Stover Harvest and Tillage System Effects on Corn Response to Fertilizer Nitrogen

Jose L. Pantoja
Ciencias de la Vida y la Agricultura
Carrera de Ingeniería Agropecuaria
Univ. de las Fuerzas Armadas
Pichincha, 171103
Ecuador

Krishna P. Woli*
John E. Sawyer
Daniel W. Barker
Mahdi Al-Kaisi
Dep. of Agronomy
Iowa State Univ.
Ames, IA 50011

Demand for corn (*Zea mays* L.) stover is increasing for livestock and bioenergy production. Excessive stover harvest (SH) could impact crop productivity and soil N cycling. A 3-yr study was conducted at two Iowa sites with continuous corn to determine the effect of SH level and tillage system on grain yield, response to N fertilization, and optimal N rate. Treatments were none, partial, and complete SH, chisel plow tillage and recently implemented no-till, and six N rates from 0 to 280 kg N ha^{-1}. Profile soil NO_3–N concentration (with no fertilizer N) increased slightly from spring preplant to early June only with no SH but were the same with all SH levels after corn harvest. Corn canopy normalized difference vegetative index (NDVI) values were greatest with both SH levels and chisel plow. Increases in NDVI due to SH was less with chisel plow than no-till. Corn grain yield was 9% (0.84 Mg ha^{-1}) greater with chisel plow than with no-till. At the economic optimum N rate (EONR), grain yield was not influenced by SH with chisel plow but was 6% greater with each SH level under no-till. The EONR was the same with both tillage systems but was 22 and 45 kg N ha^{-1} lower with partial and complete SH, respectively, than no SH. Results of this study indicate the potential for increased corn yield with SH in a no-till system and a reduced fertilizer N rate requirement with SH regardless of tillage system.

Abbreviations: CC, continuous corn; EONR, economic optimum nitrogen rate; GNU_0, grain nitrogen utilization with no fertilizer nitrogen applied; NDVI, normalized difference vegetative index; NUE, nitrogen use efficiency; PAN, plant-available nitrogen; SH, stover harvest; SOM, soil organic matter; YEONR, yield at the economic optimum nitrogen rate.

Corn stover, the vegetative plant material left after grain harvest, accounts for approximately 70% of all crop residue production in the United States (USDOE, 2011). It is an asset for recycling plant nutrients, adding C to soils, and buffering against human and natural disturbances of the soil system (Blanco-Canqui and Lal, 2009). Demand for corn stover is increasing to meet the need for livestock feed and bedding, bioenergy production, and wood replacement in various manufactured products (Sokhansanj et al., 2002). Increasing demand for corn grain and stover for ethanol production has resulted in increased corn acreage in the United States, increased continuous corn (CC) systems, and the potential for continued increase of cropland conversion to corn production (Fixen, 2007; Martin, 2010). If managed inappropriately, SH will lead to increased fertilizer use (Sulc and Tracy, 2007) and, in conjunction with SH, increased potential for negative effects on water quality, nutrient cycling, and soil fertility and productivity (Blanco-Canqui and Lal, 2009).

There are both advantages and disadvantages to corn SH. Beneficial effects of SH include faster warming of soils in spring, better seed germination, and less favorable habitat for plant pathogens, while potential adverse effects include higher fluctuations in soil temperature, decline in organic matter and thus degradation

Soil Sci. Soc. Am. J.
doi:10.2136/sssaj2015.01.0039
Received 27 Jan. 2015.
Accepted 13 May 2015.
*Corresponding author (woli@iastate.edu)

in soil quality and structure, and faster loss of stored soil moisture (Swan et al., 1996; Mann et al., 2002; Wilhelm et al., 2004; Osborne et al., 2014). When corn SH is properly managed, it can help mitigate residue management problems in high-yielding corn fields while providing significant potential benefits as a bioenergy feedstock for the cellulosic-based ethanol industry (Duffy, 2014). An increasing concern is that SH might negatively impact the soil system, crop productivity potential, and the environment (Varvel et al., 2008). Questions remain as to the net agronomic and environmental effects of SH level. Corn SH can reduce soil protection provided by crop residues, reduce soil organic matter (SOM), and alter nutrient cycling (Wilts et al., 2004; Stetson et al., 2012; Karlen et al., 2014). Information on the impacts of crop biomass harvest on the soil nutrient supply is unclear (Mulvaney et al., 2010). Corn SH could potentially affect plant N availability and fertilizer N requirements. In a study conducted in southern Minnesota, Sindelar et al. (2013) reported that CC grain yield increased with SH in moderate- to high-yielding environments where cool, early-season soil temperatures associated with stover remaining on the soil surface affected plant growth.

Practices such as corn SH may not necessarily be positive in relation to N loss because SH can increase soil erosion and NO_3–N losses in surface runoff (Wienhold and Gilley, 2010). Sindelar et al. (2015) reported that residual soil profile NO_3–N was 10 to 16 kg ha^{-1} greater with SH at fertilizer N rates >90 kg N ha^{-1}. On the other hand, retaining all corn stover could increase total N and NO_3–N in the upper 0.3-m soil by as much as 12 and 60%, respectively, as reported by Maskina et al. (1993). Therefore, it is important to evaluate if the soil supply of plant-available N (PAN), corn N use efficiency (NUE), and optimal N fertilization requirement change with SH. Utilizing conservation tillage and increasing fertilizer NUE can optimize profits, maintain crop production sustainability, and minimize N losses (Torbert et al., 2001; Vetsch and Randall, 2004).

No-till is becoming a common choice in several corn production areas to conserve soil moisture, reduce farm equipment costs, reduce nutrient and soil loss and water runoff, and save labor and time (Soane et al., 2012). Depending on soil conditions, no-till may result in higher or lower corn grain yields than conventional tillage but may not change the corn response to N fertilization (Vetsch and Randall, 2004). The tillage system does not have as large of an impact on crop N uptake and yield as the fertilizer N rate, N source, and seasonal variability (Maskina et al., 1993; Kwaw-Mensah and Al-Kaisi, 2006; Al-Kaisi and Kwaw-Mensah, 2007; Karlen et al., 2014). Karlen et al. (2014) reported that average no-till grain yields were significantly lower than those under conventional tillage with no SH harvest but not when stover was collected.

Coulter and Nafziger (2008) in Illinois found lower continuous corn yield with SH under no-till than tillage in a low-precipitation environment but not with normal precipitation. Conversely, SH generally did not affect corn and soybean [*Glycine max* (L.) Merr.] yield in a study conducted in Minnesota (Johnson et al., 2013). Therefore, there are not necessarily consistent trends for the response of corn yield with SH because corn yield might interact differently with tillage system and production conditions or produce a different response to fertilizer N rate. Coulter and Nafziger (2008) did not find a difference in the EONR between tillage systems with SH when precipitation was adequate, but there was a reduction in the EONR with no-till at one site that had low precipitation. In that study, yield at the EONR (YEONR) was 4% greater with partial or complete SH than with no SH when precipitation was adequate. Sindelar et al. (2013) reported that SH decreased the EONR by >12 and >19 kg N ha^{-1} under no-till and strip tillage, respectively, and SH increased grain yield at the EONR by 7, 9, and 6% under chisel plow, no-till, and strip tillage, respectively. The corn fertilizer N requirement with conversion to no-till may be greater until a new N equilibrium is established for the soil–plant system (Raun and Schepers, 2008). Corn production requires tillage practices that maximize corn yield but also have associated fertilizer N recommendations tailored to increase NUE (Mehdi et al., 1999). There is a similar need for optimizing N use in systems with corn SH. The objectives of this study were to determine the effect of SH level and tillage system on the corn grain yield response to N fertilization and the optimal N rate.

MATERIALS AND METHODS

Study Sites

The study was established in the fall of 2008 and conducted for 3 yr at two sites representing common soils in Iowa. The sites were located at the Iowa State University Agricultural Engineering and Agronomy Research Farm in central Iowa near Ames (42°0′38″ N, 93°44′1″ W) and the Southwest Armstrong Memorial Research and Demonstration Farm near Lewis (41°19′53″ N, 95°10′60″ W). The soil at Ames was a calcareous loamy till with high clay content and poor internal drainage, and the soil at Lewis was a silt loam formed in loess with low clay content and good internal drainage (Table 1), with the

Table 1. Site information and initial soil test values for pH, total organic C (TOC), soil test P (STP), soil test K (STK), and NO_3–N at the two study sites, fall 2008.

Site	Predominant soil series	Textural class	Soil classification	0–0.15 m pH	0–0.15 m TOC	0–0.15 m STP	0–0.15 m STK	0–0.9 m NO_3–N
					g kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
Ames	Canisteo	silty clay loam	fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll	7.2	31	9	117	2.4
Lewis	Marshall	silty clay loam	fine-silty, mixed, superactive, mesic Typic Hapludoll	6.9	24	24	123	5.3

soil total organic C at both sites within the reported range for Mollisols (18–46 g kg^{-1}) in the US Midwest (Robinson et al., 1996). Previous management of both sites was fall chisel plow with spring disking in a soybean–corn rotation (at least 15 yr with soybean in the rotation). At both sites, corn was grown the previous year and fertilized with 225 kg N ha^{-1}. Monthly mean temperature and total precipitation across the study sites were calculated from data collected at weather stations at each research farm and reported by the Iowa Environmental Mesonet Network (Arritt and Herzmann, 2013).

Experimental Design and Treatment Application

The experimental design at each site was a split-split plot with three replications in a randomized complete block. Tillage system (chisel plow or no-till) was the main plot, corn SH level (none, partial, or complete SH) the split plot, and fertilizer N rate (0–280 kg N ha^{-1} in 56 kg ha^{-1} increments) the split-split plot. Plots were 15 m long with eight rows per plot and 0.76-m row spacing. Treatments remained in the same plot location each year.

Chisel-plow tillage was performed to a 0.15- to 0.25-m depth in the fall after SH with twisted chisels on 0.3-m spacing, with spring disking and field cultivation to approximately a 0.1-m depth as needed for seedbed preparation. Fertilizer N as urea–NH_4NO_3 solution (32% N) was applied with coulter injection to every other row space (1.52 m apart) within 3 wk (V2–V3 growth stage) (Abendroth et al., 2011) after corn planting and as soil conditions allowed.

Corn SH was performed after grain harvest and before tillage by raking and baling with field-scale equipment. For complete SH, corn stalks were mowed at 0.03 to 0.05 m above the soil surface, a wheel rake was set to run on the ground with very high pressure to rake the stalks into windrows (raked twice if needed), and then the stover was baled. For partial SH, corn stalks were not mowed, a wheel rake with minimal down pressure was used to rake the stalks into windrows, and then the stover was baled. These procedures were intended to remove 50% of the corn stover for the partial level and 100% for the complete level, but actual levels varied based on soil conditions and equipment effectiveness for SH, especially for partial harvest. To determine the amount of corn stover remaining in the field, two random samples were collected with a square frame (0.093 m^2) by replicate in fall 2008 when no prior treatments had been applied and in the fall of 2009 and 2010 from plots receiving 0, 168, and 280 kg N ha^{-1} within each tillage system and replicate. These stover samples were dried in a forced-air oven at 60°C for 72 h and weighed. The results were used to estimate the amount of corn stover remaining on a dry-matter basis (Table 2) and by comparison with the dry-matter amount with no SH to calculate the percentage harvested. On average, 31% (±13%) of the corn stover was harvested with the partial SH treatment and 81% (±9%) with the complete SH treatment, which was approximately the amount mechanically feasible for maximum harvest.

Table 2. Corn stover remaining after stover harvest (SH) on a dry-matter basis as affected by SH level and fertilizer N rate across tillage systems, sites, and years.

N rate	Stover remaining		
	None	Partial	Complete
kg N ha^{-1}		Mg ha^{-1}	
		2008	
	3.29	2.04	0.41
		2009–2010	
0	2.33	1.55	0.25
168	3.26	2.43	0.51
280	3.88	2.92	0.49
Mean	3.15	2.30	0.41
		Statistical analysis for 2009–2010 ($P > F$)	
Source			
Tillage system (TS)		0.193	
Stover harvest (SH)		<0.001	
N rate (NR)		<0.001	
TS × SH		0.994	
TS × NR		0.247	
SH × NR		0.004	
TS × SH × NR		0.852	

Corn Planting and Harvest

The corn hybrid at Ames was DuPont Pioneer P35K33, with 105-d maturity, and DuPont Pioneer P33W84 at Lewis, with 110-d maturity. Each hybrid had Herculex XTRA insect protection, which includes corn rootworm (*Diabrotica* sp.) and several aboveground insects such as European corn borer (*Ostrinia nubilalis*), and glyphosate [*N*-(phosphonomethyl)glycine] and glufosinate [2-amino-4-(hydroxymethylphosphinyl) butanoic acid] herbicide resistance. The target seeding rate was 81,500 seeds ha^{-1}. Planters were equipped with no-till coulters and row cleaners to remove crop residue and aid in seed placement. Weed control and cultural practices were typical for CC at each site. Corn grain yield was determined by harvesting the middle four rows of each plot with a plot combine and adjusted to 155 g kg^{-1} moisture.

Soil Sampling and Analysis

Ten random cores per replicate were collected in fall 2008 (0–0.15 m) to determine the initial soil pH, total organic C, and soil test P and K. Soil was also sampled (0–0.9 m in 0.3-m increments) by collecting five cores across each replicate to determine the initial NO_3–N in the soil profile. After treatment initiation (2009–2011), soil was sampled (0–0.6 m in 0.3-m increments) to determine soil NO_3–N each year before planting in the spring and in early June in plots with no fertilizer N applied, and in the fall after harvest (0–0.9 m in 0.3-m increments) in plots receiving 0, 168, and 280 kg N ha^{-1}. Six cores per plot were collected in a diagonal pattern across two adjacent rows, with one core from each row and a core 0.20 m from the side of each row. All soil samples were collected by hand with a 0.02-m-diameter probe. The soil was mixed, and a subsample was saved for analysis. The samples were dried in a forced-air oven at 25°C and ground to pass a 2-mm sieve. Soil pH was determined with a 1:1 soil/water ratio. Total organic C was determined by dry combustion with a LECO CHN-2000 analyzer (LECO Corp.) (Nelson and Sommers, 1982), with total C adjusted when necessary by subtraction of inorganic C determined from a separate analysis using a modified pressure calcimeter method (Sherrod et al., 2002). Soil test P and K were determined by Mehlich-3 extraction and colorimetric determination, and NO_3–N was determined by 2 mol L^{-1} KCl extraction and colorimetric Cd reduction using a Lachat flow injection analyzer (Lachat Instruments, QuikChem 8500 Series 2) (Brown, 1998).

The soil pH at each site was neutral to slightly alkaline (Table 1), the Mehlich-3 soil test P in the low interpretation category (Sawyer et al., 2011) at Ames and in the high category at Lewis, and the K test in the low category at both sites. To avoid the potential for P and K deficiency and any issue with variations in soil tests or differences due to stover harvest, P and K (triple super phosphate and muriate of potash) were broadcast applied at a 2-yr rate as needed based on soil testing. No fertilizer N or manure was applied across the study areas in the fall or spring before planting, and the sites had no recent history of manure application.

Corn Canopy Sensing

A Crop Circle ACS-210 active canopy sensor (Holland Scientific) was used to estimate the corn canopy biomass and growth response to treatments. Corn canopy sensing was conducted when the corn receiving 168 kg N ha^{-1} reached the mid-vegetative (V10) growth stage. The ACS-210 active canopy sensor was mounted on a mast, positioned mid interrow, and carried by hand through the middle of each plot (0.6–0.9 m above the canopy) at a constant speed (1.5 m s^{-1}) (Barker and Sawyer, 2010). Sensing was conducted between 0900 and 1500 h, and reflectance measurements were captured on-the-go with a handheld datalogger. Approximately 10 values for the visible (VIS) and near-infrared (NIR) band reflectance were collected from each plot, averaged for each plot, and used to calculate the mean normalized difference vegetative index (NDVI) (Gitelson et al., 1996; Teillet et al., 1997):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{VIS}}{\mathrm{NIR} + \mathrm{VIS}} \quad [1]$$

Corn Grain Nitrogen Utilization

At physiological maturity, six corn ears were randomly collected from the center rows of plots that received no fertilizer N. The ears were dried in a forced-air oven at 60°C for 72 h and the grain was separated from the cob, milled, and a subsample analyzed for total N by dry combustion (Nelson and Sommers, 1982). Grain from the six ears was added into the machine-harvested grain weight. The results were used to estimate the grain N utilization (GNU) index using the grain yield from plot-combine harvest and the grain total N (Dobermann, 2007):

$$\mathrm{GNU} = \frac{\text{grain yield}}{\text{grain total N uptake}} \quad [2]$$

where GNU is the grain yield (in Mg ha^{-1}) reported at 155 g kg^{-1} moisture divided by the grain total N uptake (in kg N ha^{-1}). The GNU is the reciprocal of the grain N concentration expressed on an area basis. Grain N utilization was determined with no fertilizer N (GNU_0) so that the effect of SH level and tillage system on the soil potential to supply PAN would not be masked by the application of fertilizer N.

Statistical Analysis

Statistical analyses were conducted with PROC MIXED (SAS Institute, 2009) for a randomized complete block, with tillage being the main plot, SH the split plot, and N rate the split-split plot. The analyses for the amount of stover remaining in the field after SH, profile NO_3–N, NDVI, and corn grain yield were performed across sites and years, with treatments (tillage system, stover harvest, and N rate) and their interactions considered fixed and sites, years, replicates, and their interactions considered random. With the two spring samplings for soil NO_3–N, the analysis was also performed including repeated measures. Because GNU_0 was measured only on treatments with no fertilizer N applied, that analysis did not include N rate. The reason for analysis across sites was because, in most instances, analysis showed that interactions of site with other factors were not significant. Differences between means were assessed with the PDIFF option in PROC MIXED and considered significant at $P \leq 0.05$.

For NDVI and grain yield, to further investigate the significant N response ($P \leq 0.05$), the SLICE option of the LSMEANS statement was used to evaluate the response to fertilizer N rate within each tillage–SH combination. The SLICE option is a general method for partitioning analysis of the LSMEANS for an interaction as an analysis of simple effects. For NDVI and grain yield, the SLICE results for N rate were significant ($P < 0.001$) for each tillage–SH combination. Therefore, PROC REG and PROC NLIN were used to investigate quadratic and quadratic-plateau regression fits for the N rate response within each tillage–SH combination:

$$y = a + bx + cx^2 \quad [3]$$

$$y = a + bx + cx^2, \quad x < x_o \quad [4]$$

$$y = a + bx_0 + cx_0, \quad x \geq x_0 \quad [5]$$

where y represents the predicted corn response (NDVI or Mg ha^{-1} grain yield) to fertilizer N, x is the fertilizer N rate (kg N ha^{-1}), a is the intercept, b is the linear coefficient, c is the quadratic coefficient, and x_0 is the fertilizer N rate at the join point. The EONR for grain yield and YEONR were calculated from each regression model fit to the N response (Cerrato and Blackmer, 1990a) by solving for x with a US\$0.0056 kg^{-1} N to US\$1 Mg^{-1} corn grain price ratio, derived from US\$0.88 kg^{-1} N (US\$0.40 lb^{-1} N) and US\$157 Mg^{-1} grain (US\$4.00 bu^{-1}).

Regression was performed on the site-year mean data for each N rate. Models were visually inspected for shape and plateau of data, significance of model ($P \leq 0.05$), smallest model residual sums of squares, and largest coefficient of determination (R^2). According to Cerrato and Blackmer (1990a) and Bullock and Bullock (1994), the quadratic model often does not give a valid description of corn responses because it tends to indicate optimal fertilizer N rates that are too high, whereas the quadratic-plateau model best describes corn responses to fertilizer N. In our study, the quadratic-plateau model was the best fit, which matches the experience of corn canopy sensing and grain yield plateau with fertilizer N rates greater than producing the maximal response. For grain yield with no SH under both tillage systems, the segment join point with the quadratic-plateau model was slightly greater than the highest applied N rate. In those cases, however, the quadratic and quadratic-plateau models provided the same quadratic equation and EONR; therefore, for consistency, the quadratic-plateau model and join point are presented.

RESULTS AND DISCUSSION

Weather

The weather during the growing season can influence corn stover degradation, corn growth and response to fertilizer N rate, and profile soil NO_3–N (Randall and Iragavarapu, 1995; Derby et al., 2005). For both sites, spring air temperatures in 2009 (April–June) were 1°C colder than the recent historical average for the last 16 yr, and 2010 was 1°C warmer (Fig. 1a). During the reproductive corn growth stages (July–September) and compared with the average, 2009 was 2°C colder and 2010 was 1°C warmer. The temperatures in 2011 were the same as the average for the entire season. The amount of precipitation during the spring of 2009 was 5 cm lower than the average (31 vs. 36 cm), 2010 was wetter, with 5 cm more precipitation than the average, and 2011 was somewhat drier than the average (34 cm) (Fig. 1b). In 2009 and 2011, the July to September period was somewhat wetter than the average (28 vs. 26 cm); however, 2010 had much greater precipitation during that period (55 cm). During the harvest period (October), 2009 was 3°C colder and 2010 and 2011 were 2°C warmer than the average (11°C). For that period, 2009 was wetter (17 cm) and 2010 and 2011 were drier (1 cm) than the average (7 cm). There were intense precipitation events during the 3 yr of the study, and generally the 3-yr period was wetter than the recent historical average. Those conditions could have affected the response to the treatments, especially N supply and corn response to applied N.

Corn Stover Remaining after Stover Harvest

In 2008, there were no fertilizer N treatments applied to the study sites, and a uniform N rate of 225 kg N ha^{-1} was used. Therefore, the amount of corn stover produced was uniform and the amount remaining for the 2009 growing season was affected only by 1 yr of SH level and not N rate. In 2009 and 2010, the interaction between SH level and fertilizer N rate resulted in different amounts of corn stover remaining; however, the tillage system did not affect that amount or interact with SH or fertilizer N rate (Table 2). The differences in corn stover left after SH,

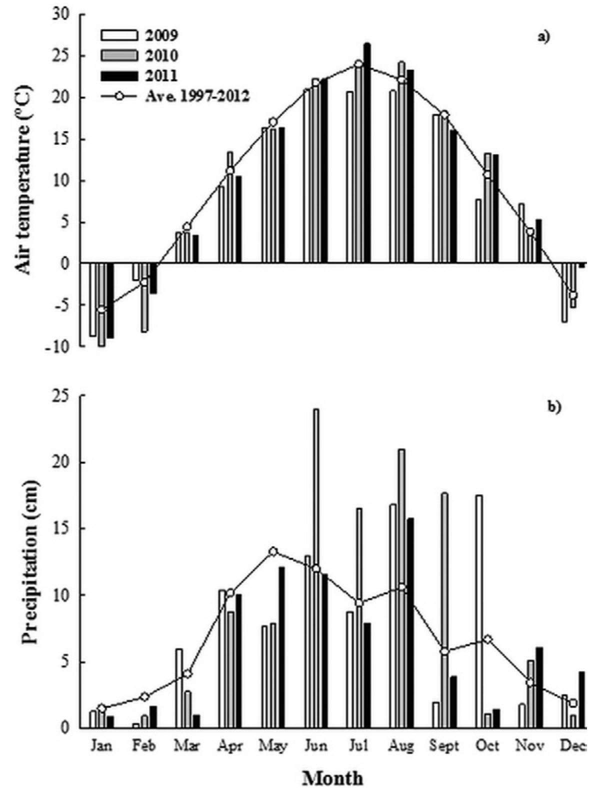

Fig. 1. Mean monthly (a) air temperature and (b) total precipitation across sites (data from Arritt and Herzmann, 2013).

accompanied by the variation with fertilizer N rate, could have affected soil conditions that might eventually influence crop development and yield.

Initial Soil Nitrate

Both sites had low initial soil NO_3–N concentration in the top 0.9 m of soil in fall 2008, with Ames lower than Lewis (Table 1). These low concentrations indicate that there was not a large pool of PAN in the soil profile. Therefore, the sites were likely to show a corn response to fertilizer N in the first year. The soil samples were collected before any N treatment had been applied; therefore, they reflect the background concentration at each site following the prior corn crop and the uniform agronomic rate for CC (225 kg N ha^{-1}) applied across each study area in spring 2008.

Spring Soil Nitrate

Across sites and years, the soil NO_3–N concentration in the control plots (no fertilizer N) were low in the spring before planting (2.4 ± 0.2 mg kg^{-1}) and early June (3.1 ± 0.2 mg kg^{-1}) at both depths in the top 0.6 m of soil. Corn SH did not affect soil NO_3–N when averaged across tillage systems and sampling times (Table 3); however, there was only a small increase in the soil NO_3–N concentration (0.75 mg kg^{-1}) from the preplant sampling to early June with no SH, indicating a potential low net N mineralization (Fig. 2). The soil NO_3–N concentration increased slightly with SH in the spring before planting, but there was no difference with SH in the early June sampling (Fig. 2). A change in soil NO_3–N from preplant to later in the spring can

Table 3. Statistical analyses for soil profile NO_3–N concentration across sites and years.

Spring sampling		Post-harvest fall sampling	
Source	***P* > F**	**Source**	***P* > F**
Sampling time (ST)†	0.012	Tillage system (TS)	0.082
Tillage system (TS)	0.038	Stover harvest (SH)	0.566
Stover harvest (SH)	0.854	N rate (NR)	<0.001
Sampling depth (SD)	<0.001	Sampling depth (SD)	<0.001
ST × TS	0.966	TS × SH	0.068
ST × SH	0.048	TS × NR	0.720
ST × SD	0.016	TS × SD	0.160
TS × SH	0.874	SH × NR	0.659
TS × SD	0.822	SH × SD	0.784
SH × SD	0.999	NR × SD	0.077
ST × TS × SH	0.845	TS × SH × NR	0.057
ST × TS × SD	0.070	TS × SH × SD	0.268
ST × SH × SD	0.338	TS × NR × SD	0.892
TS × SH × SD	0.249	SH × NR × SD	0.955
ST × TS × SH × SD	0.927	TS × SH × NR × SD	0.734

† Sampling times were in spring before corn planting and when corn was at the V5–V6 growth stages in early June.

be influenced by many site-specific factors besides the remaining corn stover, including N mineralization rates and abiotic factors such as overall soil moisture and temperature conditions (Andraski and Bundy, 2008). There was a difference in spring soil NO_3–N due to the tillage system (Table 3), with chisel plow increasing the soil NO_3–N concentration by only 0.5 mg kg^{-1} compared with no-till in both spring preplant and early June samplings (data not shown), a minor increase considering the possible differences in soil conditions between a tilled and undisturbed no-till system such as soil temperature, moisture, compaction, and surface penetration resistance. However, the no-till system was just recently implemented for the study, and that short no-till history could also negate potential tillage differences.

For spring soil NO_3–N levels to have an impact on reducing needed fertilizer N rates, the NO_3–N concentration needs to be greater than approximately 10 mg kg^{-1} for the 0- to 0.3-m soil depth (Binford et al., 1992b). That was not the case in our

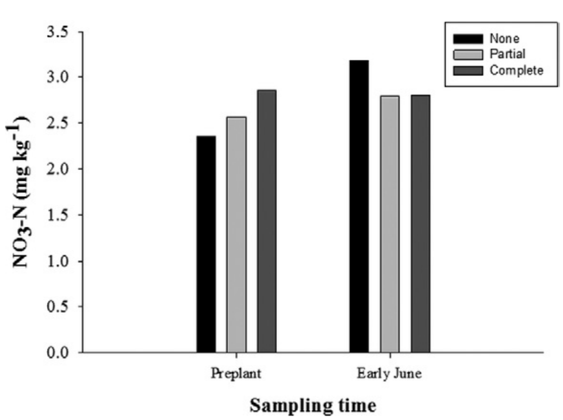

Fig. 2. Spring preplant and early June soil profile NO_3–N concentration with no fertilizer N as affected by stover harvest level (none, partial, or complete removal) and sampling time. Means across sampling depths, tillage systems, sites, and years. Bars with the same letter are not significantly different (*P* ≤ 0.05).

study because the soil NO_3–N concentration was much lower (<4 mg kg^{-1}) in all cases, and hence there was little influence of spring soil NO_3–N on the N response. The overall small differences found in the soil NO_3–N concentration between SH level, tillage system, and sampling time in the spring would be related to the low overall profile concentration from the previous year (Table 1 for fall 2008 and 2.0 ± 0.4 mg kg^{-1} for fall 2009 and 2010), potentially low net N mineralization, corn N uptake, and potentially high NO_3–N leaching or denitrification due to intense precipitation events (Hatfield et al., 2009). Despite having a lower amount of crop residue and soil coverage after SH (Table 2), the partial and complete SH treatments did not appear to affect net N mineralization or cycling into inorganic N during the spring in the short term, which was reflected in the low soil NO_3–N concentration in our study.

Corn Canopy Sensing

Corn canopy NDVI values obtained at the V10 growth stage varied with SH and tillage system (Table 4). With the significant tillage × SH interaction, NDVI with chisel plow tillage was greater than with no-till for all combinations except for chisel plow tillage and no SH compared with no-till with complete SH, and chisel plow with partial SH compared with no-till with complete SH (Table 5). Also, no-till with either SH level had higher NDVI values than no-till with no SH. These results highlight the general effect of SH on increasing early-season corn growth and canopy size. The largest increase in NDVI with SH was with no-till, where partial and complete SH resulted in a large increase in corn growth and canopy development (Table 6; Fig. 3). These results indicate that the effect of SH was greater with no-till than with chisel plow tillage, which could be a reflection of crop residue coverage and a differential in soil temperature affecting corn growth rather than soil N mineralization and the soil supply of PAN (Andraski and Bundy, 2008), especially because of the small change due to SH level or tillage system on the spring soil NO_3–N concentration. Similar results were reported by Sindelar et al. (2013) from a study conducted at two locations in southern Minnesota, where SH increased NDVI at the V8 growth stage by 20 and 13% under no-till and strip tillage, respectively, but had no effect on NDVI under chisel plow tillage.

Table 4. Statistical analyses for corn canopy normalized difference vegetative index (NDVI) and grain yield response to tillage system, stover harvest level, and fertilizer N rate across sites and years.

	P > F	
Source	**NDVI**	**Grain yield**
Tillage system (TS)	<0.001	0.002
Stover harvest (SH)	<0.001	<0.001
N rate (NR)	<0.001	<0.001
TS × SH	<0.001	0.036
TS × NR	0.831	0.204
SH × NR	0.346	0.127
TS × SH × NR	0.059	0.941

Table 5. Corn canopy normalized difference vegetative index (NDVI) and corn grain yield for the interaction of tillage system and stover harvest across sites, years, and fertilizer N rates.

Tillage system	Stover harvest	NDVI	Grain yield
			Mg ha^{-1}
Chisel plow	none	0.647 c†	8.76 c
	partial	0.677 b	9.06 b
	complete	0.689 a	9.41 a
No-till	none	0.607 d	7.63 d
	partial	0.658 c	8.44 c
	complete	0.673 b	8.60 bc

† Means within a column followed by the same letter are significantly different ($P \leq 0.05$).

The NDVI values for the control plots (no fertilizer N) were considerably lower than for the plots with fertilizer N, indicating N stress and a reduction in plant growth with no N applied. This also shows that the sites had the potential for a large response to fertilizer N. Applied N increased the canopy NDVI values up to a point where the response plateaued for each SH level and both tillage systems; with the N rate at the join point of the quadratic-plateau model indicating maximum plant canopy and N response (Table 6; Fig. 3). These results for the corn response to fertilizer N were consistent with studies conducted in Iowa to evaluate the corn canopy response to N stress and fertilizer N rate (Barker and Sawyer, 2010, 2012).

The fertilizer N rate at the maximum NDVI response with no and complete SH was lower with chisel plow tillage than no-till, indicating a potentially greater soil supply of PAN due to more soil mixing, lower amounts of remaining crop residues, and soil temperatures more conducive for N mineralization. However, the NDVI response was different between tillage systems with partial SH, as the fertilizer N rate where the NDVI plateaued was 60 kg N ha^{-1} greater with chisel plow tillage than no-till at that SH level. These response differences were mostly due to varying NDVI values at the 56 kg N ha^{-1} rate. Corn growth and N uptake are rapid at mid-vegetative growth stages, especially with adequate soil moisture (Abendroth et al., 2011). It is possible that site-specific differences in fertilizer N availability at the low fertilizer N rate, along with different soil moisture and temperature conditions due to SH, could have resulted in the variable corn NDVI responses. Also, corn response to fertilizer N in early growth stages can be influenced differently than by factors affecting the grain yield response (Binford et al., 1992a). Coulter and Nafziger (2008) indicated that leaf area index and leaf chlorophyll measured at the R2 growth stage had linear relationships with grain yield and that those relationships were consistent across SH levels and tillage systems. Those plant measurements, however, were taken at a reproductive growth stage (R2) of corn development rather than at a mid-vegetative stage (V10) as was done in our study. Canopy sensing at mid-vegetative stages can reflect early corn growth stresses due to factors affected by SH and tillage, with canopy differences indicating potential effects on corn productivity.

Sensing measurements have to be interpreted carefully due to potential plant stresses other than from the fertilizer N rate (Barker and Sawyer, 2010). Other factors affecting corn growth and canopy size are plant density, soil moisture supply, soil temperature, and weed pressure (Wilhelm et al., 2004). However, those are also factors that could affect the early-season corn growth response to SH level and tillage system. In an Indiana

Table 6. Quadratic plateau regression models and parameters describing the corn canopy normalized difference vegetative index (NDVI) and grain yield response to tillage system, stover harvest (SH) level, and fertilizer N rate across sites and years.

SH level	Regression parameters *a*	*b*	*c*	Join point	Plateau†	EONR‡	YEONR‡	R^2	*P* > F
				kg N ha^{-1}		kg N ha^{-1}	Mg ha^{-1}		
				Canopy NDVI					
Chisel plow									
None	0.569 (0.024)§	0.0024 (0.0014)	−0.000014 (0.000014)	90	0.678	–	–	0.34	0.001
Partial	0.603 (0.022)	0.0013 (0.0007)	−0.000005 (0.000004)	146	0.700	–	–	0.31	0.002
Complete	0.619 (0.019)	0.0018 (0.0009)	−0.000009 (0.000009)	99	0.707	–	–	0.35	<0.001
No-till									
None	0.537 (0.026)	0.0011 (0.0007)	−0.000003 (0.000003)	184	0.634	–	–	0.25	0.010
Partial	0.576 (0.021)	0.0024 (0.0013)	−0.000014 (0.000014)	86	0.677	–	–	0.37	<0.001
Complete	0.595 (0.021)	0.0015 (0.0008)	−0.000006 (0.000006)	130	0.695	–	–	0.36	<0.001
				Grain yield					
Chisel plow									
None	4.53 (0.83)	0.0467 (0.0139)	−0.000080 (0.000048)	290	11.31	256	11.21	0.56	<0.001
Partial	4.96 (0.81)	0.0487 (0.0149)	−0.000095 (0.000055)	257	11.21	228	11.13	0.55	<0.001
Complete	5.13 (0.80)	0.0544 (0.0161)	−0.000118 (0.000064)	231	11.41	207	11.34	0.57	<0.001
No-till									
None	3.23 (0.92)	0.0488 (0.0154)	−0.000085 (0.000053)	288	10.25	255	10.16	0.52	<0.001
Partial	3.88 (0.89)	0.0530 (0.0158)	−0.000100 (0.000057)	266	10.92	237	10.84	0.55	<0.001
Complete	4.15 (0.94)	0.0562 (0.0188)	−0.000120 (0.000075)	235	10.75	211	10.68	0.52	<0.001

† Mg ha^{-1} for grain yield.

‡ EONR, economic optimum N rate; YEONR, yield at the economic optimum N rate.

§ Values in parentheses are standard errors.

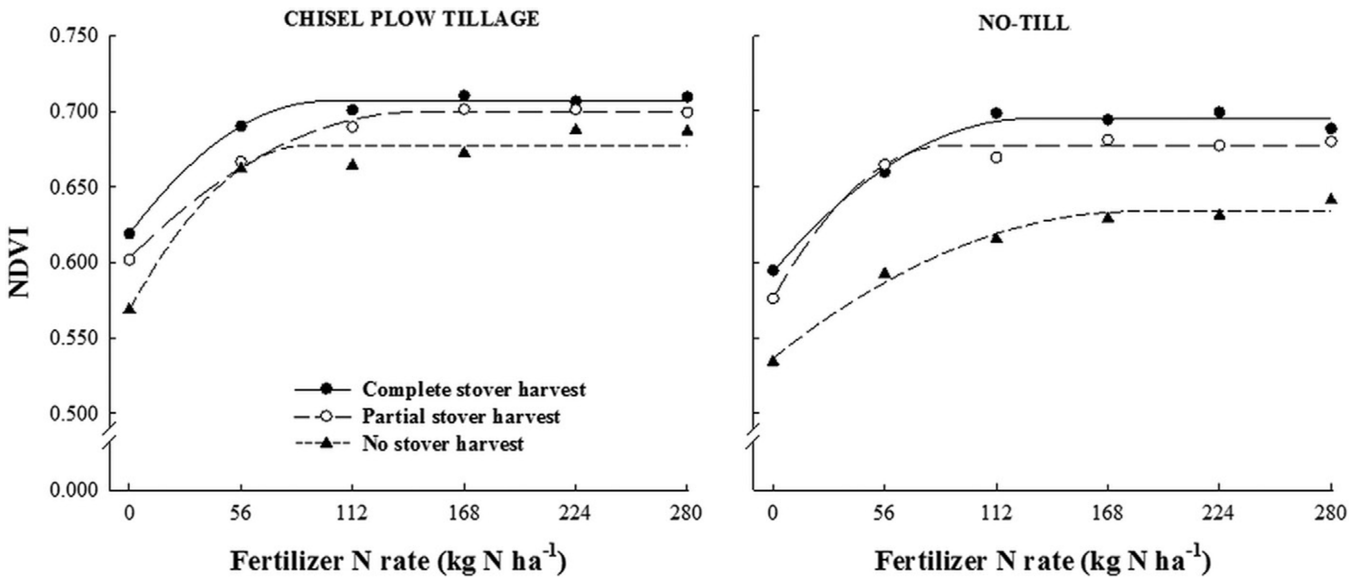

Fig. 3. Corn canopy normalized difference vegetative index (NDVI) response to tillage system, stover harvest level, and fertilizer N rate across sites and years at the V10 growth stage.

study, fall chisel plow tillage reduced corn stover on the soil surface from 21 to 46%, and the lower residue cover compared with no-till resulted in greater soil temperature in the spring, which promoted corn emergence, growth, and N uptake (Hill and Stott, 2000). In a recent study conducted at two locations in southern Minnesota, SH and/or tillage increased the soil temperature by as much as 4°C, and the difference among treatments generally existed until canopy closure (Sindelar et al., 2013). In that study, corn emergence was 6% greater with SH under no-till but was not affected by SH under chisel plow and strip tillage. Other research has found that tillage increased soil temperature compared with no-till by 1.2 to 1.4°C in a cold and wet spring (Licht and Al-Kaisi, 2005). Andraski and Bundy (2008) found a soil temperature increase from 1 to 4°C in the spring depending on the amount of crop residue remaining on the soil surface and the soil moisture.

In well-drained soils and with low annual precipitation, there are positive impacts of greater crop residue coverage, such as increased biological activity, soil moisture conservation, and stover production (Krupinsky et al., 2007; Coulter and Nafziger, 2008). However, no SH in our study, especially in the no-till system, resulted in a reduced early-season corn canopy. Corn SH combined with tillage would increase sunlight reaching the soil surface in the early season and hence increase the soil temperature and promote water evaporation (Boyd and Van Acker, 2003). These factors would promote faster early-season corn growth, especially under wet soil conditions as occurred at times, and probably contributed to the larger canopy NDVI values with SH and chisel plow.

Corn Production and Nitrogen Response

Grain Yield

Corn grain yield varied with SH and tillage system (Table 4). With the significant tillage × SH interaction, the yield with chisel plow tillage was greater than with no-till for all combinations except for chisel plow tillage and no SH compared with no-till and either partial or complete SH, and chisel plow tillage and partial SH compared with no-till and complete removal (Table 5). Also, no-till with no SH had a lower yield than with partial or complete SH, but there was no difference between partial and full SH. These results highlight the general effect of SH on increasing grain yield; however, the SH effect was not as consistent as for canopy NDVI. Corn yield with no fertilizer N was quite low, and lower with no SH than partial and complete SH levels. Application of fertilizer N increased grain yield up to a point where the response plateaued for the partial and complete SH under both tillage systems, with N rate at the join point of the quadratic-plateau model indicating maximum grain yield production and N response. However, for no SH under both tillage systems, grain yield did not reach a plateau within the highest fertilizer N rate (Table 6; Fig. 4).

Differences in weather and soil moisture conditions resulted in variations in the corn grain yield level at each site-year (individual site-year data not shown). On average, corn grain yield was 3.57 and 2.75 Mg ha^{-1} greater in 2009 than 2010 and 2011, respectively, across sites. Across years, Ames had 1.68 Mg ha^{-1} less corn grain yield than Lewis, probably a reflection of the poorly drained soil at the Ames site.

In our study, yield responses to SH level were similar to those reported in a summary by Karlen et al. (2014) for 239 site-years of field research examining the effects of zero, moderate, and high SH levels at 36 sites across seven states. They reported that moderate and high SH levels resulted in a slight increase in grain yield at 57 and 51% of the sites, respectively. Birrell et al. (2014) also reported a significant increase in grain yield due to increasing level of SH at a site near Emmetsburg, IA, in 2008; however, grain yield was not increased in 2010 and 2011 due to prior-year SH. In a long-term study conducted in east-central Minnesota,

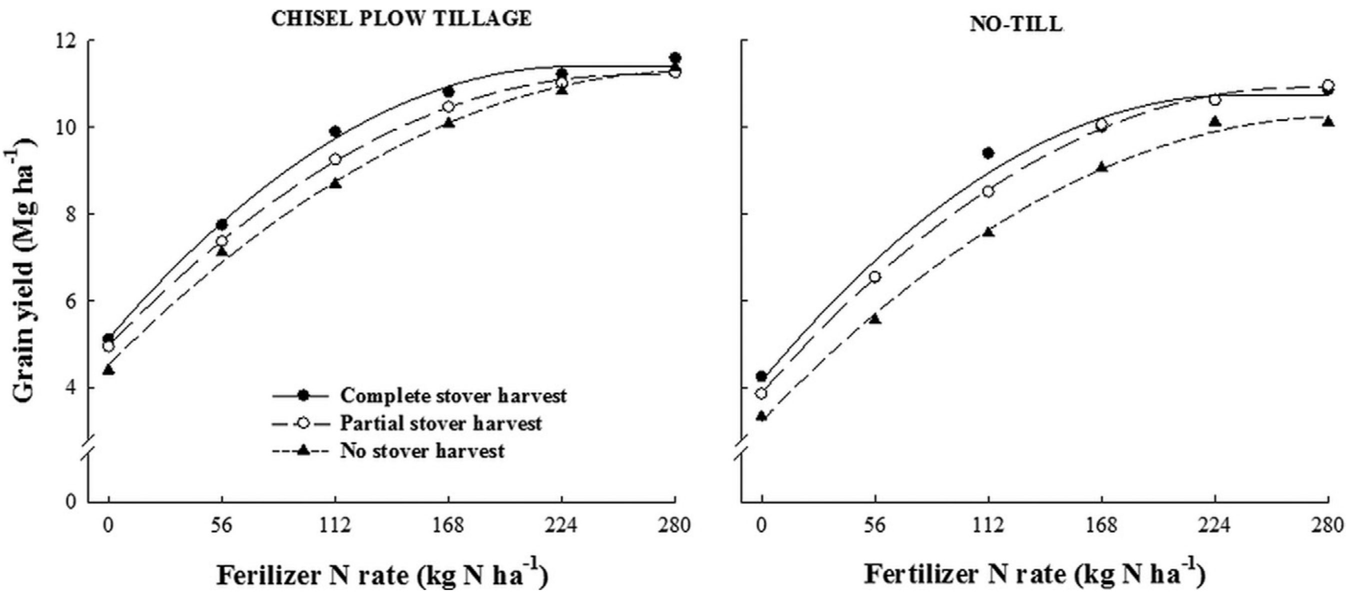

Fig. 4. Corn grain yield response to tillage system, stover harvest level, and fertilizer N rate across sites and years.

Linden et al. (2000) reported differences in grain yield due to stover management in 8 of 13 yr. The SH treatments resulted in about 1 Mg ha^{-1} greater yield in intermediate-level dry years, which had cumulative growing season precipitation 20 and 30% below the 9-yr average. Conversely, Adler et al. (2015) reported no significant effect of SH on grain yield in CC, while SH tended to increase yields in years with wet springs but decrease them in dry years. However, with a corn–soybean rotation, full stover removal always resulted in lower grain yield (Adler et al., 2015). In a no-till study conducted at Lincoln, NE, a linear response was found between grain yield and the amount of stover on the soil surface (Wilhelm et al., 1986). Each 1 Mg ha^{-1} of residue removed resulted in approximately 0.10 Mg ha^{-1} reduction in grain yield. The quantity of residue accounted for 81 and 84% of the variation in the grain yield of corn and soybean, respectively (Wilhelm et al., 1986). Also, Varvel et al. (2008) indicated that corn SH may not be sustainable overall, especially in the long term in low-yield environments such as no-till systems with low annual precipitation that limits the corn production level.

The larger yield with SH observed in our study was consistent across fertilizer N rates for each tillage system (Table 6; Fig. 4). The influence of SH level varied between tillage systems, where the increase in yield with SH was constant with chisel plow tillage (0.30 and 0.35 Mg ha^{-1} between zero and partial SH and between partial and complete SH, respectively), but the increase with no-till was greater between zero and partial SH than between partial and complete SH (0.82 vs. 0.22 Mg ha^{-1}, respectively). These results indicate a greater effect of less crop residue on the soil surface with SH in no-till than in chisel plow tillage. Corn grain yield was the same with chisel plow tillage and no SH as for no-till with partial or complete SH (8.76 compared with 8.44 and 8.66 Mg ha^{-1}, respectively). These yield responses indicate the larger impact of SH, and associated lack of residue mixing into the soil, with no-till than with chisel plow tillage.

Across tillage systems and fertilizer N rates, and compared with no SH, grain yield increased by 0.56 (7%) and 0.85 Mg ha^{-1} (10%) for partial and complete SH, respectively. Having all the corn stover remaining may help protect the soil from rainfall and erosion, but leaving all stover on the soil in our CC production system resulted in reduced early-season corn growth and ultimately less grain yield, especially under no-till (Table 6). With no SH, yield was lower than with partial and complete SH, even at the highest fertilizer N rate used. The application of fertilizer N tended to reduce the difference in yield between SH levels; however, the application of more N was needed to reach maximum grain yield with no SH because the model fits did not reach a plateau in those systems.

Although corn SH increased corn grain yield in the short term in our study, that benefit needs to be balanced against the need to maintain soil productivity by reducing soil erosion, providing biomass for SOM maintenance, and enhancing long-term productivity, as found in other studies (Wilhelm et al., 2004; Coulter and Nafziger, 2008). Even a slight increase in the average grain yield due to SH suggests that corn producers may want to consider implementing just a moderate stover harvest as a means to overcome stover management problems and related costs (Duffy, 2014) as long as soil conservation or soil properties are not compromised. That approach might be better than using aggressive tillage practices to incorporate stover into the soil (Karlen et al., 2011a, 2011b). According to Blanco-Canqui and Lal (2009), perhaps only about 25% of corn stover should be harvested, and SH has to be managed carefully on sloping and erosive soils. Also, because the no-till treatment was newly implemented for our study, SH effects on productivity may change with longer term continuous no-till.

The larger corn yields observed with chisel plow tillage compared with no-till could be due to many factors, such as the soil's physical condition, surface residue level, and soil moisture and temperature. However, the small increase in spring soil NO_3–N observed with chisel plow tillage compared with no-till with no fertilizer N, and the overall low soil NO_3–N concentration in our study, would not have contributed to the differences measured in the early-season corn canopy sensing values and grain yield (Binford et al., 1992b). On productive soils in Illinois, grain yield in CC was similar between chisel plow tillage and no-till with partial or complete SH across five environments with adequate precipitation; however, two environments with low precipitation had greater grain yield with chisel plow tillage than no-till when there was no or only partial SH (Coulter and Nafziger, 2008). Andraski and Bundy (2008) reported a 40 kg N ha^{-1} increase in net soil N mineralization in the top 0.9 m of soil with SH compared with no SH in a well-drained silt loam soil with relatively low precipitation. In our study, however, the impact of SH on profile soil NO_3–N was not observed. Site-specific differences in weather, soil properties, and N immobilization and mineralization could be reasons for these contrasting results.

Economic Optimum Nitrogen Rate

Corn SH reduced the EONR under both tillage systems (Table 6), but the EONR was the same for each tillage system at each SH level. The average EONR with partial and complete SH was 22 (9%) and 45 kg N ha^{-1} (18%) less, respectively, compared with no SH. Sindelar et al. (2013) reported that SH decreased the EONR by at least 12 and 19 kg N ha^{-1} under no-till and strip tillage, respectively, and in environments with adequate rainfall, Coulter and Nafziger (2008) found for both tillage and no-till a reduction in the EONR of 13% with partial or full residue removal compared with no removal. Coulter and Nafziger (2008) indicated that a reduction in the corn fertilizer N rate with SH could be due to less N immobilization. Microbial N demand for high C/N ratio corn stover degradation, associated lower soil temperatures, and less N mineralization with no SH would result in a high fertilizer N requirement (Halvorson and Reule, 2007), as was found in our study (EONR at 255 kg N ha^{-1}). That rate was approximately 40 kg N ha^{-1} more than the highest fertilizer N rate recommended for CC with no SH in Iowa (Blackmer et al., 1997; Sawyer et al., 2006). Because the EONR decreased with SH, the fertilizer N requirement could be adjusted for specific SH levels in CC. It would also be necessary to monitor soil tests if stover is repeatedly harvested due to increased nutrient removal, especially K. Also, if SOM declines with time for SH, soil fertility, nutrient cycling, and other properties could be adversely affected.

With chisel plow tillage, the difference in corn grain yield between no SH and both SH levels decreased as fertilizer N rates approached the highest (Fig. 4), as indicated by Coulter and Nafziger (2008), but this did not occur with no-till. Yields across N rates, the maximum N response, and YEONR were consistently greater with chisel plow tillage than no-till, with an average 0.68 Mg ha^{-1} (6%) greater yield with chisel plow tillage. However, the EONR with chisel plow tillage was only 5 kg N ha^{-1} lower than with no-till across SH levels (Table 6), a small difference considering the major changes in soil disruption and crop residue covering the soil surface between the two systems. The maximum difference in the EONR between tillage systems was only 9 kg N ha^{-1} (with partial SH).

Grain Nitrogen Utilization

The GNU_0 (no fertilizer N applied) was greater with each SH level (P = 0.015): 0.119, 0.120, and 0.123 Mg kg^{-1} N for zero, partial, and complete SH, respectively. There was no effect of tillage system or interaction of SH level × tillage system on GNU_0. The increase in GNU_0 with SH indicates a potential season-long effect on the soil supply of PAN and yield, probably due to an impact of SH on soil N cycling, less stover for microbial degradation, or a combination of both with changes in soil moisture and temperature. Grain N concentration does not necessarily provide a reliable indicator of corn N status due to differences with different soils and environments; therefore, grain N concentration data need to be interpreted carefully (Cerrato and Blackmer, 1990b). In this study, the direct comparison of SH treatments on GNU_0 does provide an indication of change in the available N supply with SH. Dobermann (2007) indicated that GNU values are usually equal to 0.06 ± 0.03 Mg kg^{-1} N with an adequate N supply, values >0.09 Mg kg^{-1} N indicate N deficiency, and values <0.03 Mg kg^{-1} N indicate excess PAN or other factors decreasing yield such as drought or heat stress, mineral toxicity, and pest damage. In our study, GNU_0 values were >0.09 Mg kg^{-1} when no N was applied, which confirmed crop N deficiency with no fertilizer N and an expected large corn response to applied fertilizer N.

Post-harvest Soil Nitrate

The post-harvest soil NO_3–N concentration was low (overall mean ranging from 1.1 ± 0.1 to 4.9 ± 0.5 mg kg^{-1}) and not affected by SH level or tillage system (Table 3). If any difference in net N mineralization due to SH level or tillage system occurred during the growing season, it was not reflected in the post-harvest soil NO_3–N. By the end of the growing season, any potential effect from SH on the soil NO_3–N concentration could have been masked by the high corn yield and N uptake, the large N response in CC to applied N, and wet periods that would have increased the potential for NO_3–N denitrification or leaching losses. There is also a possibility of NO_3–N moving out of the measured 0.9-m depth profile. The NO_3–N concentration decreased with depth, and the applied fertilizer N increased the profile NO_3–N concentration at all depths, with the greatest increase in the top two sample depths and with the highest fertilizer N rate (Fig. 5). The lack of major differences in profile soil NO_3–N in the spring and fall due to SH indicated that the amount of crop residue remaining had little influence on PAN, especially compared with the N application rate and the fact that the N was injected. Although not included as a measurement in our study, soil temperature could play a greater role in microbial processing of high C/N ratio stover, N mineralization and

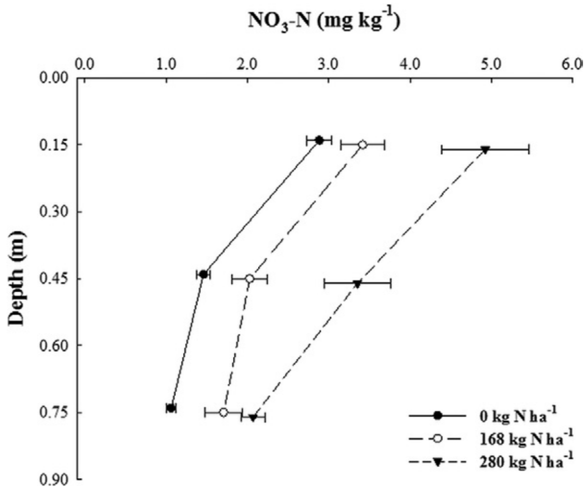

Fig. 5. Fall post-harvest soil profile NO_3–N concentration as affected by fertilizer N rate and sampling depth. Means across stover harvest levels, tillage systems, sites, and years. Horizontal bars represent the standard error of the mean.

cycling, and corn growth than corn stover alone (Andraski and Bundy, 2008).

CONCLUSIONS

Corn SH and tillage system had a minimal effect on the spring profile soil NO_3–N concentration and thus did not appear to differentially affect early-season net N mineralization. Fertilizer N rate, but not tillage or SH, had an effect on post-harvest soil NO_3–N, where higher rates resulted in greater profile NO_3–N concentrations. Stover harvest, chisel plow tillage, and fertilizer N rate increased mid-vegetative corn canopy NDVI sensing values. The NDVI increase attributable to SH was greater for no-till than chisel plow tillage. Despite the lack of a SH effect on soil NO_3–N in the spring, SH increased early-season corn growth, especially with no-till.

As with canopy NDVI, corn grain yield was increased with SH, chisel plow tillage, and fertilizer N rate. For no-till, the relative yield increase with SH was not as large or consistent as the increase in canopy NDVI. Across tillage systems and fertilizer N rates, the average yield increase compared with no SH was 7 and 10% for partial and complete SH, respectively. The yield increase with SH was smaller as the N rate increased, and at the EONR, the SH effect on grain yield was minimal with chisel plow tillage and 6% with no-till.

The EONR was not affected by tillage system, but SH reduced the EONR by 22 kg N ha^{-1} (9%) and 45 kg N ha^{-1} (18%) with partial and complete SH, respectively. With no fertilizer N applied, increased grain yield and GNU_0 with SH reflected a change in soil N cycling and a greater season-long soil supply of PAN with SH. The lower optimal N requirement with SH in CC should be accounted for when planning N applications. However, this study was conducted for a relatively short time period, including recent implementation of no-till, and therefore could not determine if the measured effect of SH would remain if a SH system and lower N input rate were practiced on a continual basis.

ACKNOWLEDGMENTS

This project was supported in part by the Iowa State University Agronomy Department Endowment. Appreciation is extended to the Iowa State University Research Farms superintendents and personnel for their support with the establishment of the study and field work.

REFERENCES

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. PMR 1009. Iowa State Univ. Ext., Ames.

Adler, P.R., B.M. Rau, and G.W. Roth. 2015. Sustainability of corn stover harvest strategies in Pennsylvania. BioEnergy Res. (February). doi:10.1007/s12155-015-9593-2

Al-Kaisi, M., and D. Kwaw-Mensah. 2007. Effect of tillage and nitrogen rate on corn yield and nitrogen and phosphorous uptake in a corn–soybean rotation. Agron. J. 99:1548–1558. doi:10.2134/agronj2007.0012

Andraski, T.W., and L.G. Bundy. 2008. Corn residue and nitrogen source effects on nitrogen availability in no-till corn. Agron. J. 100:1274–1279. doi:10.2134/agronj2008.0039

Arritt, R.W., and D. Herzmann. 2013. Iowa Environmental Mesonet. [Database.] Iowa State Univ., Ames. http://mesonet.agron.iastate.edu/agclimate/hist/dailyRequest.php (accessed 28 Jan. 2013).

Barker, D.W., and J.E. Sawyer. 2010. Using active canopy sensors to quantify corn nitrogen stress and nitrogen application rate. Agron. J. 102:964–971. doi:10.2134/agronj2010.0004

Barker, D.W., and J.E. Sawyer. 2012. Using active canopy sensing to adjust nitrogen application rate in corn. Agron. J. 104:926–933. doi:10.2134/agronj2012.0030

Binford, G.D., A.M. Blackmer, and M.E. Cerrato. 1992a. Nitrogen concentration of young corn plants as an indicator of nitrogen availability. Agron. J. 84:219–223. doi:10.2134/agronj1992.00021962008400020019x

Binford, G.D., A.M. Blackmer, and M.E. Cerrato. 1992b. Relationships between corn yields and soil nitrate in late spring. Agron. J. 84:53–59. doi:10.2134/agronj1992.00021962008400010012x

Birrell, S.J., D.L. Karlen, and A. Wirt. 2014. Development of sustainable corn stover harvest strategies for cellulosic ethanol production. BioEnergy Res. 7:509–516. doi:10.1007/s12155-014-9418-8

Blackmer, A.M., R.D. Voss, and A.P. Mallarino. 1997. Nitrogen fertilizer recommendations for corn in Iowa. PM 1714. Iowa State Univ. Ext., Ames.

Blanco-Canqui, H., and R. Lal. 2009. Corn stover removal for expanded uses reduces soil fertility and structural stability. Soil Sci. Soc. Am. J. 73:418–426. doi:10.2136/sssaj2008.0141

Boyd, N.S., and R.C. Van Acker. 2003. The effects of depth and fluctuating soil moisture on the emergence of eight annual and six perennial plant species. Weed Sci. 51:725–730. doi:10.1614/P2002-111

Brown, J.R., editor. 1998. Recommended chemical soil test procedures for the North Central Region. North Central Reg. Res. Publ. 221 (Rev) SB 1001. Missouri Agric. Exp. Stn., Columbia.

Bullock, D.G., and D.S. Bullock. 1994. Quadratic and quadratic-plus-plateau models for predicting optimal nitrogen rate of corn: A comparison. Agron. J. 86:191–195. doi:10.2134/agronj1994.00021962008600010033x

Cerrato, M.E., and A.M. Blackmer. 1990a. Comparison of models for describing corn yield response to nitrogen fertilizer. Agron. J. 82:138–143. doi:10.2134/agronj1990.00021962008200010030x

Cerrato, M.E., and A.M. Blackmer. 1990b. Relationships between grain nitrogen concentrations and the nitrogen status of corn. Agron. J. 82:744–749. doi:10.2134/agronj1990.00021962008200040019x

Coulter, J.A., and E.D. Nafziger. 2008. Continuous corn response to residue management and nitrogen fertilization. Agron. J. 100:1774–1780. doi:10.2134/agronj2008.0170

Derby, N.E., D.D. Steele, J. Terpstra, R.E. Knighton, and F.X.M. Casey. 2005. Interactions of nitrogen, weather, soil, and irrigation on corn yield. Agron. J. 97:1342–1351. doi:10.2134/agronj2005.0051

Dobermann, A. 2007. Nutrient use efficiency: Measurement and management. Paper presented at: International Fertilizer Industry Association (IFA) Workshop on Fertilizer Best Management Practices. Brussels, Belgium. 7–9 Mar. 2007.

Duffy, M.D. 2014. Estimated costs of crop production in Iowa—2014. FM-1712 (revised). Iowa State Univ. Ext., Ames.

Fixen, P.E. 2007. Potential biofuels influence on nutrient use and removal in the

U.S. Better Crops 91:12–14.
Gitelson, A.A., Y.J. Kaufman, and M.N. Merzlyak. 1996. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. Remote Sens. Environ. 58:289–298. doi:10.1016/S0034-4257(96)00072-7
Halvorson, A.D., and A.L. Reule. 2007. Irrigated, no-till corn and barley response to nitrogen fertilization in northern Colorado. Agron. J. 99:1521–1529. doi:10.2134/agronj2006.0356
Hatfield, J.L., L.D. McMullen, and C.S. Jones. 2009. Nitrate-nitrogen patterns in the Raccoon River Basin related to agricultural practices. J. Soil Water Conserv. 64:190–199. doi:10.2489/jswc.64.3.190
Hill, P.R., and D.E. Stott. 2000. Corn residue retention by a combination chisel plow. Soil Sci. Soc. Am. J. 64:293–299. doi:10.2136/sssaj2000.641293x
Johnson, J.M.F., V. Acosta-Martinez, C.A. Cambardella, and N.W. Barbour. 2013. Crop and soil responses to using corn stover as a bioenergy feedstock: Observations from the Northern US Corn Belt. Agriculture 3:72–89. doi:10.3390/agriculture3010072
Karlen, D.L., S.J. Birrell, and J.R. Hess. 2011a. A five-year assessment of corn stover harvest in central Iowa, USA. Soil Tillage Res. 115–116:47–55. doi:10.1016/j.still.2011.06.006
Karlen, D.L., S.J. Birrell, J.M.F. Johnson, S.L. Osborne, T.E. Schumacher, G.E. Varvel, et al. 2014. Multilocation corn stover harvest effects on crop yields and nutrient removal. BioEnergy Res. 7:528–539. doi:10.1007/s12155-014-9419-7
Karlen, D.L., G.E. Varvel, J.M.F. Johnson, J.M. Baker, S.L. Osborne, J.M. Novak, et al. 2011b. Monitoring soil quality to assess the sustainability of harvesting corn stover. Agron. J. 103:288–295. doi:10.2134/agronj2010.0160s
Krupinsky, J.M., S.D. Merrill, D.L. Tanaka, M.A. Liebig, M.T. Lares, and J.D. Hanson. 2007. Crop residue coverage of soil influenced by crop sequence in a no-till system. Agron. J. 99:921–930. doi:10.2134/agronj2006.0129s
Kwaw-Mensah, D., and M. Al-Kaisi. 2006. Tillage and nitrogen source and rate effects on corn response in corn–soybean rotation. Agron. J. 98:507–513. doi:10.2134/agronj2005.0177
Licht, M.A., and M. Al-Kaisi. 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Tillage Res. 80:233–249. doi:10.1016/j.still.2004.03.017
Linden, D.R., C.E. Clapp, and R.H. Dowdy. 2000. Long-term corn grain and stover yields as a function of tillage and residue removal in east central Minnesota. Soil Tillage Res. 56:167–174. doi:10.1016/S0167-1987(00)00139-2
Mann, L., V. Tolbert, and J. Cushman. 2002. Potential environmental effects of corn (*Zea mays* L.) stover removal with emphasis on soil organic matter and erosion. Agric. Ecosyst. Environ. 89:149–166. doi:10.1016/S0167-8809(01)00166-9
Martin, M.A. 2010. First generation biofuels compete. New Biotechnol. 27:596–608. doi:10.1016/j.nbt.2010.06.010
Maskina, M.S., J.F. Power, J.W. Doran, and W.W. Wilhelm. 1993. Residual effects of no-till crop residues on corn yield and nitrogen uptake. Soil Sci. Soc. Am. J. 57:1555–1560. doi:10.2136/sssaj1993.03615995005700060027x
Mehdi, B.B., C.A. Madramootoo, and G.R. Mehuys. 1999. Yield and nitrogen content of corn under different tillage practices. Agron. J. 91:631–636. doi:10.2134/agronj1999.914631x
Mulvaney, M.J., C.W. Wood, K.S. Balcom, D.A. Shannon, and J.M. Kemble. 2010. Carbon and nitrogen mineralization and persistence of organic residues under conservation and conventional tillage. Agron. J. 102:1425–1433.
Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. In: D.L. Sparks, editor, Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA and ASA, Madison, WI. p. 961–1010. doi:10.2136/sssabookser5.3.c34
Osborne, S.L., J.M.F. Johnson, V.L. Jin, A.L. Hammerbeck, G.E. Varvel, and T.E. Schumacher. 2014. The impact of corn residue removal on soil aggregates and particulate organic matter. BioEnergy Res. 7:559–567.
Randall, G.W., and T.K. Iragavarapu. 1995. Impact of long-term tillage systems for continuous corn on nitrate leaching to tile drainage. J. Environ. Qual. 24:360–366.
Raun, W.R., and J.S. Schepers. 2008. Nitrogen management for improved use efficiency. In: J.S. Schepers et al., editors, Nitrogen in agricultural systems. Agron. Monogr. 49. ASA, CSSA, and SSSA, Madison, WI. p. 675–693. doi:10.2134/agronmonogr49.c17
Robinson, C.A., R.M. Cruse, and M. Ghaffarzadeh. 1996. Cropping system and nitrogen effects on Mollisol organic carbon. Soil Sci. Soc. Am. J. 60:264–269.
SAS Institute. 2009. SAS System for Windows, Release 9.3.1. SAS Inst., Cary, NC.
Sawyer, J.E., A.P. Mallarino, R. Killorn, and S.K. Barnhart. 2011. A general guide for crop nutrient and limestone recommendations in Iowa. PM 1688. Iowa State Univ. Coop. Ext., Ames.
Sawyer, J., E. Nafziger, G. Randall, L. Bundy, G. Rehm, and B. Joern. 2006. Concepts and rationale for regional nitrogen rate guidelines for corn. PM 2015. Iowa State Univ. Ext., Ames.
Sherrod, L.A., G. Dunn, G.A. Peterson, and R.L. Kolberg. 2002. Inorganic carbon analysis by modified pressure-calcimeter method. Soil Sci. Soc. Am. J. 66:229–305. doi:10.2136/sssaj2002.0299
Sindelar, A.J., J.A. Coulter, J.A. Lamb, and J.A. Vetsch. 2013. Agronomic responses of continuous corn to stover, tillage, and nitrogen management. Agron. J. 105:1498–1506. doi:10.2134/agronj2013.0181
Sindelar, A.J., J.A. Coulter, J.A. Lamb, and J.A. Vetsch. 2015. Nitrogen, stover, and tillage management affect nitrogen use efficiency in continuous corn. Agron. J. 107:843–850. doi:10.2134/agronj14.0535
Soane, B.D., B.C. Ball, J. Arvidsson, G. Basch, F. Moreno, J. Roger-Estrade. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil Tillage Res. 118:66–87. doi:10.1016/j.still.2011.10.015
Sokhansanj, S., A. Turhollow, J. Cushman, and J. Cundiff. 2002. Engineering aspects of collecting corn stover for bioenergy. Biomass Bioenergy 23:347–355. doi:10.1016/S0961-9534(02)00063-6
Stetson, S.J., S.L. Osborne, T.E. Schumacher, A. Eynard, G. Chilom, J. Rice, et al. 2012. Corn residue removal impact on topsoil organic carbon in a corn–soybean rotation. Soil Sci. Soc. Am. J. 76:1399–1406. doi:10.2136/sssaj2011.0420
Sulc, R.M., and B.F. Tracy. 2007. Integrated crop–livestock systems in the U.S. Corn Belt. Agron. J. 99:335–345. doi:10.2134/agronj2006.0086
Swan, J.B., T.C. Kaspar, and D.C. Erbach. 1996. Seed-row residue management for corn establishment in the northern US Corn Belt. Soil Tillage Res. 40:55–72. doi:10.1016/S0167-1987(96)01046-X
Teillet, P.M., K. Staenx, and D.J. Williams. 1997. Effects of spectral, spatial, and radiometric characteristics on remote sensing vegetation indices of forested regions. Remote Sens. Environ. 61:139–149. doi:10.1016/S0034-4257(96)00248-9
Torbert, H.A., K.N. Potter, and J.E. Morrison, Jr. 2001. Tillage system, fertilizer nitrogen rate, and timing effect on corn yields in the Texas Blackland Prairie. Agron. J. 93:1119–1124. doi:10.2134/agronj2001.9351119x
USDOE. 2011. U.S. billion-ton update: Biomass supply for a bioenergy and bioproducts industry. Oak Ridge Natl. Lab., Oak Ridge, TN. http://www1.eere.energy.gov/biomass/pdfs/billion_ton_update.pdf (accessed 10 Jan. 2015).
Varvel, G.E., K.P. Vogel, R.B. Mitchell, R.F. Follett, and J.M. Kimble. 2008. Comparison of corn and switchgrass on marginal soils for bioenergy. Biomass Bioenergy 32:18–21. doi:10.1016/j.biombioe.2007.07.003
Vetsch, J.A., and G.W. Randall. 2004. Corn production as affected by nitrogen application timing and tillage. Agron. J. 96:502–509. doi:10.2134/agronj2004.0502
Wienhold, B.J., and J.E. Gilley. 2010. Cob removal effect on sediment and runoff nutrient loss from a silt loam soil. Agron. J. 102:1448–1452.
Wilhelm, W.W., J.W. Doran, and J.F. Power. 1986. Corn and soybean yield response to crop residue management under no-tillage production systems. Agron. J. 78:184–189.
Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden. 2004. Crop and soil productivity response to corn residue removal: A literature review. Agron. J. 96:1–17.
Wilts, A.R., D.C. Reicosky, R.R. Allmaras, and C.E. Clapp. 2004. Long-term corn residue effects: Harvest alternatives, soil carbon turnover, and root-derived carbon. Agron. J. 68:1342–1351.