

Halvorson AD, Johnson JM-F. 2009. Corn cob characteristics in irrigated central Great Plains studies. *Agronomy Journal*, 101: 390 - 399.

Johnson JMF, Papiernik SK, Mikha MM, Spokas K, Tomer MD, Weyers SL. 2009. Soil processes and residue harvest management. In: Lal R, Steward B. [Eds.]. Carbon management, fuels, and soil quality. New York : Taylor and Francis. pp. 1 - 44.

Karlen DL, Kovar JL, Cambardella CA, Colvin TS. 2013. Thirty-year tillage effects on crop yield and soil fertility indicators. *Soil & Tillage Research*, 130: 24 - 41.

Karlen DL, Varvel GE, Bullock DG, Cruse RM. 1994. Crop rotations for the 21st century. *Advances in Agronomy*. 53: 1 - 45.

Muth DJ. 2012. An investigation of sustainable agricultural residue availability for energy applications [Ph.D. Dissertation]. Ames : Iowa State University. 205p.

Schroeder J. 2011. Finding fuel in agricultural waste [On line]. Domestic Fuel. Cited October 28, 2013. Available from: http://domesticfuel.com/2011/01/27/finding-fuel-in-agricultural-waste/.

U.S. Department of Energy. 2011. U.S. Billion-ton update: Biomass supply for a bioenergy and bioproducts industry. Oak Ridge : Oak Ridge National Laboratory. 227p.

Wagner SW, Hanson JD, Olness A, Voorhees WB. 1998. A volumetric inorganic carbon analysis system. *Soil Science Society of America Journal*, 62: 690 - 693.

Wienhold BJ, Varvel GE, Jin VL. 2011. Corn cob residue carbon and nutrient dynamics during decomposition. *Agronomy Journal*, 103: 1192 - 1197.

Wilhelm WW, Johnson JM-F, Karlen DL, Lightle DT. 2007. Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy Journal,* 99: 1665 - 1667.