STOVER, TILLAGE, AND NITROGEN MANAGEMENT IN CONTINUOUS CORN FOR GRAIN, ETHANOL, AND SOIL CARBON

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Abstract

Interest in harvesting corn (*Zea mays* L.) cellulosic materials for ethanol production has resulted in the development of research questions regarding its potential effects on crop growth and productivity as well as soil quality. Previous research has generally occurred in environments different than those found in the Upper Midwest, meaning application of those conclusions to the Upper Midwest may not be appropriate. This research is unique because it was conducted on heavy-textured, poorly-drained soils in several tillage systems in environments where soil temperature is often a limiting factor on crop growth.

This research indicates corn stover removal in continuous corn cropping (CC) systems improves agronomic performance, but decreases soil C in as little as 3 yr. Agronomic measurements including plant emergence, plant height and normalized difference vegetative index at the eight leaf collar stage, grain yield, stover biomass yield, and stover cellulosic ethanol yield improved with stover removal. The fertilizer N rate needed to economically optimize grain yield decreased by at least 2, 12, and 19 kg N ha^{-1} for chisel, strip-till, and no-till, respectively. Greater nutrient use efficiency was also often observed with stover removal. In general, the greatest differences in N use efficiency between stover management treatments in the reduced tillage treatments occurred at low fertilizer N rates. This indicates that N availability was less when stover was retained because stover remaining on the soil surface decreased net N mineralization. However, various soil C pools were negatively affected by stover removal, particularly in surface measurements (0 to 15 cm). In contrast, retaining corn stover increased soil C in the same depths. These results indicate that the benefits of stover removal on agronomic performance and the adverse effects on soil C dynamics must be carefully deliberated when considering employing stover removal in CC cropping systems in the Upper Midwest.

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INTRODUCTION

Corn (*Zea mays* L.) is expected to play an important part in the U.S. goal to decrease foreign dependency on petroleum. Corn grain is the currently the primary component in ethanol production, but current projections suggest that the contribution of grain is nearing its limit and the expansion of biofuel production will need to be derived from cellulosic sources (Perlack, 2005). Because of its abundant production of biomass, corn is regarded as a potentially integral component in cellulosic biofuel production. Cropping systems in the Upper Midwest are anticipated to be a key area to support this aspect of the biofuel industry.

While benefits do exist when corn stover, the cellulosic component remaining after grain harvest, is removed from the field, its removal can also negatively affect soil quality (Doran et al., 1984; Wilhelm et al., 2004; Wilhelm et al., 2007; Blanco-Canqui, 2010). Therefore, careful consideration will be necessary to determine if revenue from the sale of corn stover outweighs its potentially negative impacts on soil quality. In order to maximize profitability while protecting soil quality, research is necessary to determine the combination of management practices, including tillage system, stover removal, and nitrogen (N) management that can best fulfill this goal.

DEMAND OF CORN STOVER FOR CELLULOSIC ETHANOL PRODUCTION

Corn grain is currently the primary source for ethanol production in the U.S., with 26% of the total U.S. grain supply used for ethanol production in 2011 (Renewable Fuels Association, 2012). However, to meet future biofuel demands, ethanol production will require expansion (Perlack, 2005). Increased support for decreasing the country's dependency on foreign petroleum in a sustainable manner has led to increased interest in ethanol production from lignocellulosic biomass (Wilhelm et al., 2004; Perlack et al., 2005; Graham et al., 2007). Legislation passed through the U.S. Energy Independence and Security Act of 2007 also requires annual production of 135 billion L of renewable fuel by 2022, of which 79 billion L must be produced from cellulosic or other advanced conversion processes (Sissine, 2007). To meet this demand, 218 Mg of dry feedstock per year will be required (Biomass Research and Development Board, 2008). Because of greater demand and lower estimated cost to produce cellulosic ethanol compared to gasoline (Solomon et al., 2007), the cellulosic ethanol industry is expected to rapidly expand in the near future. Recent estimates are that corn stover left after grain harvest represents 137 Mg of dry matter (DM) in Minnesota, Illinois, Iowa, and Nebraska (Wilhelm et al., 2004). While systems containing other native grasses that would be used for biofuel purposes are also of interest (Sarath et al., 2008; James et al., 2010; Propheter et al., 2010), corn stover holds a distinct advantage related to its availability because corn cropping systems are well-established (Wilhelm, 2004). Corn stover also provides some of the greatest amounts of cellulosic biomass compared to most other potential biofuel species currently being researched (Propheter et al., 2010).

Stover removal can provide benefits to a cropping system, especially in northern latitudes that are commonly affected by cool early-season soil temperatures. Several studies have shown a shorter emergence interval after planting when stover coverage was decreased (Doran et al., 1984; Wilhelm et al., 1986; Vetsch and Randall, 2002). Soil temperature also affects microbial communities, as increasing temperature increases their activity (Agehara and Warncke, 2005). Removal of stover can also decrease disease potential, as diseases such as stalk rot, gray leaf spot, and northern corn leaf blight are all harbored by corn stover (White, 1999).

TILLAGE, STOVER, AND NITROGEN MANAGEMENT ON CORN PRODUCTION AND NITROGEN USE EFFICIENCY

Many studies have researched the effects of tillage system on corn production. Initial work in tillage suggested that any tillage system that created a seedbed for accurate seed depth placement was sufficient (Cook et al., 1953), and that no-till (NT) could potentially improve crop yields because of its ability to conserve water (Shear and Jones, 1961; Jones et al., 1969; Shear and Moschler, 1969). Later research showed the effect of tillage was location dependent. Olson and Schoeberl (1970) investigated the effects of four tillage systems on corn grain yield, water use, and soil temperature in Eastern South Dakota over 4 yr and did not observe differences among tillage systems in DM yield, grain yield, or water use. They did observe a general increase in grain moisture and a decrease in soil temperature as tillage intensity decreased. Despite below-average seasonal precipitation, reduced tillage (RT) did not greatly increase water availability, resulting in similar grain yields. It was suggested that RT systems could be employed at the latitude of South Dakota without adversely affecting grain yield.

Griffith et al. (1973) evaluated the effects of eight tillage-planting systems on five soil series in Indiana. They concluded that soil temperature, plant growth, and grain yield all depended on tillage system, as they all decreased with less tillage intensity. They also noted that the impact of a given tillage system on these parameters was also dependent on soil type, drainage, and latitude. Van Doren et al. (1976) researched long-term tillage and crop rotation effects across several soils in Ohio that varied in drainage potential. They found that corn grain yields decreased with NT on poorly-drained soils, regardless of crop rotation. However, on well-drained soils, grain yield was greater with NT when compared to conventional tillage (CVT). They attributed this response to soil water conservation by stover at the soil surface. A similar study by Van Doren and Triplett (1973) also attributed grain yield increases as a function of reducing tillage to greater soil water availability.

Iragavarapu and Randall (1995) suggested that tillage system effects are dependent on geographic location; they observed that plant population, grain yield, and grain N concentration were all negatively affected by NT over 11 yr on a poorly drained clay loam in southern Minnesota. They also noted a substantial delay in silk emergence and higher moisture content in grain at harvest. These responses were supported by Swan et al. (1987), who observed that the number of growing degree days increased linearly with stover coverage. Similarly, Sauer et al. (1996) reported cooler soil temperatures caused by stover on the soil surface, likely because of reduced solar radiation absorption.

Vetsch et al. (2007) investigated the response of corn production to tillage on a poorly drained clay loam soil complex with tile drainage in southern Minnesota. Tillage systems were CT, strip-till (ST), NT, and zone-till (ZT), which was similar to ST, but 90% deeper. In a growing season with below-average precipitation, ZT and ST increased grain yield by at least 0.4 Mg ha^{-1} compared to CT and NT. They attributed the response to warmer soils caused by decreased soil surface coverage and less surface soil compaction. However, when precipitation was considered normal, grain yield did not differ among tillage systems

A number of researchers have studied the effects of stover removal, tillage, and fertilizer N rate on corn production; but few have simultaneously tested these management variables. Morachan et al. (1972) studied the effects of stover management for 13 yr in continuous corn on a silty clay loam soil in Iowa. They reported minimal differences in grain yield in the first 9 yr of the study. However, they observed reduced grain yield as the quantity of corn stover that was returned increased in the remaining duration of the study. This was attributed to an aluminum-induced calcium deficiency, as pH levels were observed to be 4.8 in the high-stover treatment and 5.3 in the check treatment. Four yr following termination of the stover treatments, grain yield was greater in the 8 and 16 Mg ha^{-1} treatments. They attributed the response to a higher nutrient status since no fertilizer had been applied (Larson et al., 1972).

Several studies have been conducted on a field experiment initially established by Doran et al. (1984) that determined the effects of stover removal in NT on a clay loam soil in Nebraska. Doran et al. (1984) reported that grain yield decreased 13 and 21% when half and none of the stover was removed from the soil surface from 1978 to 1980, respectively. Complete removal of stover the previous year also reduced successive stover biomass by 12%, but removal of half the stover had little effect, only reducing biomass yield by 2%. They concluded that grain yields were affected by variation in available soil water among stover removal treatments caused by high air temperatures; available soil water was 52 and 33% greater when stover was retained compared to complete removal on 26 June and 31 July, respectively. These dates may have coincided with important stages of physiological development; and studies have showed that water limitations during important physiological stages around pollination can negatively affect corn growth and yield (Earley et al., 1974; Frey, 1981; Sindelar et al., 2010).

Power et al. (1986a) reported the effects of the same treatments on grain yield the following three years (1980-1983) for the study initiated by Doran et al. (1984). Over this period, they observed a decrease in grain yield of 9 and 28% when half and all of the stover was removed from the soil surface, respectively. A decrease of 21% in available soil water to a 1.5 m depth after planting was also observed between the no and complete removal. They noted that precipitation was below average in 1980 and that available soil water was near zero in the complete removal treatments in early August. In comparison, available soil water was 50 to 70 mm in the treatments where stover was retained. Differences in soil temperature were also observed, as the average maximum temperature in the complete removal treatment was 57°C compared to 50°C in the treatments where stover was retained.

Wilhelm et al. (1986) expanded on the work by Doran et al. (1984) and studied the response of grain and stover yield to stover removal in a continuous corn (CC) system in NT over 4 yr. In two of the 4 yr, they observed a minimal response of grain yield to stover removal, likely because of high air temperatures and below-average precipitation. However, in the remaining 2 yr, they observed that for each Mg ha^{-1} of stover removed, grain and stover yield decreased by 0.13 and 0.29 Mg ha^{-1}, respectively. Similar to Doran et al. (1984), they concluded differences were caused by variation in available soil water among stover removal levels. Wilhelm et al. (1986) further showed that available soil water from 15 June to 31 August accounted for approximately 70% of the variation in grain yield, and that grain yield increased by 0.02 Mg ha^{-1} with each additional mm of water available to the plant.

Maskina et al. (1993) added a fertilizer N rate component (0 and 60 kg N ha^{-1}) to the original study by Doran et al. (1984). They observed that grain yield decreased by 10% with the combination of stover removal and no fertilizer N application. An application of 60 kg N ha^{-1} minimized the effect of stover removal. Likewise, stover biomass yield decreased 17%when complete stover removal occurred with no N application, but did not differ when fertilizer N was applied.

Power et al. (1998) reported that returning at least 100% of corn stover resulted in the greatest grain yields over a 10-yr period and that returning 150% of stover increased grain yield by at least 10% compared to complete removal. It was concluded by Wilhelm et al. (1986) that the positive response of stover return was caused by high soil organic matter (SOM) levels and enhanced rates of nutrient cycling. Further, the summarized data from these experiments underscores the value of cereal grain stover on the soil surface when soil water availability is of concern. Because of soil moisture concerns, environments do exist where sustained stover removal may not be appropriate (Graham et al., 2007).

Karlen et al. (1984) researched the effects of stover removal on grain yield on a Norfolk sandy loam for three yr with CVT in dryland and irrigated conditions in South Carolina. In dryland conditions, removal of corn stover produced varying effects on grain yield each year, as 90% stover removal resulted in no effect the first yr, decreased grain yield the second yr, and increased grain yield the final year when compared to treatments where stover was retained. Under irrigation, grain yield decreased the first yr with stover removal, but did not differ between stover treatments the following two yr. While no clear yield trends were found, potassium (K) availability decreased with stover removal.

Burgess et al. (1996) studied the effects of tillage and stover removal on a St. Amable-Courval loamy sand in a cropping system that was in forage grass prior to the study in Quebec. They determined that when stover was retained, grain yield in NT was at least 16% lower than the other tillage systems. When stover was removed, tillage did not affect grain and stover yields. This indicates that NT may be a more economically viable option when stover is harvested or in fields where corn is harvested for silage.

Linden et al. (2000) reported the effects of tillage [(chisel (CT) and NT] and stover removal (none and full) on long-term corn grain and stover production on a

Waukegan silt loam in east-central Minnesota. Over 13 yr, returning stover resulted in a 22% increase in grain yield compared to complete removal in years when rainfall was below average (potential water deficit of 10-30 cm). In years where water was considered not limiting, stover removal did not affect grain yield. When stover was removed in NT, grain yield was not affected over the course of the study. However, returning stover in treatments in CT greatly improved grain yield.

Dam et al. (2005) studied the response of corn growth and yield to tillage (NT, RT, and CVT) and stover removal after 11 yr on an Amable loamy sand in Quebec. Though dependent upon year, plant stands were often greater with stover removal, particularly in NT and RT systems. Also, the amount of stover on the soil surface, which was dictated by tillage system, directly affected emergence when stover was not removed, as emergence in NT was lower than the other tillage treatments in all five years where emergence was investigated. When stover removal occurred, tillage did not affect plant emergence. Based on these findings, they concluded that NT should be used when possible on a sandy soil in order to conserve soil moisture, especially in years where precipitation is below normal.

Blanco-Canqui et al. (2006b) evaluated corn stover return levels of 0, 25, 50, 75, 100, and 200% (0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1}, respectively) on corn growth and production in Ohio. While no immediate differences in grain yield were observed in the first year of the study, removing ≥50% of corn stover increased emergence and early plant height within 2 mo of emergence. No differences in leaf chlorophyll existed between any stover treatments. Yield decreases were only observed in the treatments that removed ≥75% of stover (8.75 Mg ha^{-1}). The decrease in grain yield was attributed to losses in soil moisture and increases in soil temperature with stover removal. However, data from this study did suggest that at least 5 Mg ha^{-1} of stover could be removed without adversely affecting grain yield in the short-term (≤2 yr).

Sims et al. (1998) evaluated fertilizer N rate, tillage system (CVT and NT), and stover removal (retain or remove) on irrigated Sharpsburg silty clay loam and Hastings silt loam soils in Nebraska. On the silt loam soil, grain yield was not affected by stover removal or tillage system. However, on the silty clay loam soil, greater yields were observed with stover removal in CVT, regardless of fertilizer N rate. They concluded that tillage increased grain yield when spring temperatures are cool, especially on fine-textured soils. The research also indicated that yield reductions associated with high amounts of stover may be potentially counterbalanced by increased levels of fertilizer N rate. Work by Andraski and Bundy (2008) suggested that an additional 30 kg N ha^{-1} may be necessary in NT corn in order to provide a yield benefit.

Coulter and Nafziger (2008) researched the effects of tillage systems (CT and NT), stover removal (no-, partial-, and full-removal) and fertilizer N rate selection in average and below-average in-season precipitation regimes in Illinois. Under normal precipitation, stover removal did not affect grain yield in CT. When stover was removed in NT, grain yield increased by 8% and the amount of fertilizer N needed to economically optimize grain yield decreased by 13%. Under low rainfall, full stover removal produced the greatest grain yield in CT, while the lowest yield occurred in NT. When tillage systems were compared in both precipitation regimes, tillage did not affect grain yield with full stover removal, and produced varying results with no and partial stover removal. In the normal rainfall group, greater grain yields occurred with CT for both stover removal levels. However, in the low rainfall group, tillage did not affect the response of grain yield to stover removal and NT produced higher grain yield when no stover was removed. The results from this study illustrate the sensitivity of corn productivity to stover management when precipitation is limiting.

NITROGEN FERTILIZER AND TILLAGE EFFECTS ON NITROGEN USE EFFICIENCY

On average, only 33% of fertilizer N applied to cereal crops is recovered by the grain (Raun and Johnson, 1999). However, efforts have been amplified in recent years to improve N use efficiency (NUE) (Raun et al., 2002; Solari et al., 2008; Varvel et al., 2007). Moschler et al. (1972) compared how CVT and NT affected grain yield and fertilizer efficiency on clay loam and silt loam soils for at least 5 yr in Virginia. They concluded that NUE was greater in NT as a result of increased grain yield (≥14%) and lower residual nutrient recovery. Moschler and Martens (1975) researched the response of nutrient uptake efficiency to CVT and NT after three yr on a Jefferson silt loam in Virginia. They observed that NUE was greater in CVT, particularly at lower fertilizer N rates, despite similar grain yields between tillage systems. Meisinger et al. (1985) studied NUE in corn in minimal and plow tillage in Maryland. Following four years of field trials, they concluded the amount of fertilizer N needed to maximize grain yield was lower in plow tillage. This response was likely related to increased net N mineralization with tillage (Rice et al., 1987).

Halvorson et al. (2006) investigated the response of corn to tillage and fertilizer N rate in irrigated CC on a Fort Collins clay loam soil in Colorado. They observed that maximum grain yield in CVT was 16% greater than in NT when water was not limiting in a sub-arid environment, despite the amount of fertilizer necessary to maximize grain yield being similar. They attributed this response to slower early-season growth and delayed tasseling related to cooler soil temperatures in NT. A decline in NFUE as N rate increased was also observed. Tillage system also affected productivity, as 19 and 10 kg N ha^{-1} was necessary to produce 1 Mg ha^{-1} of grain in CVT and NT, respectively.

Wortmann et al. (2011) studied the response of agronomic (AE) and physiological (PE) N use efficiencies to fertilizer N rate in different cropping systems in Nebraska. In CC, AE decreased as N rate increased. This response was expected. The response of PE to fertilizer N rate was less defined, and fertilizer N rate effects on PE beyond 140 kg N ha^{-1} were minimal. The findings of minimal effects of fertilizer N rate on PE are important because they indicate that increasing fertilizer N rate does not greatly influence the plant’s potential to convert fertilizer N uptake to grain.

SOIL ORGANIC MATTER IN AGRICULTURAL SYSTEMS

The characteristics of highly productive agricultural soils are often related to the organic fraction of soils (Brady and Weil, 2002). Soil organic matter (SOM) is known to affect many soil physical and chemical properties, including nutrient availability (Magdoff, 1991; Power, 1994; Magdoff et al., 1997), bulk density (Huntington et al., 1989; Franzluebbers et al., 2000) , water infiltration (Elliott and Efetha, 1999; Franzluebbers, 2002), water retention (Hudson, 1994; Stone and Schlegel, 2010), soil aggregation (Tisdall and Oades, 1982; Angers and Giroux, 1996; Six et al., 2000), and ion exchange capacity (Borogowski et al., 1976; Havlin et al., 2005). Since SOM has such a profound impact on many soil properties, it is regarded as the central component in soil quality. Defined by Karlen et al., (1997), soil quality is the capacity of the soil to carry out ecological functions that support terrestrial communities, resist erosion, and reduce negative impacts on associated air and water resources.

Plant residues are a primary source of C returned to the soil, and the flux of soil organic carbon (SOC) is highly related to the amount of plant material returned (Huggins et al., 1998; Varvel, 2006; Benjamin et al., 2008). While numerous studies have documented the importance of aboveground biomass return, it is equally important to consider the contribution of belowground plant components, including roots, root hairs, root exudates, and photosynthetic C that has been translocated belowground (Kuzyakov and Domanski, 2000; Kuzyakov, 2001). Unlike aboveground biomass, quantification of total C from belowground biomass has proven to be difficult to estimate (Balabane and Balesdent, 1992; Bolinder et al., 1999). However, various studies have been successful at quantifying the C contributions by roots (Barber and Martin, 1976; Huggins et al., 1998) and photosynthetically fixed C (Molina et al., 2001).

The decomposition of C occurs through enzyme-mediated oxidation, shown in Eq. 1.1 (Brady and Weil, 2002):

$$\mathrm{R-(C,4H)+2O_2 \rightarrow CO_2 \uparrow + 2H_2O + energy\ (478\ kJ\ mol^{-1}\ C)} \qquad [1.1]$$

When a C source is initially introduced to soil microbial communities, activity exponentially increases because of the abundant supply of easily-oxidized sugars, starches, and proteins. However, as these simple C sources are depleted, microbial populations also decline with the decreasing substrate supply. As these microbes perish, simple inorganic products that were necessary for microbial activity, such as nitrates ($\mathrm{NO_3^-}$) and sulfates ($\mathrm{SO_4^{-2}}$), are ultimately released, a process known as mineralization (Brady and Weil, 2002).

All organic compounds in plant tissue do not exhibit the same rates of decomposition (Brady and Weil, 2002). The order of organic compound decomposition, from rapid to slow, are sugars and starches, proteins, hemicelluloses, cellulose, fats and waxes, and lignins. In general, the decomposition rate of these organic compounds is dictated by their size and complexity. For example, lignin ($C_9H_{10}O_2$, $C_{10}H_{12}O_3$, $C_{11}H_{14}O_4$) is regarded as the slowest-decomposing organic compound because of its hundreds of complex, interlinked phenolic rings. In comparison, cellulose ($C_6H_{10}O_5$) is smaller and less complex in its molecular formula, thus allowing for more rapid decomposition. Comparison of half-lives further illustrates this trend, as the half-life of sugars and starches is on the magnitude of hours, days for cellulose, and months for lignin (Kumar and Goh, 1999). In addition to the depleted amount, any C that does remain generally can become protected by the soil physically by aggregation (Elliot et al., 1991; Six et al., 1999) or chemically by humification (Chen and Aviad, 1990; Inbar et al., 1990).

Because of variation in degradability of these organic compounds, SOM can be classified into three distinct groups known as active, slow, and passive. The active SOM pool consists of organic materials with relatively high C/N ratios (~15-30) and the shortest half-life (~1-2 yr) of all SOM pools (Brady and Weil, 2002). This fraction includes carbohydrates, polysaccharides and fulvic acids, These fractions are all easily decomposed and have a high nutrient or energy value. It is also within this pool that particulate organic matter (POM) is contained. Because of its short half-life in comparison to other fractions, it is highly responsive to management, such as tillage, biomass return, cropping system, and fertilizer N rate (Wander et al., 1998; Mikha and Rice, 2004; White and Rice, 2009), and is highly influential on structural stability (Haynes et al., 1991; Six et al., 2000; Carter, 2002). The slow SOM pool consists of organic tissues that are high in lignin and other decomposition-resistant substances. This pool has a half-life ranging from 15 to 100 yr and a C/N ratio generally ranging from 10-25. It also plays an integral role in maintaining microbial activity, as it supplies a food sources for resident microbes and is a source of mineralizable nitrogen. The final pool of SOM is the passive, or recalcitrant, pool. This is the largest of all fractions and accounts for 60-90% of SOM. This pool has a half-life of 500-5000 yr and a C/N ratio in the range of 7-10. It consists of the most stable materials, including physically- and chemically-protected humus. This fraction contributes to CEC, among others, which, at least partially, explains the static nature of CEC.

Because of the labile nature of the active SOC pool, it is subjected to the most scientific research interested in SOC dynamics (Gregorich et al., 1994; Hassink, 1995; Wander et al., 1998). The common types of SOM in this fraction include microbial biomass, POM, and light fraction (LF). Particulate SOM, also known as macroorganic, is composed of fine plant and microbial matter, including fungal spores, hyphae, and charcoal, which represents a transition stage between fresh biomass matter and humified SOM (Carter, 2002). Because of its sizable representation in total SOM (18-40%) and relatively low half-life (Carter, 1996), POM is regarded as an important biologically active pool that is relatively responsive to soil management (Wander, 2004). It is often more responsive than other forms in the active fraction (Franzluebbers, et al., 2000; Carter, 2002). Since it represents a distinct component of the total SOM pool, it has often been used as an index of the labile SOM pool (Carter, 1996; Wander and Bollero, 1999). While POM is generally regarded as highly sensitive to management, diligence in its measurement is necessary because it is also sensitive to other factors, such as time of sampling (Willson et al., 2001), sampling depth (Wander et al., 1998), soil texture (Needleman et al., 1999; Malhi et al., 2003), precipitation regime (Marriott and Wander, 2006), and spatial variation (Bird et al., 2001). Some research indicates that LF can be more responsive to management than POM (Carter et al., 1998). However, LF measurement is a more labor-intensive process, and therefore, POM is a preferred method in studies where the quantity of samples is large (Wander, 2004).

Quantification of particulate organic matter N (POM-N) is also necessary in order to assess overall POM quality (Wander, 2004). Since mineralizable N can be derived from fractions other than POM (Boone, 1994), it is highly recommended that POM-N only be considered an index of labile N, and not an actual predictor (Wander, 2004). Despite this, the POM-C/N ratio has been shown to be directly proportional to the whole soil C/N ratio when POM accounts for a larger proportion of SOM (Wander, 2004). However, in soils where the proportion is small (<25%), a clear correlation does not exist. Therefore, assumptions made on soil C/N through the knowledge of POM-C/N must be aware of its proportion in total SOM.

THE ROLE OF SOIL ORGANIC CARBON ON SOIL QUALITY

It is understood that SOC is essential to soil quality; and when all other factors are constant, the amount of stover retained can influence SOM levels (Karlen et al., 1994; Follett, 2001; Adviento-Borbe et al., 2007). While removal of the stover does limit the amount of C that can be returned, tillage also plays an integral role in the C cycle. The physical event of tillage degrades plant material through cutting and chopping and increases the surface area available to microorganisms. In addition to the physical effect on the plant material, tillage aerates the soil, stimulating microbial activity. Tillage also redistributes concentrated pools of soil microbes (Staley, 1999). After completion of a tillage process, a more homogenous balance of plant matter, microbes, and oxygen is reached throughout the zone that has been tilled (Brady and Weil, 2002). The degree of homogenization is dependent on the type of tillage used and their degree of intensification.

Stover on the soil surface is important for protecting soil particles from detachment and dispersal caused by raindrop impact. This detachment and subsequent dispersal can ultimately affect soil and water quality (Cruse and Herndl, 2009). Shaffer et al. (1995) reported the negative effects of erosion on grain yield. Research has suggested that 70 (McAloon et al., 2000) to 80% (Nelson, 2002) of crop stover needs to remain in the field after stover management to maintain acceptable protection from soil erosion. The USDA-Natural Resource Conservation Service generally regards 30% stover coverage satisfactory for soil protection from erosion (Mann et al., 2002).

Johnson et al. (2006) estimated that 7.6 and 5.3 Mg ha^{-1} of stover was necessary to maintain current SOC levels in moldboard plow (MP) and conservation tillage (NT or CT), respectively. In a corn-soybean [*Glycine max* (L.)] (CS) cropping system, these amounts increased to 12.5 and 7.9 Mg ha^{-1}, respectively. When compared to the estimated 7.5 Mg ha^{-1} of corn stover produced in the U.S. in 2000, it was concluded that SOC levels are being depleted in CS systems. Therefore, on the basis of this review, they concluded that corn stover harvest seems best suited to CC systems with conservation tillage.

Wilhelm et al. (2007) estimated the amount of corn stover that must be retained to suppress soil wind and water erosion on ten soils in the Corn Belt. In CC, the maintenance of SOC levels required 4.5 and 4.6 Mg ha^{-1} more corn stover than the amount necessary to protect the soil from erosion for MP and conservation tillage, respectively. These estimates by Johnson et al. (2006) and Wilhelm et al. (2007) suggest the acceptable amount of stover that can be removed should be based on the amount needed to maintain SOC, and not on the amount needed to protect against soil erosion. While the initial studies have begun to identify acceptable threshold levels of crop stover removal in hopes of maintaining SOC levels, continued research is necessary to improve initial recommendations on the amount of stover that can be removed without jeopardizing SOC.

STOVER AND NITROGEN MANAGEMENT EFFECTS ON SOIL ORGANIC MATTER

The quantity of crop stover returned to the soil has long been understood to affect various soil dynamics, notably SOC. Several soil properties are affected by SOC, including N mineralization-immobilization dynamics, cation exchange, buffer action, water retention, aggregate stability, and bulk soil density (Pierzynski et al., 2000; Baldock and Nelson, 2000; Dick and Gregorich, 2004). Larson et al. (1970) investigated the response of SOC to varying amounts of stover returned to the soil on a Marshall silty clay loam soil in Iowa. They concluded that retaining 6 Mg ha^{-1} yr^{-1} of corn stover would be necessary to maintain SOC levels in MP tillage. Barber (1979) researched the effect of 0, 100, and 200% corn stover return in continuous cropping conditions with MP tillage for 12-yr on a Raub silt loam in Indiana. He found that SOM increased as the amount of stover retained increased following six and eleven years of stover removal. Despite complete above-ground biomass removal, SOC was 8% greater in the full stover removal treatment compared to a 5-yr fallow treatment. However, when the fallow plot was cropped for 5 yr with full stover return, differences in SOC did not exist between it and the full removal treatment

As suggested by Allmaras et al. (2000), tillage can strongly influence SOC dynamics. For example, Angers et al. (1992) found that SOM in the surface 6 cm decreased by 40 to 50% following five continuous yr of plow tillage in a field cropped to corn or barley (*Hordeum vulgare* L.) when compared to undisturbed native prairie. . Several have suggested that C sequestration can be increased by reducing tillage (Huggins et al., 2007; Dick et al., 1998; Janzen et al., 1998; Peterson et al., 1998). In NT systems, SOC loss is often less since soil disturbance is minimized (Paustian et al., 1997a; Six et al., 1999). Therefore, if less SOC is being lost in NT, the amount of C input necessary to maintain SOC should theoretically decrease. West and Post (2002) analyzed data from 67 long-term studies and showed that shifting several cropping systems from CT to NT would sequester approximately 0.50 Mg C ha^{-1} yr^{-1}. Research also indicates C stabilization is greater in NT because macroaggreagates are not being disturbed by tillage (Olchin et al., 2008).

Cropping system can also influence SOC dynamics, as the amount of plant material returned to the soil can be dependent on cropping system. Robinson et al. (1996) assessed the effects of cropping system (CC, CS, and corn-corn-oat-meadow (alfalfa [*Medicago sativa* L.] or alfalfa and red clover [*Trifoliumpratense* L.]) and fertilizer N rate on SOC on soils ranging from loam to clay loam with MP tillage in Iowa. They observed a positive linear relationship between the amount of crop stover returned to the soil and SOC in the surface 15 cm. Though dependent upon location, at least 40% of the variability in SOC was explained by annual crop stover return. Linear regressions also estimated that SOC increased by at least 0.26 g kg^{-1} for each additional Mg ha^{-1} of stover return. A number of studies support this response that SOC increases as the amount of biomass returned increases (Zielke and Christenson; 1986; Karlen et al., 2006; Coulter et al., 2009).

Havlin et al. (1990) researched the effects of tillage and cropping system on a Grundy silty clay loam and Muir silt loam after at least ten yr in Kansas. On the Grundy soil, they did not observe any response of SOC or total N (TN) to tillage system. Lack of differences in the Grundy soil may have been attributed to high SOC and TN contents, as values of 22.9 and 1.85 g kg^{-1} were observed in the surface 2.5 cm for SOC and TN, respectively, when averaged across tillage systems. However, on the Muir soil, SOC and TN were 39 and 32% greater in the surface 2.5 cm in NT compared to CVT, respectively. This work suggests differences in SOC and TN between tillage systems are highly associated with soil surface measurements since no differences existed at depths beyond 2.5 cm. The regression of SOC sequestration on stover yield also illustrates the effect of tillage. On the Muir soil, 2.24 g kg^{-1} of SOC was retained for each Mg ha^{-1} of stover produced in NT compared to 0.87 g kg^{-1} in CVT. On the Grundy soil, 1.50 g kg^{-1} of SOC was retained with NT compared to 0.56 g kg^{-1} in CVT. For each Mg ha^{-1} of stover, TN was 325 and 167% greater with NT in the Muir and Grundy soils, respectively.

Several have researched the effects of fertilizer N rate on SOC dynamics (Halvorson et al., 2001; Gregorich et al., 1997; Jantalia and Halvorson, 2011). Gregorich et al. (1996) evaluated the contribution of C from corn stover and the effect of N fertilizer application after 30 yr of production on a Brookston clay loam soil in Ontario through the ^{13}C technique ($\delta^{13}C$). They found that fertilizer N rate had an effect on the fraction of SOC from corn stover. On average, 22 to 30% of the SOC in the surface 26 cm was derived from corn in the fertilized soils compared to 15 to 20% in the unfertilized soils. Below the surface 26 cm, corn represented 6 to 10% of the SOC. This latter fraction was likely primarily derived from root matter and soluble exudates. Also, the half-life of SOC in both soils was estimated to be 19 yr. This indicates that fertilizer N rate did not affect SOC turnover. However, this conclusion disagrees with Khan et al. (2007) and Mulvaney et al. (2009). They suggested that SOC decomposition is stimulated by fertilizer N application since N is usually a limiting nutrient in microbial activity, which ultimately leads to a depletion of soil N

Gregorich et al. (1997) also reported that fertilizer N application had a significant effect on LF C, as 70% of LF C was derived from corn with fertilization compared to 41% without fertilization. These results suggest that long-term fertilizer N application increased SOC storage. However, Layese et al. (2002) used $\delta^{13}C$ in a long-term N fertilization study with stover removal and found that high rates of fertilizer N could not maintain SOC levels when stover was removed. This conclusion underscores the importance of returning crop stover to the soil.

Blevins et al. (1983) studied the effects of fertilizer N rate (of 0, 84, 168, and 336 kg N ha^{-1} rates) and tillage (CVT and NT) on SOC and TN after 10 yr of CC on a Maury silt loam in Kentucky. Regardless of fertilizer N rate, SOC and TN increased with NT in the surface 5 cm. However, differences in SOC and TN generally did not exist between tillage systems at depths beyond the surface 5 cm. The lack of differences at depths below the surface depth is supported by Bakermans and deWit (1970) and Doran (1980), among others. When fertilizer N rate was analyzed, the addition of 84 kg N ha^{-1} generally increased SOC at all depths. Fertilizer N rate did not affect TN in either tillage system. These results were supported by Bloom et al. (1982), who observed increases in SOC with fertilizer N application in Minnesota.

The effect of fertilizer N on SOC dynamics in various cropping systems has also been researched. Varvel (1994) studied the effects of fertilizer N on SOC and TN across several cropping systems in disk tillage on a Sharpsburg silty clay loam in Nebraska. In cropping systems that incorporated non-legume species, including corn and grain sorghum [*Sorghum bicolor* (L.)], the addition of N through fertilization increased SOC and TN levels in the surface 7.5 cm, but produced no effect at lower depths following 8 yr of fertilization. The response of TN to fertilization in this study varied compared to Blevins et al. (1983), who did not observe any response of TN to fertilization. They also reported that 6.2 Mg ha^{-1} yr^{-1} of corn stover was produced during the duration of the study at the highest fertilizer N rate, which resulted in an increase in SOC concentration. They also showed that, with high rates of fertilizer N (>180 kg ha^{-1}), CC sequestered 1358 kg ha^{-1} of SOC and 189 kg ha^{-1} of N over the duration of the study. In comparison, the lack of fertilizer N application resulted in a loss of 534 kg ha^{-1} of SOC and a gain of 14 kg ha^{-1} of TN. These data indicate that in intensively managed, high-fertility conditions, some stover can be removed without adversely depleting SOC pools.

Varvel and Wilhelm (2008b) evaluated SOC levels across several cropping systems with varying N rates on a Hoard silt loam in disk tillage in central Nebraska. When cropped in CC for 15 yr, SOC concentration exhibited a positive linear response to fertilizer N in the surface 7.5 cm. The application of 100 and 200 kg N ha^{-1} resulted in an increase of SOC by 12 and 18%, respectively, compared to the unfertilized treatment. In comparison, SOC at depths beyond 7.5 cm was not affected by fertilizer N, which was similar to reported results in the 1994 study (Varvel, 1994). Jagadamma et al. (2008) investigated the response of SOC and TN to fertilizer N rate in CC and a CS cropping system following 23 yr of production. Similar to previous studies, they observed an increase in SOC and TN as fertilizer N rate increased. They also observed a decrease in the soil C/N ratio with increasing fertilizer N rates. Correlation coefficients showed that TN was partially responsible for this trend, as 59% of the variation in the C/N ratio was explained by TN.

Wilts et al. (2004) researched the relationship between fertilizer N and corn stover removal on SOC in Minnesota. On a Hamerly clay loam, McIntosh silt loam, and Winger silty clay loam in west central Minnesota, they tested the effects of stover removal and fertilizer N in MP tillage after 30 yr of production. They observed that SOC decreased by 21.9 and 16.4 Mg ha^{-1} with stover removal in the surface 30 cm when 87 and 166 kg N ha^{-1} were applied annually for 30 yr, respectively. Fertilizer N application resulted in a reduction of SOC flux by at least 29% compared to the unfertilized treatment when stover was retained. When stover was removed, fertilizer N application resulted in a reduction in SOC flux by 15%.

Allmaras et al. (2004) expanded upon the study by Wilts et al. (2004). In addition to fertilizer N rate and stover removal, three tillage systems were included in the design. They found that 200 kg N ha^{-1} application of fertilizer increased SOC in the surface 30 cm after 13 yr of CC when stover was not removed, regardless of tillage system. Changes in SOC were attributed to an increase in plant-derived C availability, as the addition of N fertilizer resulted in an increase of 19% aboveground C when averaged across tillage systems without stover removal. With fertilizer N application and stover removal, a net gain of 0.2 Mg C ha^{-1} was observed for MP tillage, but a decline of 10.0 and 12.6 Mg C ha^{-1} was observed for NT and CT, respectively.

Dolan et al. (2006) also researched the response of SOC and TN to fertilizer N rate (0 and 200 kg N ha^{-1}), tillage system (MP, CT, and NT), and stover removal (no- and full-removal) on a Waukegan silt loam soil after 23 yr of CS cropping system in Minnesota. They found that SOC and TN were not improved by reducing tillage. They also did not find a significant response of SOC or TN to long-term fertilizer N application. Despite the lack of effect of fertilizer N application, tillage, and stover removal on SOC and TN, they concluded extraneous factors including landscape position, and sampling protocol (i.e., sampling depth and intervals) may have influenced their findings. Finally, they cautioned that these factors should be considered when assessing C sequestration potential, particularly among tillage systems.

Coulter et al. (2009) researched the effect of fertilizer N on SOM in CC and CS cropping systems on an Elpaso silty clay loam, Belknap silt loam, and Drummer silty clay loam soil in Illinois. Regardless of rotation, they did not observe any effects of N on

SOC, total N, POM-C, or the C/N ratio. However, they observed that POM-N increased as fertilizer N rate increased, though, no additional increase was observed beyond 250 kg N ha^{-1}. They concluded that cropping system had more influence on SOM than fertilizer N rate. Their conclusions contradicted previous results in Illinois by Khan (2007), who stated that losses in SOC in the Morrow Plots were because of fertilizer N application.

The findings from these studies suggest that tillage, stover removal, and fertilizer N rate selection can impact SOC dynamics. Maintaining SOC is integral to production, as it has been suggested that in addition to improving grain yields, elevated SOC levels improve fertilizer use efficiency (Cassman, 1999). The findings support the hypothesis that decreased tillage may lead to increased C sequestration (Clay et al., 2012) and that a proportion of corn stover can potentially be removed without adversely depleting SOC levels. The data also suggest that SOC levels generally increase as fertilizer N increases, especially in the surface measurements. Research does indicate that SOC storage can be soil texture-driven (Omay et al., 1997; Needleman et al., 1999). While data suggest a proportion of stover removal may be acceptable and recommendations justified by scientific data are beginning to be reported (Blanco and Lal, 2009), the response of SOC to these management variables may be dependent on climatic conditions. Therefore, understanding how SOC dynamics are affected by management is necessary across a range of environments before accurate recommendations can be determined.

CELLULOSIC ETHANOL PRODUCTION FROM CORN STOVER

Several components of the cell wall are utilized in the production of cellulosic ethanol through a series of biochemical and enzymatic processes. The quantities of celluloses, hemicelluloses, and lignin, among many cell wall components, are responsible for dictating the ethanol production potential or forage quality of a given plant material (Jung et al., 1998; Pordesimo et al., 2004). Corn stover is primarily composed of para-crystalline cellulose microfibrils contained in a hemicellulosic matrix (Carpita, 1996; Dhugga, 2007). Ultimately, the potential ethanol yield of a feedstock is not only dependent upon the concentration of pentose (galactose, glucose, and mannose) and hexose (arabinose and xylose) polysaccharides, but also the level of lignification. The amount of lignin in a crop can affect its conversion efficiency. In order to improve conversion efficiency, the plant material is often subjected to a thermochemical pretreatment of the feedstock with either a weak acid, steam, or weak alkali in order to degrade the lignin network surrounding the hemicellulose matrices (Yang and Wyman, 2004; Wyman et al., 2005; Mosier et al., 2005). Once pretreated, the feedstock is subjected to saccharification, consisting of hydrolysis of the polysacharides with enzymes, fermentation of the simpler monosaccharides released through hydrolysis, and final distillation, which ultimately yields ethanol (Himmel, 2007; Templeton et al., 2008; Lorenz et al, 2009).

Lignification is the biochemical formation of phenylpropanoid macromolecules, and is important to several plant characteristics including stalk strength and cell wall polysaccharide protection from pests and pathogens (Sarkanen and Ludwig, 1971;

Hatfield and Vermerris, 2001; Hatfield and Fukushima, 2005). High lignin content is often viewed as a negative characteristic because degradability of cellulosic material for ethanol conversion or ruminant digestion is strongly dependent on the extent of lignification (Jung and Deetz, 1993; Yang and Wyman, 2004). Jung and Casler (2006a, 2006b) found that Klason lignin concentration was negatively correlated with polysaccharide degradability. They also found that Klason lignin concentration was maximized at approximately the same time period as glucose and xylose concentrations were maximized. Pordesimo et al. (2004) demonstrated that lignin content increased with crop maturity and lignin content differed among plant fraction.

Research on the use of corn stover for biofuel production has greatly expanded. Plant breeding research has focused on strategies to decrease lignin content while not adversely affecting grain yields (Lorenz, 2009; Lorenzana et al., 2010). Dhugga (2007) expressed concern over this interaction, as research suggests that decreasing lignin content is generally accompanied by lower biomass production. However, Lewis et al. (2010) reported that including stover quality for biofuel purposes as a breeding objective could be successfully accomplished without adversely affecting grain yield.

Several life cycle analyses have indicated that cellulosic ethanol offers several benefits over starch-derived ethanol (grain) (Farrell et al.; 2006; Wang et al., 2007; Kim et al., 2009). A life cycle analysis by Searchinger et al. (2008) concluded that the use of crop residue, such as corn stover, for cellulosic ethanol production may be more advantageous than other biofuel species because the land-use change from the current grain production cropping system to a biofuel cropping system would increase greenhouse gas emissions. Corn stover has also been suggested to be the most economically-feasible feedstock at the present time. Huang et al. (2009) concluded that corn stover was the most economically-feasible feedstock option when compared to aspen (*Populus tremuloides*), poplar (*Populus* spp.), and switchgrass (*Panicum virgatum* L.) because it had the lowest production cost and lowest waste effluent production. James et al. (2010) concluded that dedicated biomass crops would likely not replace corn cropping systems where stover is removed for cellulosic ethanol production in the Upper Midwest. They estimated that economic values of these feedstocks in order to reach break-even with the value of corn cropping systems with grain production and stover removal would need to be \$110 Mg^{-1} for poplar, \$200 Mg^{-1} for Miscanthus (*Miscanthus* × *giganteus*), and \$115 Mg^{-1} for switchgrass (*Panicum virgatum* L.).

Most information that exists on cellulosic ethanol production is based on several species and does not address the influence of management. These studies, however, show the competitive effectiveness of the use of corn stover for biofuel production. Propheter et al. (2010) compared corn, grain sorghum, forage sorghum, switchgrass, big bluestem (*Andropogon geradii* Vitman), and miscanthus in Kansas. They found that corn ethanol production, while less than sweet sorghum, was similar to or greater than the dual-purpose forage sorghums, and greater than grain sorghum and the perennial grasses. Wortmann et al. (2010) compared the ethanol potential and energy yield of corn to grain sorghum and sweet sorghum. While they only considered corn grain, they did show it produced 30 and 65% more energy than grain from grain sorghum and sweet sorghum biomass, respectively. If corn stover would be considered, these ratios would be expected to increase, though the exact amount is unknown. While both of these studies researched corn ethanol production, ethanol production from corn stover was not exclusively studied in either experiment.

Research results on the effects of N management on corn grain production in high-yielding cropping systems are widely available (Halvorson et al., 2006; Stanger and Lauer, 2008; Coulter and Nafziger, 2008). However information on the effects of agronomic management on ethanol potential from corn stover is limited. Reicks et al. (2009) studied the effects of fertilizer N rate on ethanol production in corn, but their research was solely focused on starch ethanol production. Studies such as Cox and Cherney (2001), Sheaffer et al. (2006), and Lawrence et al. (2008) have reported how N management affects silage production and quality. However, applying these conclusions to the biofuel-based research questions is generally not appropriate because the individual contributions of grain and cellulosic components are unattainable, since all plant components are combined and inseparable. Research indicates the necessity to divide stalk/leaf and cob fractions because distinct differences between fractions exist. Corn cobs offer an advantage over stover because they are denser (Morey et al, 1984; Kaliyan and Morey; 2008). This is important because transportation of cellulosic materials is a key problem in the adoption of cellulosic ethanol production (Hoskinson et al., 2007; Petrolia, 2008). Crofcheck and Montross (2004) reported that cobs produced higher glucose concentrations during hydrolysis compared to other cellulosic sources. Research has also shown that the chemical composition of corn cobs is less sensitive to crop maturity when compared to other stover fractions, thus potentially stabilizing its ethanol potential (Pordesimo et al., 2003). By separating these cellulosic fractions, identification of the correct components that maximize ethanol production will be attainable. To date, only one study by Sindelar et al. (2012) in Minnesota has researched how fertilizer N rate affects cellulosic biomass and ethanol production in corn. They found that stover and cob ethanol yields increased as fertilizer N rate increased and that yields ranged from 2414 to 3842 L ha^{-1} for stover and 513 to 906 L ha^{-1} for cobs at the agronomically optimum N rates. They also found that stover and cob ethanol yields were often maximized at fertilizer N rates that were less than those for grain yield maximization. These findings are important because they indicate that cellulosic ethanol production can often be maximized when grain yield maximization is the primary goal.

SUMMARY

In order to meet future projected demand of 79 billion L of renewable fuel from cellulosic sources by 2022, the use of corn stover and cobs for cellulosic ethanol production may become mandatory. The Midwest is targeted to provide a large proportion of corn stover for cellulosic ethanol production. However, complete removal of corn stover would lead to depletion of SOM. This would eventually deteriorate soil quality because SOM is known to positively influence soil density, infiltration, structure, nutrient availability, ion exchange capacity, and water retention, among others. It is understood that sustained, long-term stover removal is likely not an option without some agronomic or environmental penalty. However, in CC cropping systems, the potential for a sustained proportion of annual removal may be possible while maintaining SOM levels. Preliminary suggestions are that the amount of corn stover that can be removed without adversely affecting SOM is dependent on cropping system and the type of tillage used. Recommendations that do exist are vague and may be region-specific based on the varying reports of management effects on SOM. However, previous research seems to suggest that stover removal for ethanol production may be best suited for CC cropping systems. Minnesota is expected to be heavily involved in the cellulosic ethanol industry. Therefore, understanding how stover removal affects crop productivity and SOM dynamics in Minnesota is necessary.

OBJECTIVES

The objectives of this research are to:

1. quantify the effects of stover management, tillage system, and fertilizer N rates on corn growth, yield, and NUE in CC cropping systems.
2. determine if the amount of fertilizer N necessary to economically optimize grain yield is different when corn stover is removed.
3. validate reported cellulosic ethanol yields in Minnesota, and determine whether stover management and tillage system affects these responses to fertilizer N rate.

4. determine how stover removal in CC cropping systems affects soil C and N dynamics, including POM-C and N, and whether this is affected by tillage system and fertilizer N application.

CHAPTER 2: AGRONOMIC RESPONSES OF CONTINUOUS CORN GROWTH AND PRODUCTION TO STOVER, TILLAGE, AND NITROGEN MANAGEMENT

MATERIALS AND METHODS

Field experiments were established in the fall of 2008 following corn on a subsurface tile drained Knoke loam soil (fine, smectitic, calcareous, mesic Mumulic Vertic Endoaquolls) at the University of Minnesota Southwest Research and Outreach Center near Lamberton (44°14′ N, 95°18′ W) and on a subsurface tile drained Nicollet-Webster clay loam soil complex (fine-loamy, mixed superactive, mesic Aquic Hapludolls and fine-loamy, mixed, superactive, mesic Typic Endoaquolls, respectively) at the University of Minnesota Southern Research and Outreach Center near Waseca, MN (44°3′ N, 93°31′ W). The experimental design was a split plot arrangement in a randomized complete block design with four replications. Main plots were a factorial arrangement of stover management (retained or removed) and tillage system [chisel (CT), strip-till (ST), and no-till (NT)]. Split plots were fertilizer N rate (0, 45, 89, 134, 179, and 224 kg N ha^{-1}) and were 6.1 m wide (eight 76-cm rows) and were 9.2 m long at Lamberton and 7.0 m long at Waseca. All plots remained in the same location through the duration of the study.

Stover management and tillage treatments were initiated in the fall of 2008 and annually performed following grain harvest. The stover removal treatment was achieved by chopping stalks, raking, and baling with field-scale equipment in order to emulate probable removal rates by producers. Stover was not chopped in plots where retained. Tillage treatments were then implemented within 5 d after stover management. The CT treatment was a chisel operation to a depth of 20 cm in the fall, followed by field cultivation to a depth of 9 cm in the spring prior to planting. The ST treatment tilled a 20-cm wide band to a depth of 20 cm between the previous year's corn rows in the fall with an Orthman 1tRIPr (Orthman Manufacturing, Inc., Lexington, NE) at Lamberton and a Redball strip-till unit (Will-Rich, LLC, Wahpeton, ND) at Waseca.

Corn was planted 5 cm deep at 84,000 seeds ha^{-1} in late April or early May with a commercial planter equipped with row cleaners. Corn in the NT and ST treatments was planted 38 cm away from the previous year's corn rows. Hybrid in all site-years was DEKALB DKC52-59, a 102-d relative maturity hybrid with transgenic resistance to glyphosate [potassium *N*-(phosphonomethyl)glycine], European corn borer (*Ostrinia nubilalis* [Hübner]), and corn rootworm (*Diabrotica spp.*). Starter N and P were applied simultaneously with planting as ammonium polyphosphate [$(NH_4)_3HP_2O_7 + NH_4H_2PO_4$] at 6.5 kg N ha^{-1} and 9.6 kg P ha^{-1}.

Fertilizer N was broadcast applied by hand without incorporation within 5 d after planting as ammonium nitrate (NH_4NO_3). Sulfur was broadcast applied at 17 kg S ha^{-1} as gypsum ($CaSO_4 \bullet H_2O$). Sulfur application is recommended in Minnesota when corn is grown continuously or in reduced tillage systems (Kaiser et al., 2011). Phosphorus and K were applied according to University of Minnesota guidelines. Soil-test P and K levels were generally high or very high, but were amended with triple superphosphate [$Ca(H_2PO_4)_2 \bullet H_2O$] and potash (KCl) to ensure these nutrients would not be limiting. Preemergence herbicides were applied following planting, consisting of 1.8 L ha^{-1} of acetochlor [2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl) acetamide], 0.22 L ha^{-1} of mesotrione [2-[4-(methylsolfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione], and

1.2 L ha^{-1} of glyphosate. A postemergence glyphosate application at 2.1 L ha^{-1} also occurred in each site-year when necessary.

Immediately after planting in 2010 and 2011, soil temperature sensors (TidBit v2 Water Temperature Data Logger; Onset Computer Corp., Pocasset, MA) were placed in the seed furrow at a depth of 5 cm in the 179 kg N ha^{-1} treatment of all stover management × tillage system treatments at each site. Soil temperature was logged in 1-hr increments for 60 d after planting (DAP), and expressed as a daily average. Surface area coverage by corn stover was measured using the line-transect method at 45º diagonal to the rows following planting (Sloneker and Moldenhauer, 1977). Corn plant emergence was measured no later than the four leaf collar stage (V4; Abendroth et al., 2011). All plants within rows 2, 3, 6, and 7 were counted and expressed as percentage of emergence. Relative extended-leaf plant height (RPH) and normalized difference vegetative index (NDVI) were measured at the eight leaf collar stage (V8; Abendroth et al., 2011). Individual heights of ten random plants were measured from the soil surface to the uppermost extended leaf, averaged within each plot, and normalized relative to the maximum average plant height measurement within each block of each site-year. For measuring NDVI, a Greenseeker (NuTech Industries, Inc., Ukiah, CA) handheld sensor was positioned approximately 0.8 m directly above the row of the crop canopy and carried at a constant speed over the length of the plot (Martin et al., 2007). Measurements for NDVI were taken from two harvest rows from each plot.

Leaf area index (LAI) and relative leaf chlorophyll (RLC) was measured at the silking stage (R1; Abendroth et al., 2011) using an AccuPAR LP-80 ceptometer (Decagon Devices, Pullman, WA) within 1130 and 1400 h when sunlight was unobstructed (Board et al., 1992; Flenet et al., 1996). Four measurements within each plot were recorded by placing the ceptometer diagonally across two rows of the harvest area at the soil surface, with a second sensor simultaneously placed above the crop canopy. Leaf area index was then calculated automatically by the ceptometer through a series of equations that accounts for the extinction coefficient for the canopy, beam fraction of photosynthetically active radiation (PAR), canopy transmission (the ratio of PAR below the canopy to PAR above the canopy), and leaf absorptivity in the PAR band. Leaf chlorophyll was measured on the ear leaf of 30 plants in rows 3 and 6 of each plot with a Minolta SPAD-502 (Konica Minolta, Osaka, Japan) chlorophyll meter (Peterson et al., 1993; Varvel et al., 1997). The average reading from each plot was normalized relative to the maximum leaf chlorophyll reading within each block of each site-year.

Grain yield and moisture content were determined by harvesting four rows and adjusting yields to 150 g kg^{-1} moisture. Average kernel weight was determined from samples collected at grain harvest. Samples were dried in a forced-air oven at 60°C until constant mass, and 300 kernels were counted and weighed immediately after drying. Kernel number (kernels m^{-2}) was calculated by converting grain yield data to a per-meter basis and dividing by kernel weight.

Prior to statistical analysis, residuals were evaluated for normality using the UNIVARIATE procedure of SAS (SAS Institute, 2005) and for common variance using scatterplots of residuals vs. predicted values (Kutner et al., 2004). Data were then analyzed using the MIXED procedure of SAS at $\alpha = 0.05$. Site, stover management, tillage system, fertilizer N rate, and their interactions were considered fixed effects. Random effects included year, block (nested within site), and all interactions associated with these effects. In-season plant measurements, grain yield, and grain yield components from Lamberton in 2009 were excluded from the analysis because of uncertainty that responses were a result of treatment effects. This is because there was often no or inconsistent responses of several growth and yield variables to high fertilizer N rates (~ >134 kg N ha^{-1}). Also, residual soil NO_3-N levels were often greater in low N treatments following the growing season in 2009, and this further increased uncertainty. Soil temperature, which was analyzed individually by site-year since date of planting varied among site-years, was aggregated into 5-d increments and analyzed using repeated measures, with the aggregate serving as the repeated effect. Several covariance structures were evaluated for the repeated measures analysis, and the structure that produced the smallest criterion estimates was selected (Littell et al., 2006). The amount of random variation associated with year and its interactions with fixed effects was determined from covariance parameter estimates. When applicable, mean comparisons between stover management treatments or among tillage systems were made using Fisher's protected LSD test ($\alpha = 0.05$).

When the main effect of fertilizer N rate or interactions among fertilizer N rate and the other fixed effects were significant for a given response variable, regression analysis was preformed. Linear [1] and quadratic [2] regression was performed using the MIXED procedure, while quadratic-plateau [3] regression analysis was performed using the NLIN procedure of SAS (SAS Institute, 2005):

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X \qquad [1]$$

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X + \hat{\beta}_2 X^2 \qquad \text{IF } X < X_0 \qquad [2]$$

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X_0 + \hat{\beta}_2 X_0^2 \qquad \text{IF } X \geq X_0 \qquad [3]$$

where $\hat{Y}$ is the predicted response variable, $\hat{\beta}_0$ is the intercept, $\hat{\beta}_1$ is the linear coefficient, $\hat{\beta}_2$ is the quadratic coefficient, X is the fertilizer rate, and X_0 is the fertilizer N rate at which the quadratic and plateau portions of the model intersect. The best-fit regression model was selected based on its ability to produce the smallest model-fit residuals when compared to other regression models. The economically optimum fertilizer N rate (EONR) for grain yield was estimated from each regression equation by solving for X after setting the first derivative to the fertilizer N cost/corn grain price ratio. Fertilizer N and corn grain prices used in the EONR analysis were based on 4-yr averages from 2009 to 2012 and were \$1.21 kg^{-1} N (Economic Research Service, 2012) and \$180 Mg^{-1} grain (National Agricultural Statistics Service, 2012), respectively (USDA-ERS, NASS; 2012).

RESULTS AND DISCUSSION

Growing Conditions

Variation in cumulative precipitation and distribution across the growing season existed among years within each site (Table 2.1). In 2009, total precipitation at Lamberton was 71 and 51% of the 30-yr average (1979 to 2008), respectively, with the majority of the deficit resulting from below-average precipitation from May through July. Despite the lower precipitation at Lamberton in 2009 compared to the remaining site-years, grain yield was within 5% of that in all other site-years (data not shown). In 2010, both sites received at least 52% more precipitation than the 30-yr average. While most months received precipitation that was greater than the 30-yr average, the majority of this surplus occurred in September. Precipitation in this month was 259 and 274% greater than the 30-yr average at Lamberton and Waseca, respectively. This increased precipitation in September slowed physiological maturation and grain dry-down. In 2011, total precipitation was similar to the 30-yr average at Lamberton, but was 14% below average at Waseca. A positive net precipitation was observed through June at Lamberton and through August at Waseca. Precipitation deficits occurred during the reproductive stages (August and September) at both sites. Despite these deficits, grain yield was not drastically different when compared to other years, suggesting that stored soil water was sufficient at critical development stages.

Average monthly air temperature did vary among years at both sites (Table 2.1). In 2009, average monthly air temperature from June through August was 1.2 to 3.1ºC cooler than 30-yr averages. Average monthly air temperature in September was 1.9 and 1.8ºC warmer at Lamberton and Waseca, respectively, which expedited physiological maturation and grain dry-down. In 2010, monthly air temperatures were within 1ºC of 30-yr averages through July. In August, average air temperature was 2.7 and 2.1ºC warmer than 30-yr averages at Lamberton and Waseca, respectively. Conversely, average air temperatures in September were 0.8 and 1.1ºC cooler than 30-yr averages. These cooler air temperatures further delayed grain dry-down when paired with the above-average precipitation. In 2011, average air temperatures in May were 1ºC cooler than the 30-yr average. This slightly delayed emergence and slowed initial plant growth. Average air temperatures in June in 2011 were relatively similar to 30-yr averages, but were 3.0 and 2.6ºC greater in July at Lamberton and Waseca, respectively. This did not adversely affect grain production, though. Air temperature in September was again cooler at both sites in 2011 when compared to the 30-yr average. This generally did not delay physiological maturation and grain dry-down.

Soil Temperature

In general, soil temperature at 5 cm was warmer in 2011 when compared to 2010, as soil temperature averaged across the entire growing season was 2.6 and 2.8 ºC warmer in 2011 than 2010 at Lamberton and Waseca, respectively (Fig. 2.1). The response of soil temperature to stover management and tillage system often depended upon day of growing season (Table 2.2), with most differences occurring within 25 to 35 DAP (Fig 2.1). In all site-years, soil temperature when stover was retained within NT was often cooler than most other combinations of stover management and tillage system, especially following periods of days where soil temperature increased rapidly. This was related to the quantity of stover remaining on the soil surface and its effect on the surface energy balance. This is because crop stover on the soil surface increases the reflectance of solar radiation and reduces evaporation, which results in lower soil temperature (van Wijk et al., 1959; Horton et al., 1994; Sauer et al., 1996). Kaspar et al. (1990) and Andraski and Bundy (2008) also observed cooler soil temperatures as a function of retaining stover. Furthermore, Kaspar et al. (1990) showed that the presence of crop biomass on the soil surface reduced daily maximum soil temperatures by 9 to 26% over a 20-d period early in the growing season. In this study, differences in soil temperature among tillage systems were typically non-significant at 35 DAP and beyond in any site-years (Fig 2.1). The lack of differences beyond this period is related to canopy closure, which decreases exposure of the soil surface to solar radiation. The observed moderation of soil temperature around this time period, as related to canopy closure, agrees with Andraski and Bundy (2008). While exceptions did exist, removal of stover within ST and NT often resulted in soil temperatures that were similar to or warmer than those within CT when stover was retained (Fig 2.1).

The comparison of soil temperature within ST when stover was retained with the remaining stover management × tillage system treatments was inconsistent across site-years (Fig. 2.1). Within 25 d after planting at both sites in 2010, soil temperature within ST when stover was retained was often warmer than soil temperature within NT when stover was retained and generally cooler than all other stover management × tillage system treatments. At Lamberton in 2010, soil temperature within ST and NT when stover was retained was generally similar at 15 DAP and beyond. At both sites in 2011, ST with stover removal often resulted in soil temperatures that were warmer than within NT up to 25 d after planting, and soil temperature was often similar to that in treatments where stover was removed. These data do suggest that ST generally increases soil temperature in the seed furrow when compared to NT up to canopy closure, as temperature differences as great as 4ºC were observed.

Surface Stover Coverage

Coverage of the soil surface by corn stover after planting was affected by the interaction between stover management and tillage system (Table 2.3). Regardless of tillage system, surface stover coverage decreased by 29 to 45% with corn stover removal (Table 2.4). When stover was retained, surface stover coverage was 43, 81, and 65% within CT, NT, and ST, respectively. These values are similar to those reported by Vetsch and Randall (2002) and Vetsch et al. (2007) in southern Minnesota. Conversely, when stover was removed, surface stover coverage was 14, 36, and 25% within CT, NT, and ST, respectively. Based on the threshold of approximately 30% necessary for protection against soil erosion by the Natural Resources Conservation Service (NRCS), the harvest of corn stover within CT and ST would produce field conditions that would provide inadequate protection against soil erosion.

While tillage system did influence surface stover coverage, the magnitude of response was dependent upon stover management (Table 2.3). When stover was retained, surface stover coverage decreased as tillage intensity increased. Strip-tillage and CT decreased surface stover coverage by 16 and 38% from NT (Table 2.4). When stover was removed, differences in surface stover coverage among tillage systems decreased and surface stover coverage within ST was similar to CT and NT. Also, 14% of surface coverage still occurred when stover was removed within CT. This indicates that the stover management × tillage system treatment that had the most adverse influence on surface stover coverage still provided some degree of coverage, though it was less than half of the NRCS threshold.

Corn Emergence

Corn emergence was affected by the interaction between stover management and tillage system, but not by fertilizer N rate or its interactions (Table 2.3). When stover was removed, corn emergence within NT increased by 6%, but was similar between stover management treatments within CT and ST (Table 2.4). Reduced emergence within NT was likely related to cooler soil temperature, as temperatures up to 30 d after planting were often lower than the other tillage systems when stover was retained (Fig. 2.1). These findings coincide with others who reported that stover thickness/coverage negatively affects emergence (Kasper et al., 1987; Mehdi et al., 1999; Blanco-Canqui et al., 2006b). Despite stover surface coverage being 40% greater when stover was retained, corn emergence within ST did not differ between stover management treatments. This indicates that the tillage band of 20 cm by ST can prevent the negative effects of stover coverage on corn emergence in the Upper Midwest. Others in the western Corn Belt have also concluded that managing stover by removal or tillage can positively affect emergence. For example, Kaspar et al. (1990) reported that removal of stover in an 8-cm band enhanced corn emergence by 2.5 d in Iowa. Licht and Al-Kaisi (2005) reported that emergence between ST and CT was similar in three of four site-years. In southern Minnesota, Vetsch and Randall (2002) observed that emergence was faster within CT than ST by 1 d, though the authors did conclude that the difference was insignificant from a practical standpoint.

Relative Plant Height of Corn

Relative corn plant height at the V8 growth stage serves as a direct indicator of early-season plant performance. It was affected by the interactions between stover management, tillage system, and fertilizer N rate (Table 2.3). The main effect of year accounted for 34% of the random variability in the data. This was likely affected by the variation in rainfall, air temperature, and soil temperature. The random variation among the interactions of year with site, stover management, tillage system, and fertilizer N rate were each less than 11%. This indicates that while RPH may have varied slightly among years, its response to stover management, tillage system, and fertilizer N rate were consistent across years.

There was a quadratic-plateau response of RPH at the V8 growth stage to fertilizer N rate for all stover management × tillage system treatments (Fig. 2.2). Regardless of stover management or tillage system, increasing fertilizer N rate increased RPH. However, the magnitude of the response to fertilizer N rate was dependent upon stover management and tillage system. Within CT, the amount of N necessary to maximize RPH decreased by 33% when stover was removed, and maximum RPH was 5% greater when stover was removed. Within NT, not only did the fertilizer N rate necessary to maximize RPH decrease by 18% when stover was removed, but RPH at that fertilizer N rate also increased by 11% compared to RPH when stover was retained. Within ST, the fertilizer N rate that maximized RPH was similar between stover management treatments, but RPH at the optimum fertilizer N rate was 16% greater with stover removal.

Normalized Difference Vegetative Index

Normalized difference vegetative index serves as an indicator of total plant biomass, and research has shown that NDVI can be used as an in-season predictor for grain yield potential (Teal et al., 2006; Martin et al. 2007). The main effect of year accounted for 26% of the random variation in NDVI at the V8 growth stage, while the sum of total random variation accounted for by interactions among year and the fixed effects was 15%. This means the response of NDVI to stover management, tillage system, and fertilizer N rate was consistent across years. Normalized difference vegetative index was affected by fertilizer N rate and the interaction between stover management and tillage system (Table 2.3). Across stover management treatments and tillage systems, there was a quadratic-plateau response of NDVI to fertilizer N rate (Fig. 2.3). Based on this regression, NDVI was maximized at a fertilizer N rate of 215 kg N ha^{-1}, which produced a maximum NDVI of 0.791

Tillage system did influence NDVI at the V8 growth stage, and the magnitude of difference was dependent upon stover management (Table 2.3). When stover was retained, NDVI within CT was 7 and 16% greater than ST and NT, respectively (Table 2.4). Also, NDVI was 8% greater within ST when compared to NT. Similar to previous in-season measurements, differences did not exist among tillage systems when stover was removed and ranged from 0.771 to 0.788. When the effect of tillage system on NDVI was assessed, the degree of difference in NDVI between stover management treatments increased as tillage intensity decreased (Table 2.4). When stover was removed within NT, NDVI increased by 20%. In comparison, NDVI increased by 13% with stover removal within ST. Within CT, which had the least amount of soil surface coverage by corn stover, removal did not increase NDVI.

Leaf Area Index

Leaf area index is an indicator of the plant's surface area that can intercept solar radiation, which is associated with grain yield potential under non-limiting conditions

(Eik and Hanway, 1966). Crop management decisions, such as fertilizer N rate selection, can positively influence LAI and, therefore, potentially increase grain yield potential (Muchow and Davis, 1988).The main effect of year accounted for 24% of the total random variation in LAI at the R1 growth stage. There were no interactions between year and the other fixed effects that accounted for >4%. This indicates the response of LAI to stover management, tillage system, and fertilizer N rate was consistent across years. Leaf area index was affected by the main effects of stover management and fertilizer N rate (Table 2.3). Unlike previous measurements, tillage system did not influence LAI. There was a quadratic response of LAI to fertilizer N rate (Fig 2.4). While plateaus where LAI was maximized were not identified within fertilizer N rates used in the study, LAI at the maximum fertilizer N rate (224 kg N ha^{-1}) was 6.28 m^2 m^{-2}. This represents an increase of LAI by 65% from LAI when solely relying on indigenous N and further demonstrates that fertilizer N rate has a positive effect on the plant through the VT growth stage.

Leaf area index increased by 15% when stover was removed. This significant increase and the non-significant effect of tillage system indicates that stover removal affects growth and development of the plant through VT more than tillage selection in the Upper Midwest. It also suggests the effect of tillage system on corn growth and development may decrease as the growing season progresses since measurements were affected by tillage system at V8 (emergence and RPH), but not at VT (LAI). Findings by Al-Darby and Lowery in Wisconsin (1986) and Cox et al. in New York (1990) support the lack of a tillage effect on LAI in this study. However, they differ from Fortin et al. (1994), who observed no change of LAI with stover removal in Michigan.

Leaf Chlorophyll

Leaf chlorophyll is an indicator of plant N content, which is critical to grain yield and quality. The main effect of year accounted for 18% of the total random variation associated with RLC at the R1 growth stage. All interactions among year and the fixed effects accounted for less than 15% of the random variation. This indicates the response of RLC to the fixed effects was consistent across years. The response of RLC to fertilizer N rate differed among sites, tillage systems, and stover management treatments (Table 2.3). At Waseca, the predicted fertilizer N rate that maximized RLC was 223 kg N ha^{-1}, while RLC at Lamberton was not maximized within fertilizer N rates used in the study (Fig 2.5A).

Stover management affected the response of RLC to fertilizer N rate (Table 2.3). When stover was removed, the response was best described by quadratic-plateau regression (Fig. 2.5B). This was expected because it is documented that leaf chlorophyll generally exhibits a quadratic-plateau response to fertilizer N rate (Blackmer and Schepers, 1994; Scharf et al., 2006; Hawkins et al., 2007). In comparison, quadratic regression best described the response of RLC to fertilizer N rate when stover was retained because RLC was not maximized at fertilizer N rates used in the study. Because of this, the fertilizer N rate that maximized RLC was at least 6% less with stover removal (211 and >224 kg N ha^{-1} when stover was removed and retained, respectively; Fig 2.5B). Differences in the response of RLC to fertilizer N rate among tillage systems were less evident when compared to the other significant interactions, but were apparent when fertilizer N rates where RLC was maximized were compared. When averaged across sites and stover management treatments, CT was the only tillage system where RLC was maximized within the range of fertilizer N rates in the study (Fig 2.5C). While RLC within ST was not maximized within the range of fertilizer N rates in the study, it should be noted that the predicted fertilizer N rate for maximization was only slightly beyond (227 kg N ha^{-1}) the range. Relative leaf chlorophyll within NT was greater than those within CT and ST as fertilizer N rates increased beyond 179 kg N ha^{-1}. It is unclear what caused this occurrence beyond random variation.

These data further support the positive effect of stover management through removal and tillage on in-season growth and development. In scenarios where at least 71% of stover was removed from the soil surface (stover removal averaged across tillage systems, and CT averaged across stover management treatments), RLC was maximized within fertilizer N rates used in this study (Fig. 2.5). In these scenarios, the reduced amount of fertilizer N necessary to maximize RLC may have been associated with increased N mineralization rates, which can be influenced by soil temperature (Ellert and Bettany, 1992; McCarthy et al., 1995; Halvorson et al., 2001). Conversely, in scenarios where stover was not removed and remained on the soil surface (63% surface coverage when averaged across tillage systems), net mineralization of N was probably reduced. This increased the amount of fertilizer N necessary for optimization. Furthermore, reduced tillage and stover remaining on the soil surface have both been shown to affect N immobilization (Rice and Smith, 1984; Power et al. 1986b; Schomberg et al., 1994).

Grain Yield

The interaction between year and site accounted for 30% of the total random variation in grain yield. This indicates that grain yield varied between sites. Grain yield at

Lamberton was 10.3 and 8.9 Mg ha^{-1} in 2010 and 2011, respectively. Grain yield at Waseca averaged 10.1, 9.4, and 10.5 Mg ha^{-1} in 2009, 2010, and 2011, respectively. The sum of total random variation of the interactions between year and the other fixed effects was less than 12%. This suggests that the response of grain yield to tillage system, stover management, and fertilizer N rate was relatively consistent across site-years. The response of grain yield to fertilizer N rate was dependent on stover management and tillage system (Table 2.3). This response was consistent between sites.

Regardless of tillage system or fertilizer N rate, grain yield increased with stover removal (Fig. 2.6). This indicates that stover removal positively influences grain production in addition to in-season growth and development. The difference in grain yield between stover management treatments did depend on tillage system and fertilizer N rate. In this study, EONRs were identified from the quadratic-plateau regression models when stover was removed within all tillage systems, and ranged from 205 to 222 kg N ha^{-1}. Conversely, EONRs were not identified within the fertilizer N rates used in this study in any tillage system when stover was retained. This indicates the amount of fertilizer N necessary to economically optimize grain yield is reduced with stover removal. These results agree with Coulter and Nafziger (2008), who reported that stover removal decreased the EONR by 11% in environments with normal rainfall in Illinois. The lower EONR with stover removal within NT (>6%) also agrees with Sims et al. (1998). They reported N availability was influenced by tillage system and surface stover coverage, and additional fertilizer N would be necessary to overcome these N availability issues. While increases of grain yield with stover removal within NT and ST were expected, the magnitude of difference in grain yield between stover management treatments within CT was somewhat unexpected. Despite often being regarded as a limiting factor in the Upper Midwest, soil temperature was generally similar between stover management treatments (Fig. 2.1). This indicates that another mechanism, possibly increased availability of N through decreased N immobilization by stover on the soil surface, contributed to the response of increased grain yield.

The lack of stover management with tillage and stover management (NT and retaining stover) on grain yield was evident when parameter estimates of grain yield regressed on fertilizer N rate were compared. β_0, the coefficient that represents the predicted grain yield when solely relying on indigenous N, was 13 to 20% (0.71 to 1.25 Mg ha^{-1}) less than those within CT and ST when stover was retained, respectively (Fig. 2.6). The remaining regression coefficients were similar among tillage systems without stover removal. This indicates the response of grain yield to fertilizer N was similar among tillage systems when stover was retained. Based on these relationships, yield reductions with NT and retaining stover are consistent across all fertilizer N rates. The reduced grain yields in this study with NT and retaining stover were expected because other studies on fine-textured soils in the Upper Midwest have reported reduced grain yields with NT compared to other tillage systems (Iragvarapu and Randall, 1995; Linden et al., 2000; Vetsch et al., 2007). These grain yield reductions with NT in this study were probably caused by the cumulative and confounded effects of soil temperature and N immobilization (Iragvarapu and Randall, 1995; Halvorson et al., 2001).

While these findings support the hypothesis that stover removal increases grain yield, other studies have reported negative effects of stover removal on grain yield when soil moisture was inadequate for continuous corn production (Wilhelm et al., 1986;

Blanco-Canqui et al., 2006b; Coulter and Nafziger, 2008). In this study, growing conditions were generally favorable for high levels of grain production since soil moisture was non-limiting. Based on these results, grain yield can be expected to increase with stover removal in environments where the presence of stover on the soil surface limits plant growth through cooler soil temperatures and water availability during the growing season is usually not limiting.

Grain Yield Components

The main effect of year accounted for 26% of the total random variation associated with kernel number. The interactions of year with stover management, tillage system, and fertilizer N rate each accounted for less than 8% of total random variation. Kernel number was affected by a stover management × fertilizer N rate interaction (Table 2.3). Though the response to fertilizer N rate differed between stover management treatments, removing stover increased kernel number by as much as14% (Fig. 2.7). Kernel weight was not affected by any of the fixed main effects (Table 2.3), and ranged from 275 to 290 mg kernel^{-1} among all stover management × fertilizer N rate treatments (data not shown). The lack of response of kernel weight to fertilizer N rate was supported by others who have observed no or inconsistent responses (Thiraporn et al., 1992; Zhang et al., 1993; O’Neill et al., 2004).

The responses of grain kernel weight and number to fertilizer N rate suggest N deficiencies were severe enough to affect the number of kernels produced, but not their weight. It is documented that kernel number determination occurs around flowering, an interval approximately 15 d before and after silking (Kiniry and Ritchie, 1985; Jacobs and Pearson, 1991; Uhart and Andrade, 1995), and that physiological stresses, such as N deficiencies, during flowering affect photosynthetic rates and assimilate production and partitioning (Donald and Hambilin, 1976; Andrade et al., 2002). Also, kernel number determination is susceptible to the availability of photosynthetic products during flowering (Tollenaar, 1977; Schussler and Westgate, 1995). Since kernel number was generally greater with stover removal, it suggests that the degree to which N stress at flowering affects kernel determination may decrease when stover is removed, probably because of increased N availability through greater net N mineralization.

CONCLUSIONS

Removal of corn stover enhanced several growth and yield measurements in continuous corn over a 3-yr period in southern Minnesota. The response of several of these variables to fertilizer N rate was also improved by stover removal, increasing tillage intensity, or both. The magnitude of improvement of these variables was often dependent upon the amount of stover that remained on the soil surface, dictated by stover removal and tillage system. Positive responses of soil temperature, a primary limiting factor in the Upper Midwest, were also observed with stover removal, especially within NT. Regardless of tillage system, stover removal increased grain yield and decreased the amount of fertilizer N necessary for economic optimization. This was likely because of increased N availability through increased N mineralization, decreased N immobilization, or both. Differences in grain yield among stover management treatments were related to kernel number, not kernel weight.

These results demonstrate that removal of corn stover is better suited to NT than CT and ST systems. In general, growth and yield measurements within NT were often similar to CT and ST when corn stover was removed. Also, the 30% surface coverage threshold for soil erosion protection established by the NRCS was satisfied by NT, but not CT or ST when stover was removed. While measurements among tillage systems were generally similar when stover was removed, the decision to adopt NT in continuous corn cropping systems with stover removal should ultimately depend upon the ability of NT to maximize economic productivity and minimize soil erosion potential and loss of soil organic C. Finally, it is important to note that these positive crop responses to stover removal occurred over a 3-yr period. Therefore, sustained stover removal over a longer time period would likely reduce soil and crop productivity.

TABLES AND FIGURES

Table 2.1. Monthly rainfall and average air temperature during growing seasons in 2009, 2010, and 2011, and the 30-yr average at Lamberton and Waseca, MN.

	Lamberton				Waseca			
Month	2009	2010	2011	30-yr average†	2009	2010	2011	30-yr average
	------------------------------- Precipitation, mm -------------------------------							
May	41	51	123	87	48	83	110	100
June	82	159	214	105	70	243	132	116
July	42	96	91	94	39	168	183	115
August	88	122	18	97	85	62	23	130
September	71	269	1.3	75	38	322	21	86
Total	324	697	447	458	280	878	469	547
	-------------------------- Average air temperature, °C ------------------------							
May	14.3	15.6	13.6	14.6	14.5	15.1	13.9	14.6
June	19.0	20.1	20.0	20.2	18.9	19.4	20.4	20.1
July	19.5	22.9	25.2	22.2	18.9	22.5	24.6	22.0
August	19.7	23.3	21.5	20.6	19.1	22.8	21.2	20.7
September	17.8	15.1	15.3	15.9	17.8	14.9	15.1	16.0

† 30-yr average (1979-2008).

Table 2.2. Tests of fixed effects for soil temperature over a 60-d period in 2010 and 2011 at Lamberton and Waseca, MN.†

Fixed source of variation	Lamberton		Waseca	
	2010	2011	2010	2011
Tillage system (T)	0.11	0.63	0.01	<0.001
Stover management (R)	0.002	<0.001	<0.001	0.008
Day (D)	<0.001	<0.001	<0.001	<0.001
T × R	0.12	0.03	0.01	0.25
T × D	<0.001	<0.001	<0.001	<0.001
R × D	<0.001	<0.001	<0.001	<0.001
T × R × D	<0.001	<0.001	<0.001	0.58

† Soil temperature measured in the seed furrow at a depth of 5 cm.

Table 2.3. Tests of fixed effects for surface stover coverage, plant emergence, relative plant height (RPH) and normalized difference vegetative index (NDVI) at the V8 growth stage, leaf area index (LAI) and relative leaf chlorophyll (RLC) at the R1 growth stage , grain yield, and kernel number.†

Fixed source of variation	Surface stover coverage	Plant emergence	RPH	NDVI	LAI	RLC	Grain yield	Kernel number
Site (S)	0.07	0.24	0.16	0.69	0.48	0.34	0.65	0.58
Tillage system (T)	0.01	0.03	0.04	0.02	0.95	0.92	0.25	0.22
Stover management (R)	0.007	0.03	0.12	0.07	0.04	0.09	0.04	0.01
Fertilizer N rate (N)	-‡	0.83	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
S × T	0.69	0.88	0.40	0.69	0.46	0.39	0.76	0.68
S × R	0.21	0.96	0.92	0.74	0.42	0.94	0.72	0.52
S × N	-	0.72	0.64	0.23	0.11	0.01	0.05	0.08
T × R	0.02	0.004	0.11	0.04	0.48	0.39	0.23	0.20
T × N	-	0.62	0.08	0.45	0.65	0.03	0.22	0.24
R × N	-	0.93	0.24	0.53	0.43	0.04	0.05	0.05
S × T × R	0.10	0.66	0.26	0.48	0.71	0.81	0.14	0.17
S × T × N	-	0.30	0.32	0.67	0.62	0.38	0.52	0.81
S × R × N	-	0.80	0.22	0.35	0.56	0.58	0.16	0.21
T × R × N	-	0.63	0.03	0.31	0.55	0.49	0.04	0.24
S × T × R × N	-	0.57	0.56	0.50	0.82	0.43	0.17	0.26

† Data from Lamberton 2009 was only included in the analysis of surface stover coverage and plant emergence.

‡ The effect of fertilizer N rate on surface stover coverage was not analyzed.

Table 2.4. Surface stover coverage, plant emergence, and normalized difference vegetative index (NDVI) as affected by stover management and tillage system.

Dependent variable	Stover management	Tillage system		
		Chisel	No-till	Strip-till
Surface stover coverage	Retained	43 Ac†	81 Aa	65 Ab
	Removed	14 Bb	36 Ba	25 Bab
Plant emergence	Retained	93 Aa	88 Bb	92 Aa
	Removed	94 Aa	93 Aa	94 Aa
NDVI	Retained	0.747 Aa	0.645 Bc	0.699 Bb
	Removed	0.788 Aa	0.771 Aa	0.787 Aa

† Upper-case letters denote differences between stover management treatments within a tillage system and lower-case letters denote differences between tillage systems within a stover management treatment, $\alpha = 0.05$.

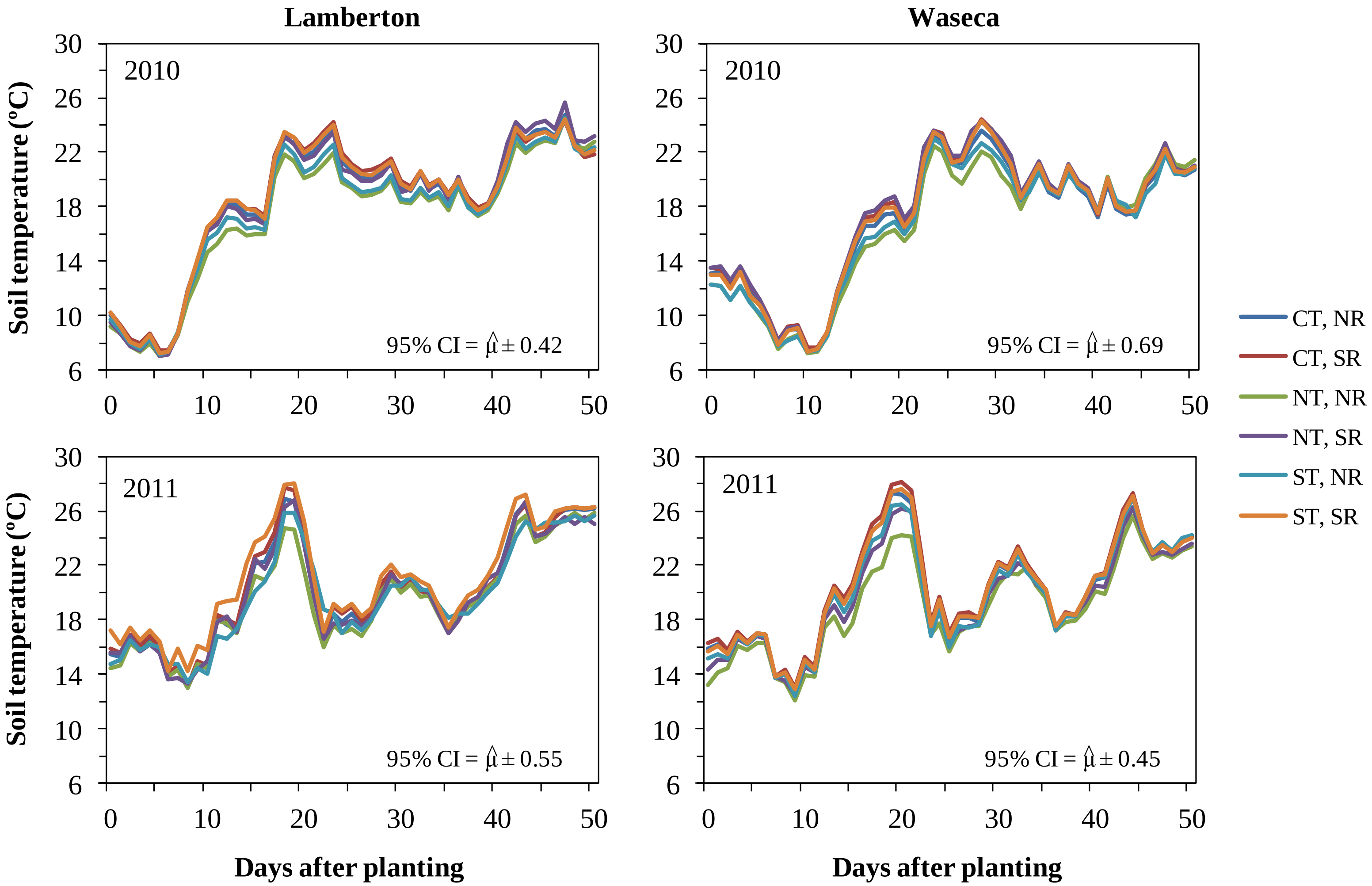

Fig 2.1. Soil temperature in the planting furrow at 5 cm through 50 d after planting among two stover management treatments [retained (NR) and removed (SR)] and three tillage systems [chisel (CT), no-till (NT), and strip-till (ST)] at Lamberton and Waseca, MN, in 2010 and 2011.

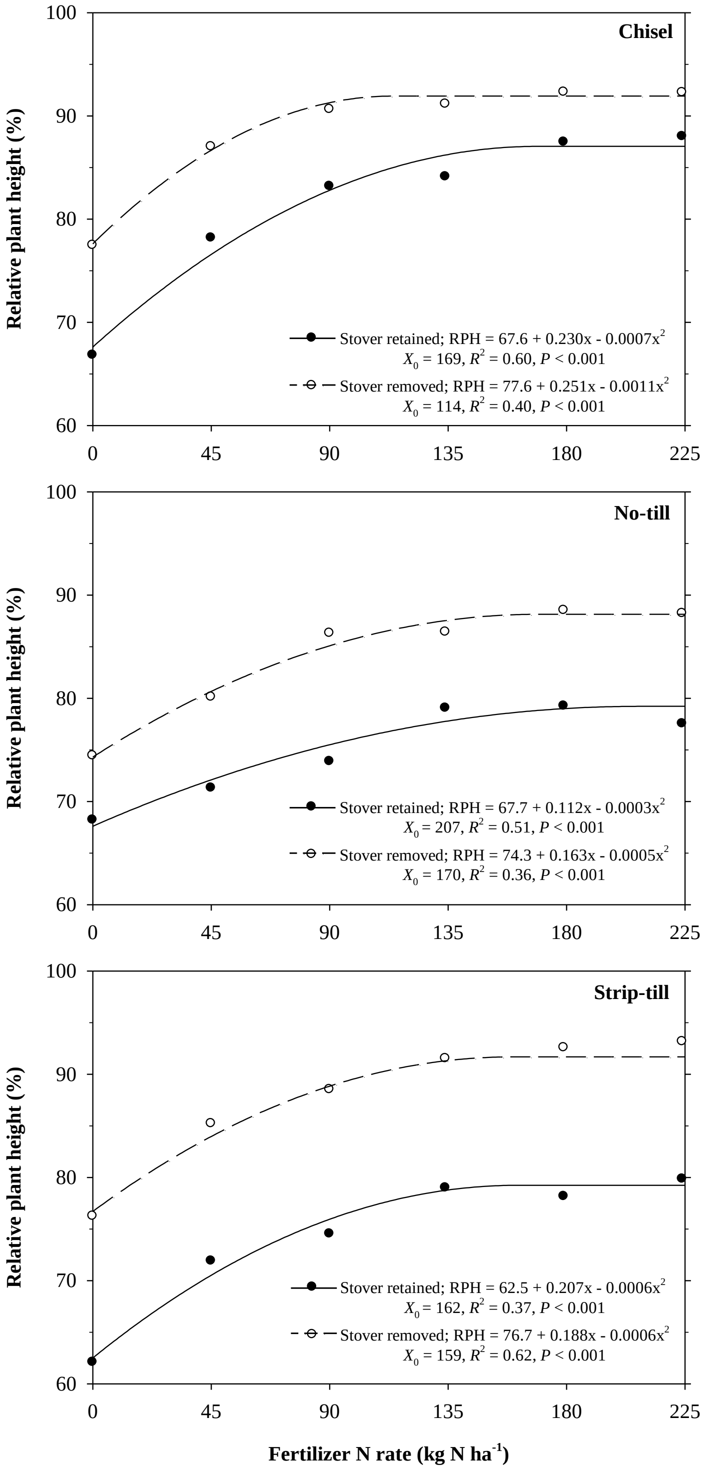

Fig 2.2. Response of relative plant height (RPH) to fertilizer N rate as affected by stover management and tillage system, averaged across years and sites.

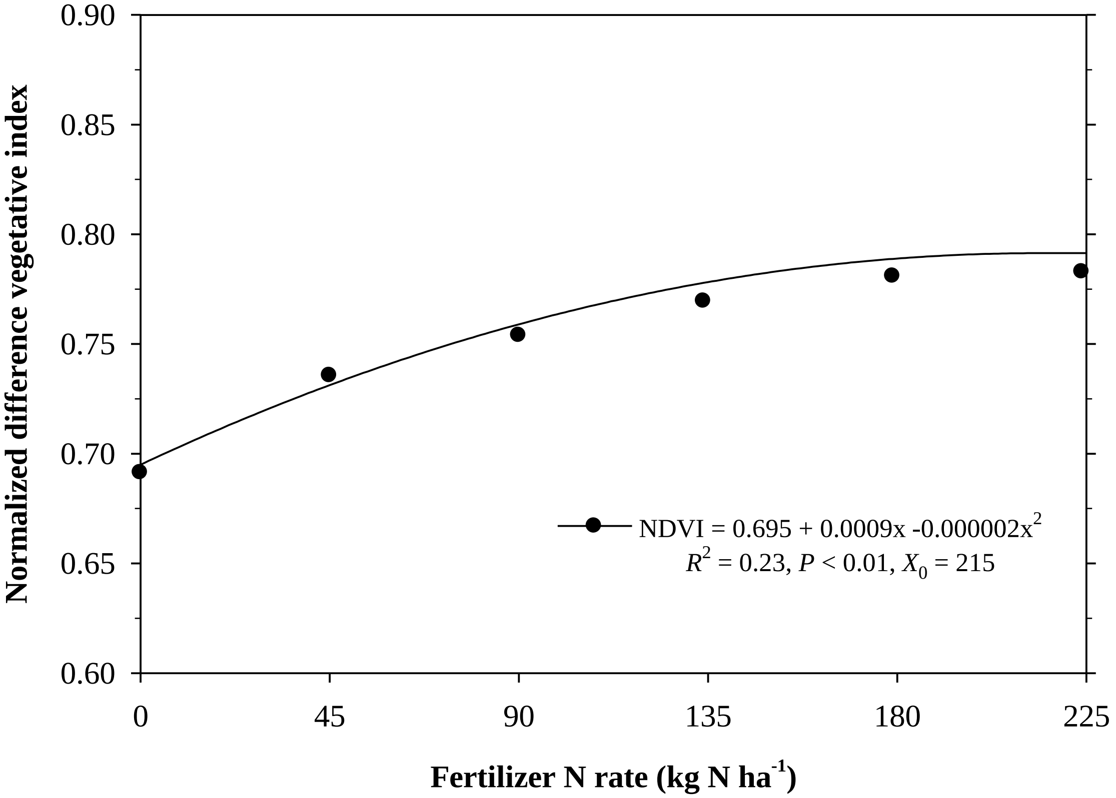

Fig 2.3. Response of normalized difference vegetative index (NDVI) to fertilizer N rate, averaged across years, sites, tillage systems, and stover management treatments.

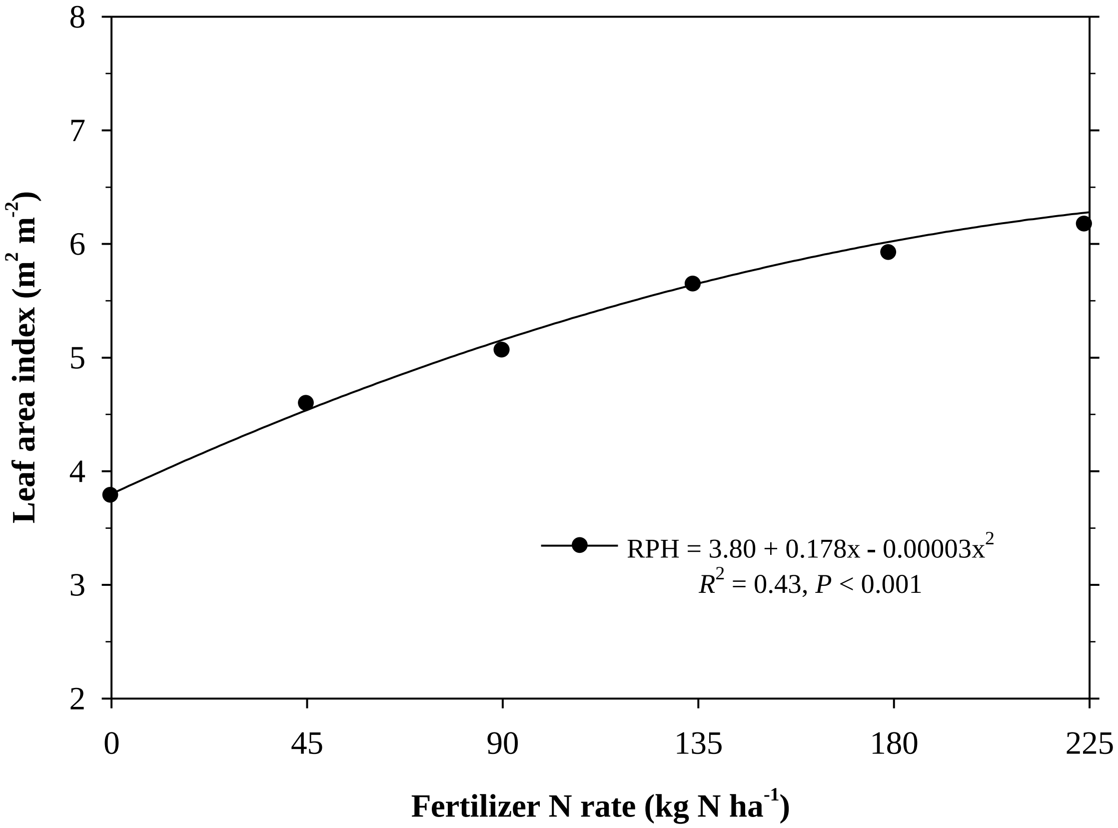

Fig 2.4. Response of leaf area index (LAI) to fertilizer N rate, averaged across years, sites, tillage systems, and stover management treatments.

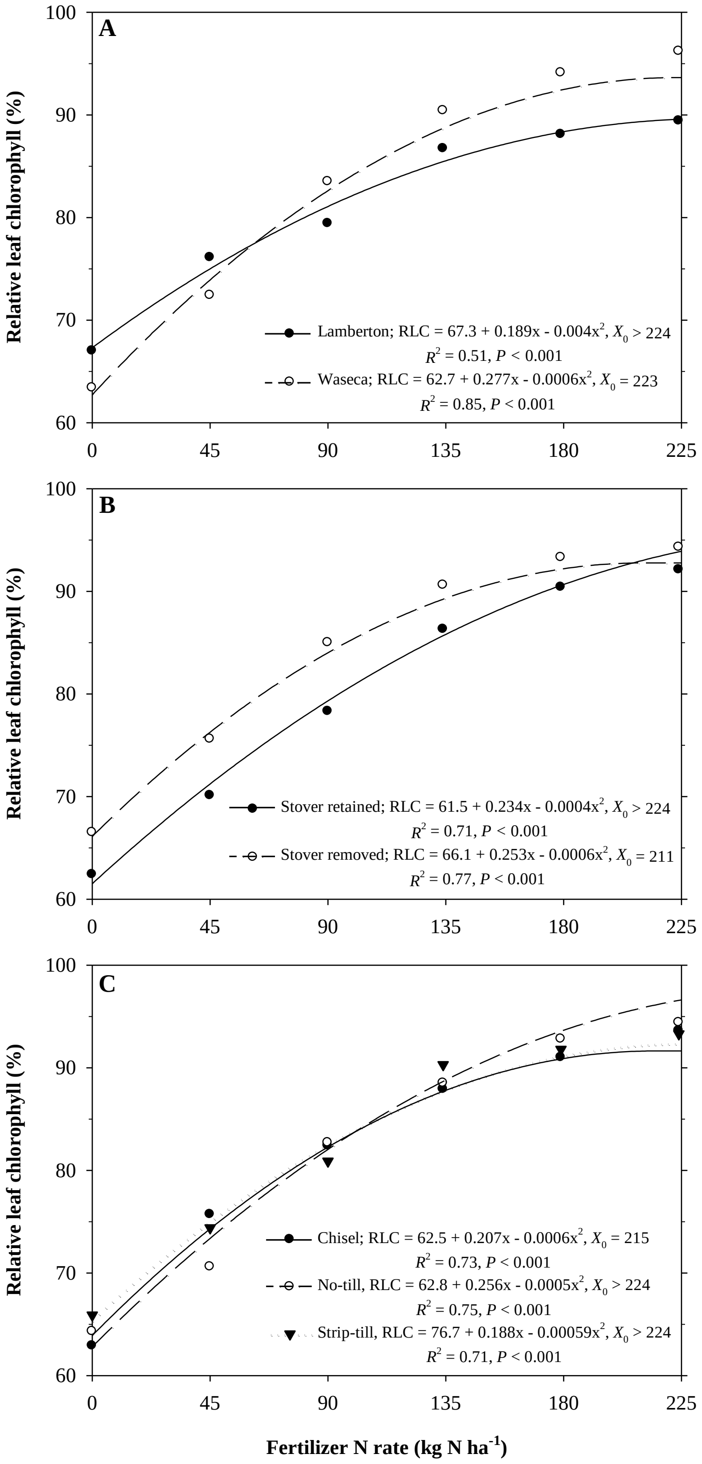

Fig 2.5. Response of relative leaf chlorophyll (RLC) to fertilizer N rate as affected by (A) site, (B) stover management, and (C) tillage system, averaged across years.

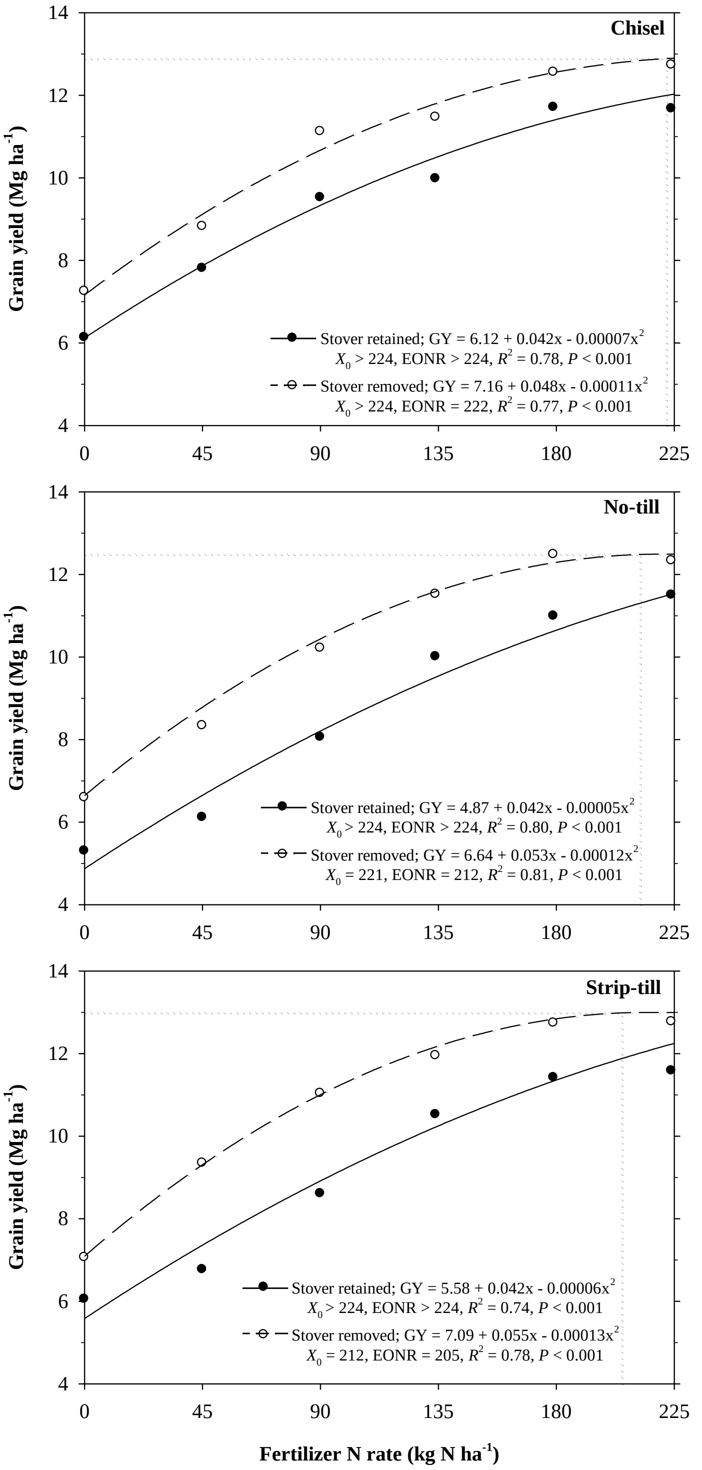

Fig. 2.6. Response of grain yield (GY) to fertilizer N rate as affected by stover management and tillage system, averaged across years and sites. Dotted lines indicate the economically optimum N rate (EONR) and grain yield at the EONR.

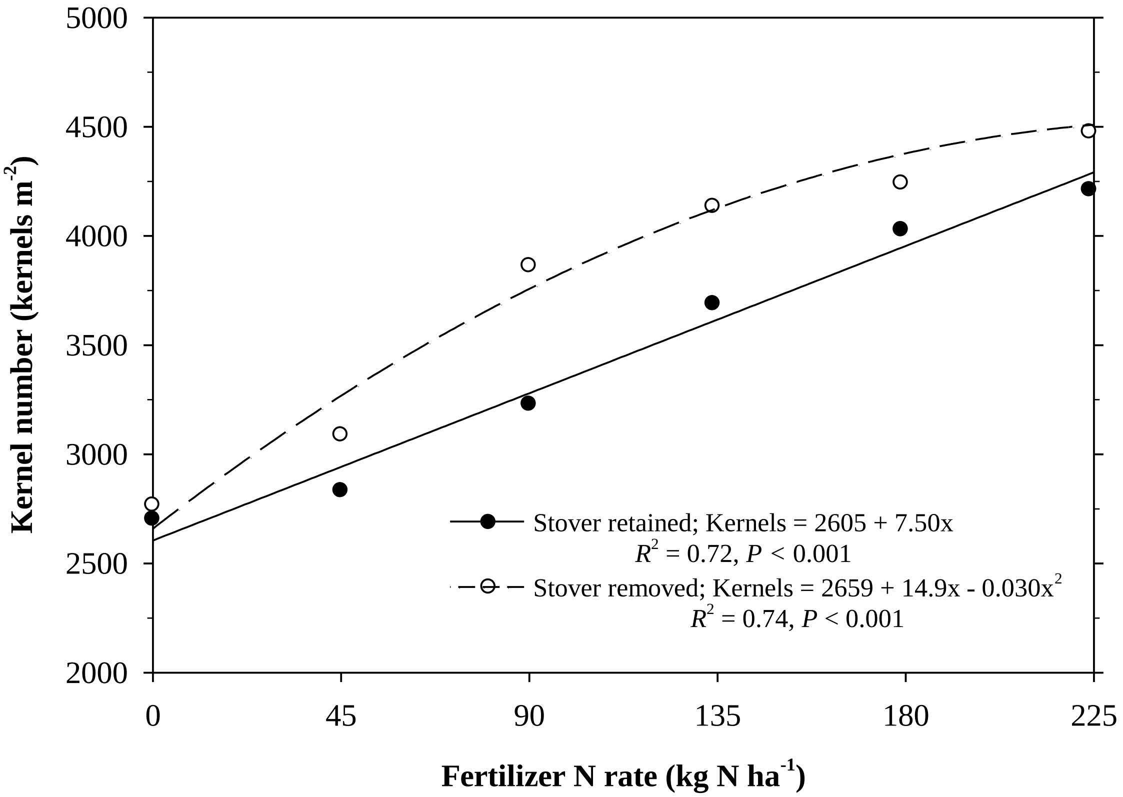

Fig. 2.7. Response of kernel number (kernels m-2) to fertilizer N rate as affected by stover management, averaged across years, sites, and tillage systems.

CHAPTER 3: NITROGEN USE EFFICIENCY AS AFFECTED BY STOVER, TILLAGE, AND NITROGEN MANAGEMENT

MATERIALS AND METHODS

In the fall of 2008, plots were established following corn in a split plot arrangement of a randomized complete block design with four replications on a subsurface tile drained Knoke loam soil (fine, smectitic, calcareous, mesic Mumulic Vertic Endoaquolls) at the University of Minnesota Southwest Research and Outreach Center near Lamberton (44°14′ N, 95°18′ W) and on a subsurface tile drained Nicollet-Webster clay loam soil complex (fine-loamy, mixed superactive, mesic Aquic Hapludolls and fine-loamy, mixed, superactive, mesic Typic Endoaquolls, respectively) at the University of Minnesota Southern Research and Outreach Center near Waseca, MN (44°3′ N, 93°31′ W). Main plots were a factorial arrangement of two stover management treatments (retain and remove) and three tillage systems [chisel (CT), strip-till (ST), and no-till (NT)]. Split plots were fertilizer N rate (0, 45, 89, 134, 179, and 224 kg N ha^{-1}). Split plots (eight 76-cm rows) were 6.1 m wide and were 9.2 m long at Lamberton and 7.0 m long at Waseca. Plot location was consistent throughout the duration of the study.

Stover management and tillage treatments were established in the fall of 2008 performed annually in the fall after grain harvest. When stover was removed, it was achieved by chopping standing stalks with a stalk chopper, raking, and baling with field-scale equipment in order to emulate probable removal rates by producers. Stover was not chopped in plots where retained. Tillage occurred within 5 d after stover management. The CT treatment was a chisel operation to a depth of 20 cm in the fall, followed by field cultivating to a depth of 9 cm in the spring prior to planting. The ST treatment was a fall event with an Orthman 1tRIPr (Orthman Manufacturing, Inc., Lexington, NE) at Lamberton and a Redball (Will-Rich, LLC, Wahpeton, ND) strip-till unit at Waseca. While units varied slightly, both were equipped with mole knives which tilled a 20-cm wide band to a depth of 20 cm in between the previous year's corn rows, and created a berm 8 cm in height.

Plots at both sites were planted in late April or early May with a commercial planter equipped with row cleaners. Corn in the NT treatment was planted 38 cm away from the previous year's corn rows. DEKALB DKC52-59, a 102-d relative maturity hybrid with transgenic resistance to glyphosate, European corn borer (*Ostrinia nubilalis* [Hübner]), and corn rootworm (*Diabrotica* spp.) was planted at all site-years 5 cm deep at 84,000 seeds ha^{-1}. Starter N and phosphorus (P) were applied simultaneously with seed planting as ammonium polyphosphate [$(NH_4)_3HP_2O_7 + NH_4H_2PO_4$] at 6.5 kg N ha^{-1} and 9.6 kg P ha^{-1}. Fertilizer N was broadcast applied by hand without incorporation within 5 d after planting as ammonium nitrate (NH_4NO_3). Soil-test P and K levels were high or very high, but were amended with triple superphosphate [$Ca(H_2PO_4)_2 \bullet H_2O$] and potash (KCl) according to University of Minnesota guidelines to ensure these nutrients would not be limiting (Kaiser et al., 2011). Sulfur was broadcast applied as gypsum ($CaSO_4 \bullet 2H_2O$) at 17 kg S ha^{-1}. Sulfur application in corn is recommended in Minnesota when grown continuously or in reduced tillage systems (Kaiser et al., 2011).

Stover (stalks, leaves, husks, and tassels) and cob yields were determined from six plants in each plot that were sampled from non-grain harvest, non-border rows within 7 d of grain harvest. Plants were cut at the crown, ears were removed from the plant, and stover was chopped using a mechanical chipper. Chopped stover and ears were dried at 60°C in a forced-air dryer to a constant weight, which typically required 48 h. Grain was shelled from the cobs and discarded, while cobs were retained. Stover and cob samples were then weighed and ground with a Thomas-Wiley Laboratory Mill equipped with a 2-mm screen (Thomas Scientific, Swedesboro, NJ) and subsampled. Subsamples were analyzed for total N concentration through the Dumas dry combustion method (Simone et al., 1994) with an Elementar variomax CN analyzer (Elementar, Hanau, Germany). Grain yield (GY) was measured by harvesting two rows of each plot using a plot combine. A grain sample from each plot was collected during grain harvest with the plot combine. Whole-kernel samples were analyzed for grain protein through near infrared reflectance spectroscopy (NIRS) with a Foss NIRSystems Model 6500 (Foss NIRSystems, Laurel, MD). Grain protein was then divided by 6.25 to obtain grain N concentration (Frey, 1949). Respective yields were then multiplied by N concentration to determine N uptake by grain (UG) and total above-ground material (UT).

Residual soil NO_3-N (RSN) was measured each fall after grain harvest. Two cores that were 3.8 cm in diameter were collected from interrows of each plot using a hydraulic probe to a depth of 1.2 m. Cores were separated into 30-cm increments, and one composite soil sample was created for each depth from each plot. Soil samples were air-dried, ground to pass through a 2 mm screen, and analyzed for RSN by the cadmium reduction method (Gelderman and Beegle, 1998). Total RSN, expressed as kg N ha^{-1}, was calculated from multiplying obtained NO_3-N concentrations by an estimated volume of soil in a 30-cm depth (4,485 Mg soil ha^{-1}). This estimated volume assumes bulk density is consistent among depths.

Nitrogen Use Efficiency Calculations

Several nitrogen use efficiency (NUE) calculations were used to assess the effects of fertilizer N rate, tillage system, and stover management on the crop's efficiency to utilize indigenous and fertilizer N (Moll et al., 1982; Cassman et al., 2002; Wortmann et al., 2011). Recovery efficiency (RE) indicates the total recovery of inorganic (fertilizer) N in respect to the amount applied, determined by Eq. [3.1]:

$$RE = \frac{(UT_N - UT_C)}{N\ Rate_N} \qquad [3.1]$$

where UT_N is total N uptake at a given fertilizer N rate and UT_C is total N uptake at the control, which is defined as the treatment combination with no tillage (NT), stover was retained, and no fertilizer N was applied. This calculation, or any others that consider UT, does not account for N uptake by below-ground plant material or for N that was collected by the plant but lost to postanthesis volatilization (Francis et al., 1993; Wortmann et al., 2011). Internal efficiency (IE) is a measure of the plant's grain yield efficiency as related to total plant N uptake of indigenous and fertilizer N, determined by Eq. [3.2]:

$$IE = \frac{GY_N}{UT_N} \qquad [3.2]$$

where GY_N is the grain yield at a given fertilizer N rate. Nitrogen harvest index (NHI) is the efficiency of the allocation of N to the grain in respect to total plant N, determined by Eq. [3.3]:

$$NHI = \frac{UG_N}{UT_N} \qquad [3.3]$$

Physiological efficiency (PE) represents the response in efficiency of the plant to fertilizer N application in regards to converting N uptake to grain yield, calculated through Eq. [3.4]:

$$PE = \frac{(GY_N - GY_C)}{(UT_N - UT_C)} \qquad [3.4]$$

where GY_C is the grain yield in the control. Partial factor productivity (PFP) is the ratio between grain yield and fertilizer N rate, and represents the total amount of grain production as a function of the amount of fertilizer N applied, determined by Eq. [3.5]:

$$PFP = \frac{GY_N}{N\ Rate_N} \qquad [3.5]$$

Agronomic efficiency (AE) represents the increase in grain yield as a function of the amount of fertilizer N applied, calculated through Eq. [3.6]:

$$AE = \frac{GY_N - GY_C}{N\ Rate_N} \qquad [3.6]$$

Data Analysis

Residuals were evaluated for normality prior to statistical analysis using the UNIVARIATE procedure of SAS (SAS Institute, 2005) and for common variance using scatterplots of residuals vs. predicted values (Weisberg, 2005). Data were then analyzed using the MIXED procedure in SAS at $\alpha = 0.10$. Site, tillage system, stover management, fertilizer N rate, and their interactions were fixed effects, while random effects were year, block (nested within site), and all interactions associated with these effects. The amount of explained random variation associated with year and its interactions with fixed effects was determined from covariance parameter estimates and is reported as a percentage of total random variation.

When the main effect of fertilizer N rate or its interactions with fixed effects were significant, linear or quadratic regression models were constructed using the MIXED procedure of SAS (SAS Institute, 2005), according to Eq. [3.7] and [3.8], respectively:

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X \qquad [3.7]$$

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X + \hat{\beta}_2 X^2 \qquad [3.8]$$

where $\hat{Y}$ is the predicted response variable, $\hat{\beta}_0$ is the intercept, $\hat{\beta}_1$ is the linear coefficient, $\hat{\beta}_2$ is the quadratic coefficient, and X is the fertilizer N rate. The best-fit regression model was determined through orthogonal contrasts in the MIXED procedure of SAS at α = 0.10. Parameter estimates among treatments were evaluated through comparisons of 90% confidence intervals.

RESULTS AND DISCUSSION

Nitrogen Uptake

The interaction of year with site accounted for 48 and 30% of the total random variation associated with grain and plant N uptake, respectively, while the total random variation associated with the main effect of year was only 13 and 12%, respectively. The response of grain and plant N uptake to fertilizer N rate differed between tillage systems, as indicated by the significant fertilizer N rate × tillage system interaction (Table 3.1). Regardless of tillage system, though, linear increases of UG occurred as fertilizer N rate increased (Fig 3.1). These increases of UG with increasing fertilizer N rate agree with Halvorson et al. (2006), Barbieri et al. (2008), and Holou et al. (2011). When solely relying on indigenous soil N, UG differed among tillage systems, as UG within no-till was at least 15% less than the other tillage systems. This implies that the indigenous N supply was lower within NT, likely because of decreased mineralization mediated by soil temperature (Halvorsen et al., 2001; Andraski and Bundy, 2008), increased immobilization (Doran, 1980; Rice and Smith, 1984), or both. Differences in UG among tillage systems decreased as fertilizer N rate increased, and with a fertilizer N rate of 224 kg N ha^{-1}, UG among tillage systems only differed by 3%, and the least squared means were not statistically different ($P \geq 0.10$). The similar predicted UGs at the maximum fertilizer N rate among NT and the other tillage systems is a product of the elevated accumulation rate ($\hat{\beta}_1$), which was 18 and 25% greater than accumulation rates within ST and CT, respectively. These findings agree with Licht and Al-Kaisi (2005), who reported that UG was similar among CT, ST, and NT at three of four site-years in Iowa. Unlike tillage system, the effect of stover management on UG was consistent across fertilizer N rates, and increased from 97 to 117 kg N ha^{-1} (20%) with stover removal. Greater UG may have been a product of the 17% increase of grain yield with stover removal (Chapter 2).

Similar to UG, UT also increased linearly as fertilizer N rate increased, and the response also differed among tillage systems (Fig 3.2). Increases in UT with increasing fertilizer N rate agrees with Varvel and Peterson (1990) and Wortmann et al. (2011). Also, Halvorson et al. (2006) reported a linear response of UT to fertilizer N rate in Colorado. When solely relying on indigenous soil N, UT within NT was 13 and 16% less than UT within ST and CT, respectively. Thus, the greatest benefit of fertilizer N on UT occurred within NT, as the N accumulation rate ($\hat{\beta}_1$) was 11 and 13% greater than predicted rates within ST and CT, respectively. Because of this elevated accumulation rate, predicted plant N uptake at 224 kg N ha^{-1} (the maximum fertilizer N rate) was similar. The effect of stover management on UT was consistent across all fertilizer N rates and tillage systems, and UT increased from 138 kg N ha^{-1} to 162 kg N ha^{-1}(17%) with stover removal.

Recovery Efficiency

Recovery efficiency is the change in UT from the control per unit of fertilizer N applied. The interaction of year with site accounted for 26% of the total random variation associated with RE, while random variation associated with interactions between year and the other fixed effects accounted for only 13%. This indicates that the response of RE to tillage system, stover management, and fertilizer N rate was consistent across years. The response of RE to fertilizer N rate was dependent upon stover management and tillage system (Table 3.1). Depending on tillage system × stover management treatment combinations, RE decreased linearly by 20 to 48% as fertilizer N rate increased from 45 to 224 kg N ha^{-1} (Fig 3.3). This was expected since potential for loss of N through plant derived-volatilization, denitrification, leaching, and soil-derived volatilization generally increase as fertilizer N rate increases (Baker and Johnson, 1981; Francis et al., 1993;

MacKenzie et al., 1997), which can decrease NUE (Raun and Johnson, 1999; Cassman et al., 2002; Raun and Schepers, 2008). The observed response of decreasing RE with increasing fertilizer N rate agrees with Varvel and Peterson (1990), Jokela and Randall (1997), and Al-Kaisi and Kwaw-Mensah (2007), and these RE estimates are similar to those by Wortmann et al. (2011).

The effect of stover management on RE differed among tillage systems (Table 3.1). Within CT, the rate of decline in RE as fertilizer N rate increased ($\hat{\beta}_1$) was 43% less when stover was removed (Fig 3.3). Despite the rate of decline of RE with increasing fertilizer N rate being slightly greater with stover removal within NT, RE was greater with stover removal. This was demonstrated by the $\hat{\beta}_0$ estimate, which was 39% greater when stover was removed. Within ST, greater PE with stover removal occurred, particularly at low fertilizer N rates, as RE was 53% greater with stover removal when solely relying on indigenous N. However, the rate of decline in RE as fertilizer N rate increased ($\hat{\beta}_1$) was accelerated with stover removal by 171%, which was opposite of the response within CT. Regardless of tillage system, RE was greater than 100% in several individual plots when stover was removed, suggesting N availability exceeded only N applied through fertilization, likely because of soil processes such as enhanced mineralization of N (Motavalli et al., 1992; Wortmann et al., 2011).

The response of RE to fertilizer N rate within each tillage system was dependent upon stover management (Fig 3.3). When stover was retained, RE within CT was greater than those within other tillage systems at low fertilizer N rates (≤90 kg N ha^{-1}), while no differences existed in RE between NT and ST. For example, RE within CT at a fertilizer N rate of 45 kg N ha^{-1} was 27 and 28% greater than those within NT and ST, respectively, while RE for CT and NT at this fertilizer N rate were similar (0.619 and 0.614 kg kg^{-1}, respectively). The reduced RE with reduced tillage is probably related to the immobilization of fertilizer-derived N by stover remaining on the soil surface (Doran, 1980; Rice and Smith; 1984, Mengel, 1996), thus decreasing its availability for recovery by the plant. However, as fertilizer N rate increased, differences in RE between CT and the other tillage systems decreased, and RE at a fertilizer N rate of 224 kg N ha^{-1} within CT was 11 and 16% less than RE within NT and ST, respectively. Al-Kaisi and Kwas-Mensah (2007) support this observation, as N recovery at tasseling within CT was equal to the greatest at a fertilizer N rate of 85 kg N ha^{-1}, but equal to the lowest at 250 kg N ha^{-1}. When stover was removed, differences in RE among tillage systems were less pronounced. However, with a fertilizer N rate of 224 kg N ha^{-1}, RE within ST was 11 and 10% less than those within CT and NT, respectively, and the reason for this is unclear other than attributing it to random variation.

Internal Efficiency

Internal efficiency is GY per unit of N taken up by the plant. The interaction of year with site accounted for 42% of the total random variation associated with IE. All other random variation associated with year and its interactions with fixed effects accounted for 9%. This indicates the response of IE to tillage system, stover management, and fertilizer N rate was consistent across years. Internal efficiency decreased linearly as fertilizer N rate increased when stover was retained, and quadratically when removed (Table 3.1; Fig 3.4). Also, IE was 9% greater with stover removal when the plant was solely relying on indigenous N, but did not differ between stover management treatments when fertilizer N was applied.

The lower IE indicates that N taken up by the plant was less efficiently converted to grain yield. Furthermore, NHI, a component of IE, was not affected by fertilizer N rate, stover management, or tillage system in this study (Table 3.1), meaning the allocation of N to grain relative to UT was consistent. The relationship between stover management treatments where IE was greater when solely relying on indigenous N but similar when fertilizer N was applied suggests that the increased availability of N when stover is removed, possibly by greater net N mineralization, is not efficiently utilized in regards to grain quality, despite grain yields that were 17% greater when stover was removed (Chapter 2).

Physiological Efficiency

Physiological efficiency is the change in GY from the control per unit of change in UT from the control. While PE is a component of IE, its estimate primarily focuses on the contribution of fertilizer N (Cassman et al., 2002). In this study, the main effect of year and its interaction with site accounted for 31 and 38% of the total random variation associated with PE, and the cumulative total of variation associated with interactions between year and all other fixed effects was 3%. This indicates the response of grain yield to tillage system, stover management, and fertilizer N rate was consistent across years. Physiological efficiency of grain decreased quadratically as fertilizer N rate increased, and the response was similar between stover management treatments and tillage systems (Table 3.1; Fig. 3.5). However, the high degree of variability among site-years led to the weak quadratic relationship between fertilizer N rate and PE. Decreasing PE as fertilization N rate increased was also observed by Wortmann et al. (2011), which improves confidence in interpretation of the response in this study. The regression model predicted that PE would remain relatively unchanged with fertilizer N rates of 0 to 134 kg N ha^{-1}, but would decrease slightly to 68.9 and 65.4 kg kg^{-1} at fertilizer N rates of 179 and 224 kg N ha^{-1} (Fig. 3.5).

Across the range of all fertilizer N rates, the maximum amount of change in PE was only 8% (Fig 3.5). While the strength of the regression is quite weak and the predictive power of the regression is low, there is adequate evidence to suggest that PE was not substantially influenced by fertilizer N rate in this study, at least not at the magnitude reported by Wortmann et al. (2011), who found that PE in continuous corn decreased by 38% as fertilizer N rate increased from 100 to 200 kg N ha^{-1}. Any decreases, though small, became evident as fertilizer N rates approached economically optimum N rates (EONRs) for grain yield, which ranged from of 205 to ≥224 kg N ha^{-1} (Chapter 2). The lack of response of PE to stover management and tillage also indicates that stover management did not affect the efficiency of grain yield as a function of N uptake from fertilizer N.

Partial Factor Productivity

Partial factor productivity is GY per unit of fertilizer N applied. The interaction of year with site accounted for 22% of the total random variation associated with RE. All other remaining variation associated with year and the other fixed effects was 17%. This indicates the response of grain yield to fertilizer N rate, stover management, and tillage system was consistent across years. Despite the response of PFP to fertilizer N rate depending upon tillage system and stover management, PFP decreased quadratically as fertilizer N rate increased, (Table 3.1; Fig. 3.6). Also, the magnitude of decline of PFP decreased as fertilizer N rates approached EONRs for grain yield, which ranged from 205 to ≥224 kg N ha^{-1} (Chapter 2).

Stover management affected the response of PFP to fertilizer N rate, but it was dependent on tillage system. Within CT, removal of stover improved PFP by 5 to 12%, and the response of PFP to fertilizer N rate was more consistent between stover management treatments when compared to the other tillage systems. Within NT and ST, stover removal improved PFP, and the difference in PFP between stover management treatments decreased as fertilizer N rate increased. For example PFP differed between stover management treatments within NT and ST by 35 and 39%, respectively, at a fertilizer N rate of 45 kg N ha^{-1} and by 5 and 10%, respectively, at a fertilizer N rate of 179 kg N ha^{-1}. Two possible mechanisms are likely contributing to the increase of PFP with stover removal. First, N availability is likely being reduced because of increased immobilization of N by remaining stover (Green and Blackmer, 1995), thus limiting its utilization by the plant. Second, removal of stover increased soil temperature within 35 d after planting, (Chapter 2), especially within NT. This increased soil temperature may have promoted uptake and increased N mineralization rates. Andraski and Bundy (2008) suggested that soil temperature, rather than N immobilization, was the primary mechanism affecting net N mineralization. Within CT, where soil temperature was similar between stover management treatments (Chapter 2), increases in PFP would theoretically have been caused by decreased N immobilization, assuming soil temperature was the primary mechanism influencing N mineralization rates. Nitrogen immobilization potential was lower with stover removal because N sink capacity was reduced (less stover present to immobilize N). While these results indicate N mineralization rates are likely slower when stover is retained, the responses within CT do indicate that decreased N immobilization may be responsible for improved responses in PFP.

Agronomic Efficiency

Agronomic efficiency is the change in GY from the control per unit of fertilizer N applied. The sum of all interactions of fixed effects with year accounted for only 15% of the total random variation associated with AE, indicating its response to tillage system, stover management, and fertilizer N rate was consistent across all sites and years. Stover removal increased AE across all tillage systems, though the magnitude of increase differed among fertilizer N rates (Table 3.1; Fig 3.7). Within CT, quadratic decreases in AE occurred as the fertilizer N rate approached the EONR for grain yield ($\geq$222 kg N ha^{-1}; Chapter 2), and the response was more consistent between stover management treatments when compared to the other tillage systems. Within ST, AE increased 20 to 25% with stover removal at fertilizer N rates less than the EONRs. Within NT and ST, differences in AE between stover management treatments decreased as fertilizer N rates increased and approached the EONRs. For example, AE was 56 and 49% greater with stover removal at a fertilizer N rate of 45 kg N ha^{-1} within NT and ST, respectively. In comparison, AE was 30 and 16% greater at a fertilizer N rate of 134 kg N ha^{-1} within NT and ST, respectively. Similar to PFP, these responses in the respective tillage systems again indicate that stover removal likely increased N availability to the plant, particularly at low fertilizer N rates.

The likelihood that N availability is influencing AE was further evident when comparing tillage systems within each stover management treatment. When stover was retained, AE within CT at a fertilizer N rate of 45 kg N ha^{-1} was 22 and 51% greater than those within ST and NT, respectively (Fig 3.7). However, these IEs differed by 4 and 9%, respectively, when fertilizer N rates increased to 179 kg N ha^{-1}. Based on these relationships, N availability as a function of the amount of stover remaining on the soil surface is probably the primary mechanism affecting AE at lower fertilizer N rates (~ ≤90 kg N ha^{-1}) because plants at these fertilizer N rates are strongly relying on indigenous N. As fertilizer N rates continued to approach EONRs for grain yield and differences among tillage systems continued to decrease, the effect of indigenous N availability on AE also appeared to decrease. This occurs because plants are primarily relying on fertilizer N instead of indigenous N. Findings by Russelle et al. (1983) supports this theory, as they observed that fertilizer-derived N accounted for approximately 21% of total plant N at a fertilizer N rate of 90 kg N ha^{-1} and approximately 31% of total plant N at a fertilizer N rate of 180 kg N ha^{-1}. Fewer differences among tillage systems existed when stover was removed, as AE among tillage systems differed by 6 to 22% at a fertilizer N rate of 45 kg N ha^{-1}. Since soil temperature generally did not differ between tillage systems when stover was removed, differences in AE were again potentially a result of immobilization of N by stover that still remained on the soil surface after removal occurred or by intact, undisturbed root masses that do represent a measurable amount of cellulosic material and exhibit a high C/N ratio (Johnson et al., 2006, 2007).

Residual Soil Nitrate-N

The interaction of year with site accounted for 21% of the total random variation associated with RSN. Other than the year by fertilizer N rate interaction (4%), no other interactions between fixed effects and year accounted for measurable random variation. Residual soil NO_3-N increased quadratically as fertilizer N rate increased, and the response to fertilizer N depended on stover management (Table 3.1). At fertilizer N rates ≤90 kg N ha^{-1}, RSN did not differ between stover management treatments (Fig. 3.8). However, as fertilizer N rates increased beyond this, RSN increased with stover removal by 26, 34, and 40% at fertilizer N rates of 134, 179, and 224 kg N ha^{-1}, respectively. These responses at fertilizer N rates ≥134 kg N ha^{-1} agree with Burgess et al. (1999), who reported elevated RSN in treatments where stover was removed. While differences existed between stover management treatments, it should be noted that, even at the highest fertilizer N rate, these amounts of RSN are relatively small. In comparison, Jokela and Randall (1989) observed that fall RSN totals in a 1.5-m profile at Waseca, MN, ranged from 88 to 252 kg N ha^{-1} with a fertilizer N rate of 100 kg N ha^{-1} and, 180 to 314 kg N ha^{-1} with a fertilizer N rate of 200 kg N ha^{-1} when all fertilizer N was applied preplant. These low RSN amounts were not unexpected, though, since REs were generally greater than expected. Regardless of the amount of RSN, these results demonstrate that removal of stover can increase RSN, especially as fertilizer N rates approach the EONR, which may potentially threaten water quality through increased NO_3-N leaching potential (Follett and Hatfield, 2001; Randall et al., 2008).

Tillage system did not influence RSN (Table 3.1), as levels of 33.6, 33.7, and 33.1 kg N ha^{-1} were observed for CT, NT, and ST, respectively, when averaged across sites, fertilizer N rates, and stover management treatments. It was hypothesized that RSN would differ among tillage systems when stover was retained, but would be similar when stover was removed. However, the responses of RSN to fertilizer N rates between stover management treatments within each tillage system were consistent ($P = 0.45$; Table 3.1). The lack of differences in RSN among tillage systems were supported by Kitur et al. (1984), Burgess et al. (1999), and Al-Kaisi and Kwaw-Mensah (2007), but differs from findings by Randall (1990) and Angle et al. (1993). The results in this study suggest that the RSN portion of the soil N balance will increase when stover is removed and fertilizer N rates ≥134 kg N ha^{-1} are used, regardless of tillage system.

CONCLUSIONS

Increasing fertilizer N rate affected all N uptake and NUE components except NHI. In most cases, the response of a given uptake or NUE component to fertilizer N rate was improved with stover removal or increasing tillage intensity. In several cases, the greatest gains with stover removal occurred at low fertilizer N rates (≤ 90 kg N ha^{-1}), or in reduced tillage systems, likely because less N immobilization occurred. This is because N sink capacity was reduced since less stover was present to act as a sink and decrease its availability. Though stover removal did affect most NUE components, its effects on the physiological components were limited (IE and PE) to nonexistent (NHI), indicating stover removal effects on physiological performance are relatively small.

While stover removal improved several NUE components, particularly at low fertilizer N rate application (~ ≤90 kg N ha^{-1}), it also increased RSN. Though RSN in the 1.2-m profile was similar between stover management treatments at fertilizer N rates ≤90 kg N ha^{-1} application, RSN increased with stover removal by 26, 34, and 40% at fertilizer N rates of 134, 179, and 224 kg N ha^{-1}, respectively. This indicates that sink capacity (ability of the system to store RSN) is greatly reduced when corn stover is harvested and that fertilizer N rates as low as 134 kg N ha^{-1} can increase RSN leaching potential in cropping systems where stover is removed.

While data from this study showed that removing corn stover improved several NUE components, it is necessary to note that these responses were a function of short-term (≤ 3 yr) stover management. If sustained long-term stover removal without any organic amendments occurs and indigenous nutrient pools, particularly N, are depleted, improvement in these NUE components will likely decrease. These improvements were, at least partially, related to elevated indigenous N availability caused by increased N mineralization. The increase in RSN with stover removal at fertilizer N rates ≥134 kg N ha^{-1} indicates that heightened N management through practices such as split or sidedressed application (Raun and Johnson, 1999) and in-season canopy sensing (Roberts et al., 2010) may be necessary in cropping systems where stover removal occurs in order to minimize negative environmental impact.

TABLES AND FIGURES

Table 3.1. Tests of fixed effects for N uptake by grain (UG) and total aboveground plant (UT), recovery efficiency (RE), internal efficiency (IE), N harvest index (NHI), physiological efficiency (PE), partial factor productivity (PFP), agronomic efficiency (AE), and residual soil nitrate-N (RSN).

Fixed source of variation	UG	UT	RE	IE	NHI	PE	PFP	AE	RSN
Site (S)	0.68	0.75	0.76	0.94	0.58	0.68	0.68	0.40	0.56
Tillage system (T)	0.36	0.30	0.29	0.69	0.64	0.71	0.20	0.22	0.72
Stover management (R)	0.10	0.11	0.12	0.58	0.16	0.63	0.05	0.04	0.09
Fertilizer N rate (N)	<0.001	<0.001	0.04	0.03	0.31	0.07	<0.001	<0.001	0.001
S × T	0.86	0.56	0.66	0.38	0.72	0.68	0.78	0.66	0.59
S × R	0.69	0.57	0.45	0.79	0.49	0.62	0.34	0.29	0.37
S × N	0.59	0.96	0.94	0.41	0.85	0.25	0.98	0.14	0.26
T × R	0.40	0.55	0.26	0.29	0.66	0.25	0.10	0.13	0.21
T × N	0.07	0.10	0.04	0.57	0.22	0.13	0.02	0.09	0.22
R × N	0.57	0.66	0.10	0.03	0.11	0.16	0.001	0.002	0.02
S × T × R	0.15	0.79	0.19	0.38	0.31	0.26	0.14	0.12	0.46
S × T × N	0.51	0.58	0.89	0.49	0.27	0.44	0.94	0.86	0.31
S × R × N	0.79	0.94	0.78	0.47	0.48	0.31	0.11	0.26	0.56
T × R × N	0.33	0.19	0.02	0.14	0.37	0.60	0.004	0.01	0.45
S × T × R × N	0.89	0.60	0.28	0.21	0.21	0.47	0.14	0.13	0.38

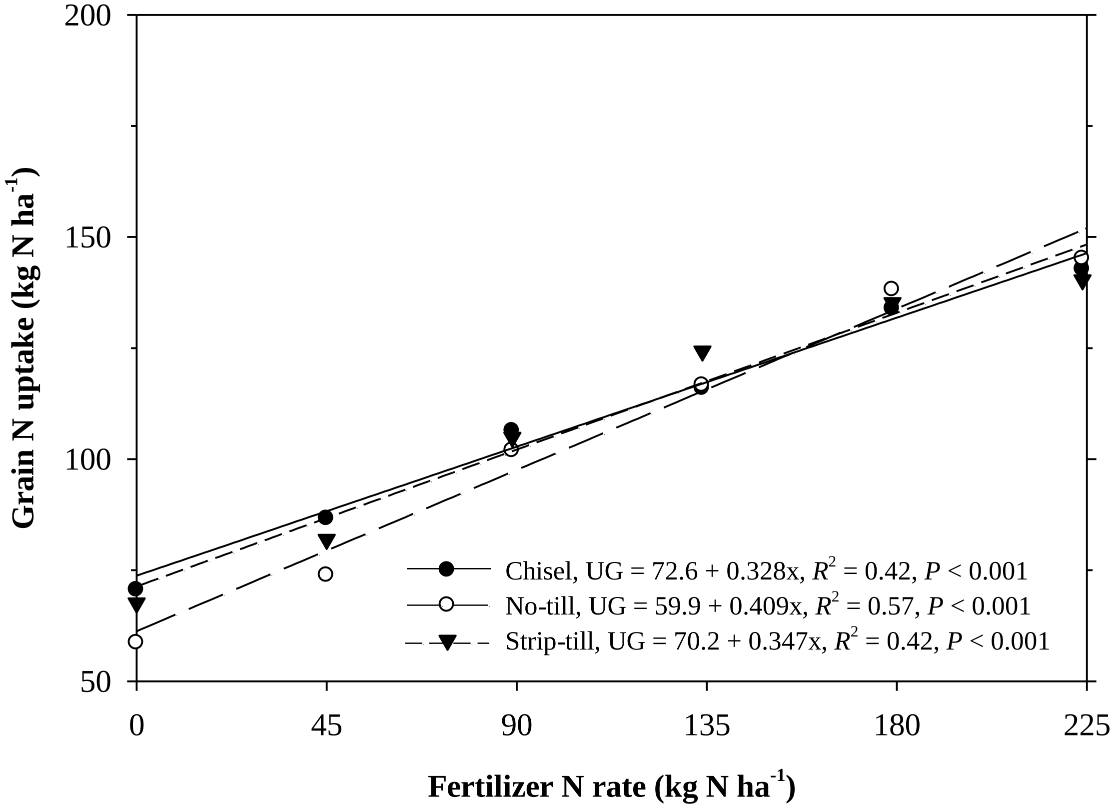

Fig. 3.1. Response of grain N uptake (UG) to fertilizer N rate as affected by tillage system, averaged across years, sites, stover management treatments.

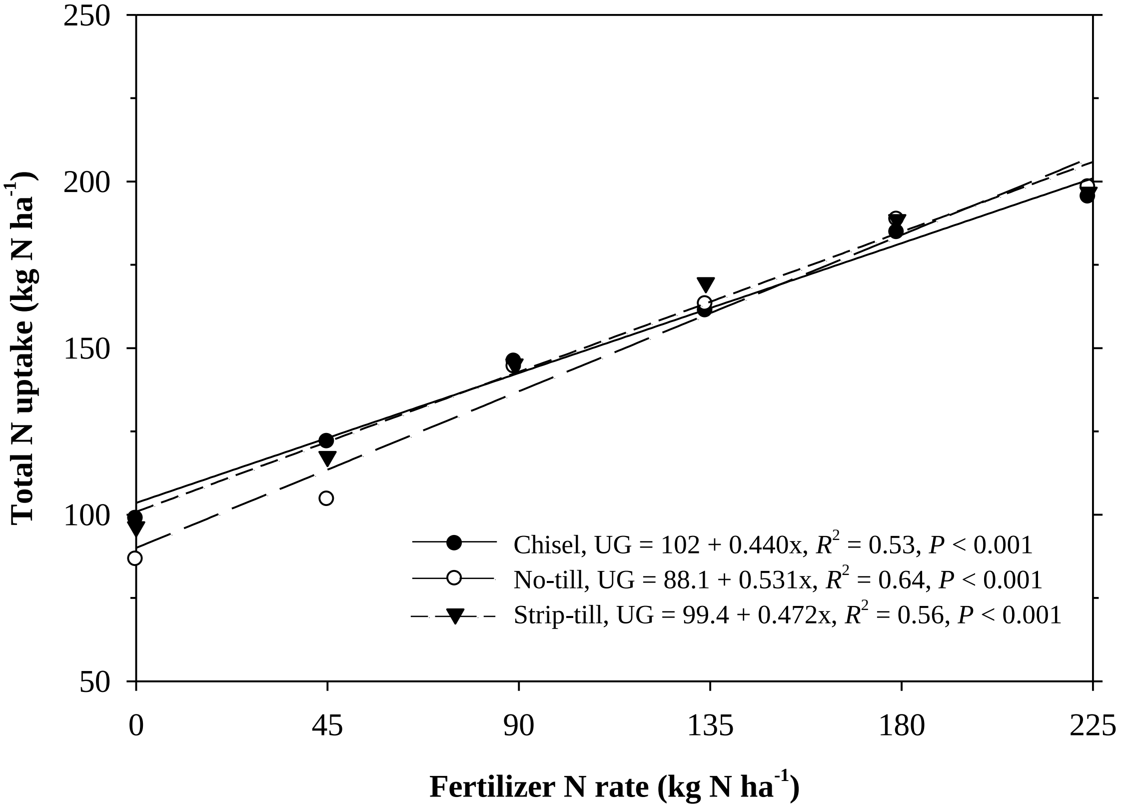

Fig. 3.2. Response of total aboveground plant N uptake (UT) to fertilizer N rate as affected by tillage system, averaged across years, sites, and stover management treatments.

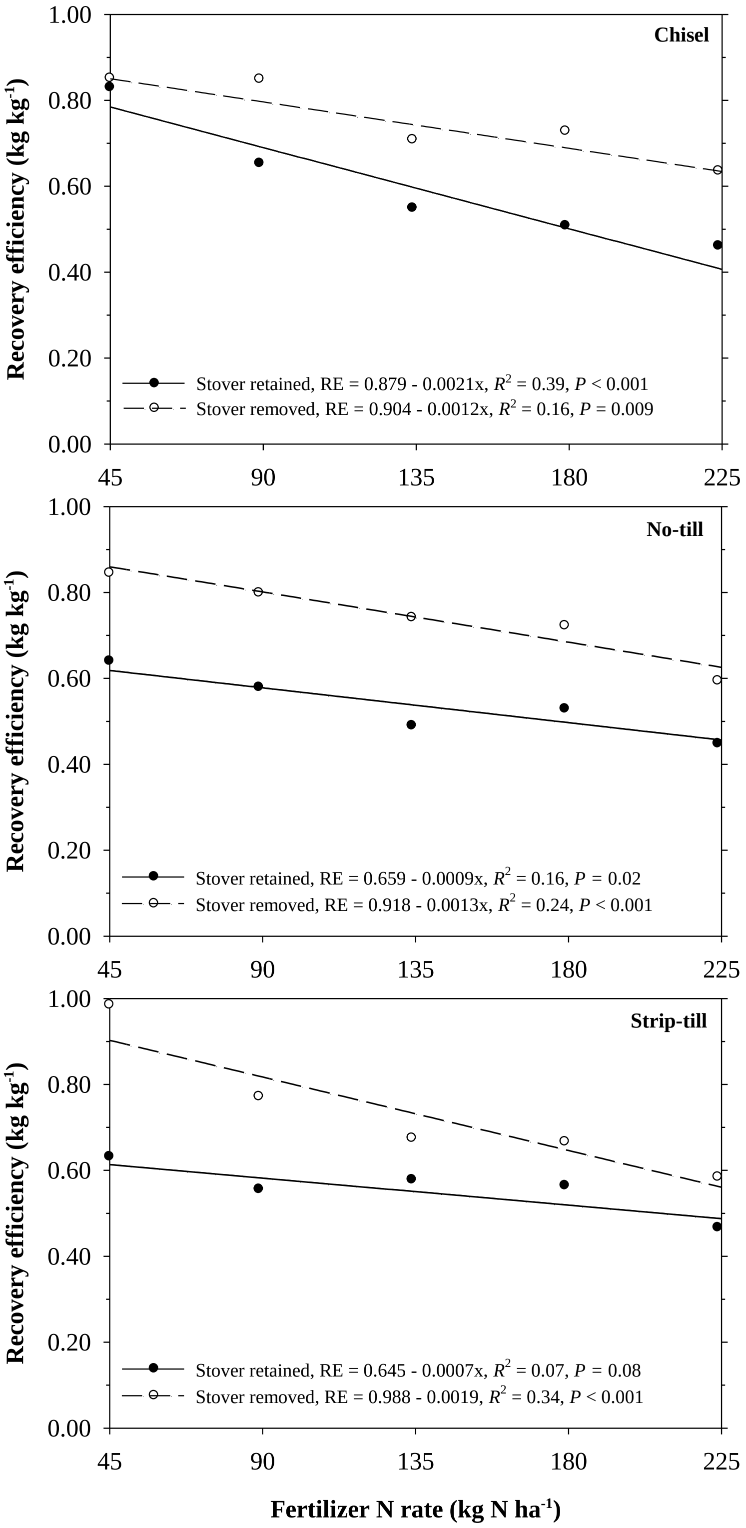

Figure 3.3. Response of recovery efficiency (RE) to fertilizer N rate as affected by stover management and tillage system, averaged across years and sites.

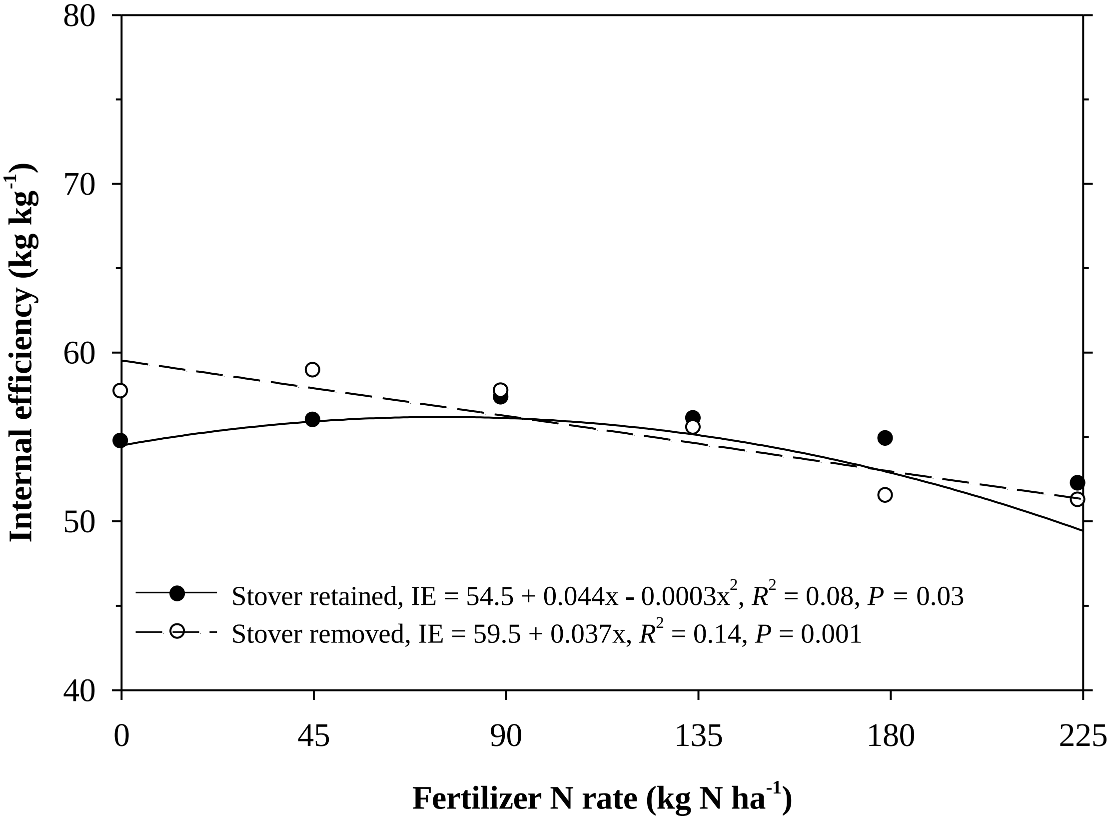

Fig. 3.4. Response of internal efficiency (IE) to fertilizer N rate as affected by stover management, averaged across years, sites, and tillage systems.

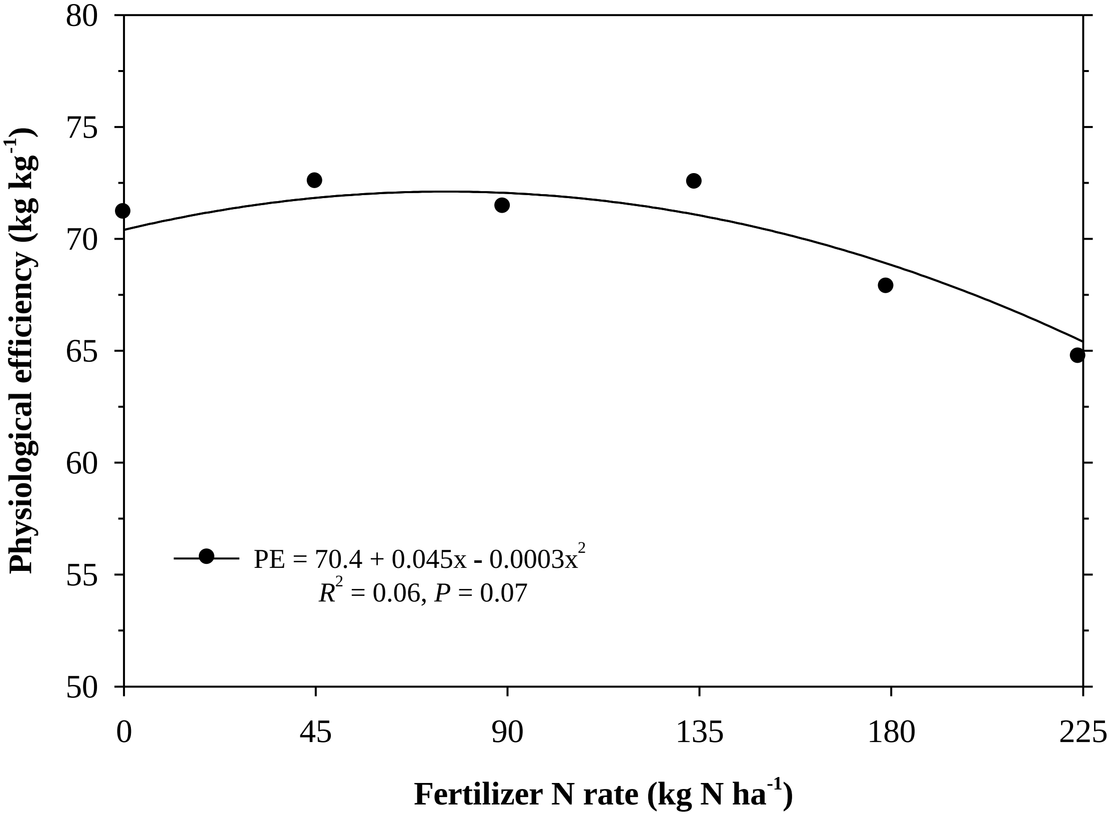

Fig. 3.5. Response of physiological efficiency (PE) to fertilizer N rate, averaged across years, sites, stover management treatments, and tillage systems.

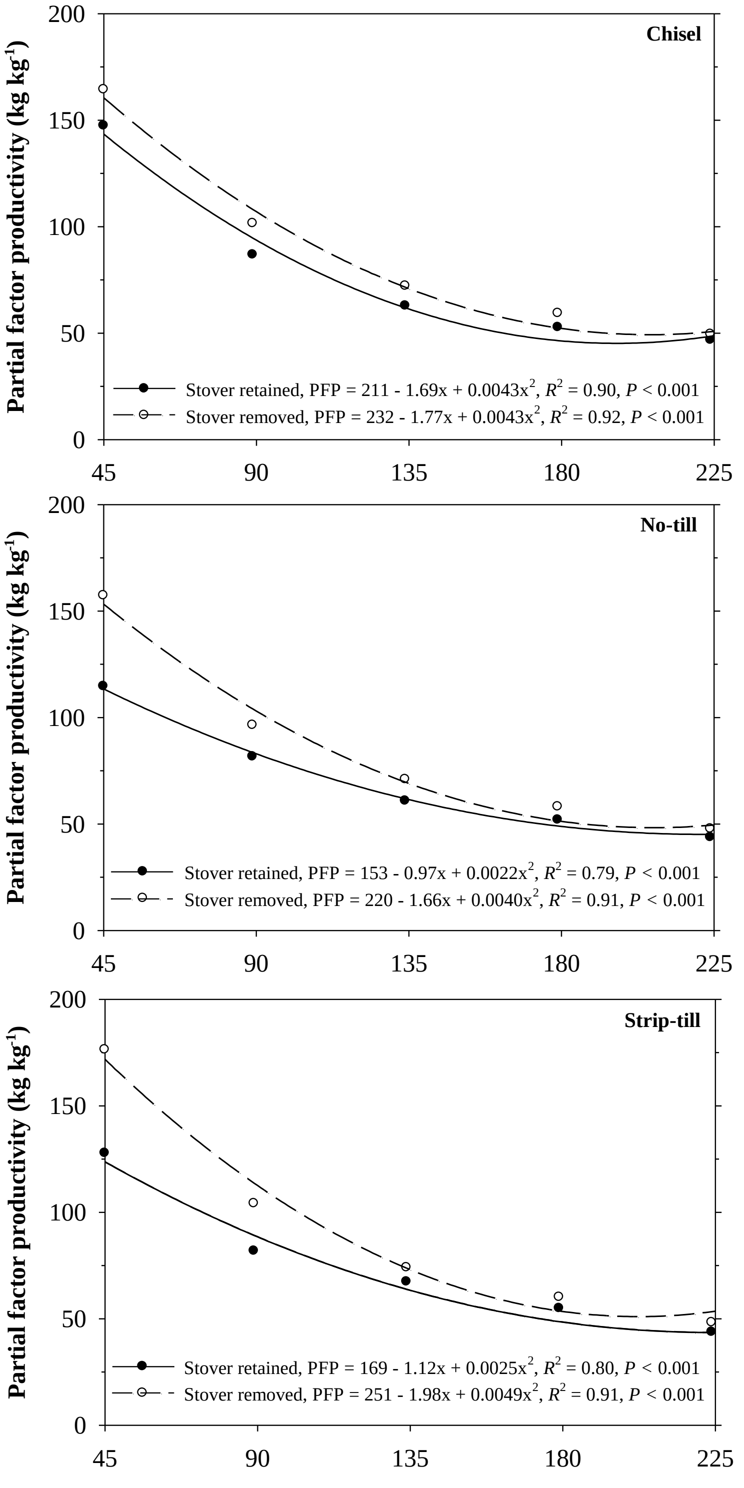

Figure 3.6. Response of partial factor productivity (PFP) to fertilizer N rate as affected by stover management and tillage system, averaged across years and sites.

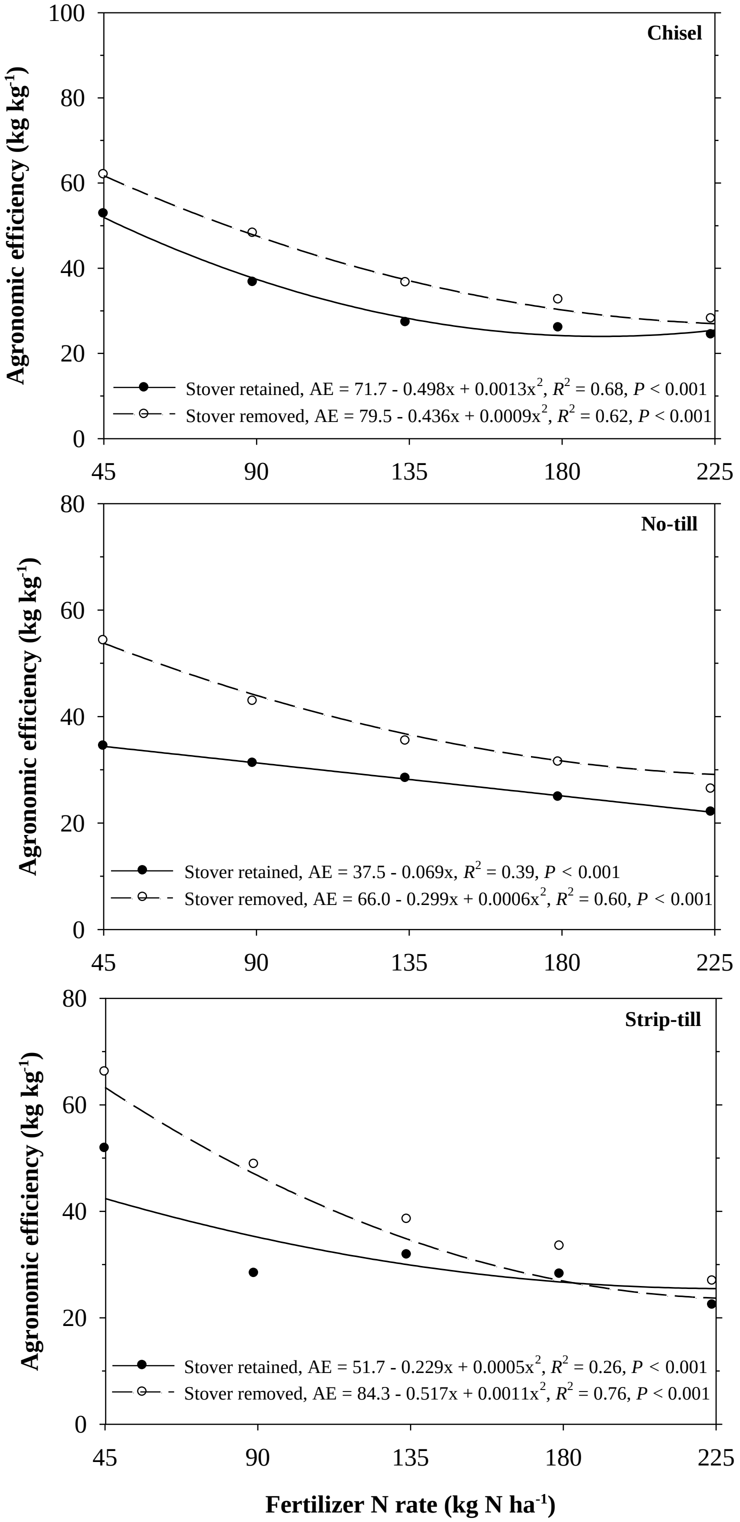

Figure 3.7. Response of agronomic efficiency (AE) to fertilizer N rate as affected by stover management and tillage system, averaged across years and sites.

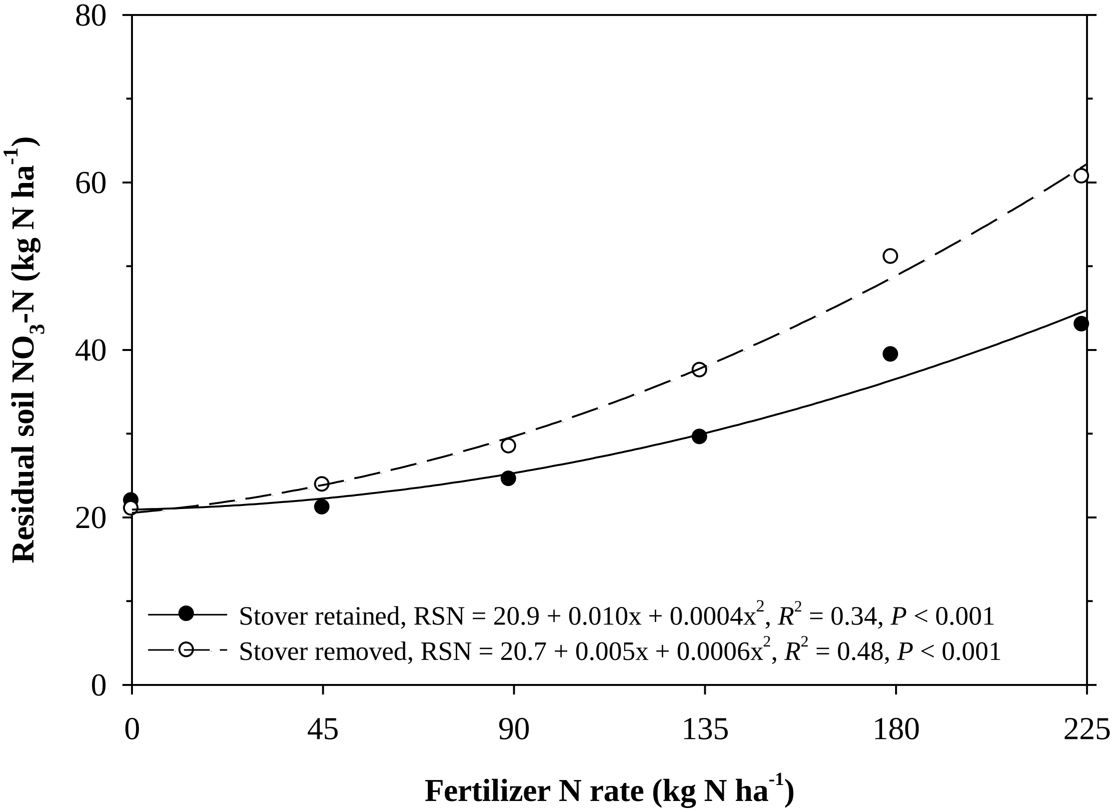

Fig. 3.8. Response of residual soil NO_3-N (RSN) to a depth of 1.2 m to fertilizer N rate as affected by stover management, averaged across years, sites, and tillage systems.

CHAPTER 4: CELLULOSIC BIOMASS AND ETHANOL PRODUCTION RESPONSE TO STOVER, TILLAGE, AND NITROGEN MANAGEMENT

MATERIALS AND METHODS

Research plots were established as a split plot arrangement in a randomized complete block design with four replications in the fall of 2008 following corn in fields with subsurface tile drainage at University of Minnesota Research and Outreach Centers near Lamberton (44°14′ N, 95°18′ W) and Waseca, MN (44°3′ N, 93°31′ W). Soils were a Knoke loam (fine, smectitic, calcareous, mesic Mumulic Vertic Endoaquolls) at Lamberton and a Nicollet-Webster clay loam complex (fine-loamy, mixed superactive, mesic Aquic Hapludolls and fine-loamy, mixed, superactive, mesic Typic Endoaquolls, respectively) at Waseca. Main plots were a factorial arrangement of stover management and tillage system, while split plots were fertilizer N rate. Plots remained in the same location throughout the duration of the study, and were 6.1 m wide (eight 76-cm rows) by 7.0 and 9.2 m long at Waseca and Lamberton, respectively.

Stover and tillage treatments were initially applied in the fall of 2008 and performed annually following grain harvest. The stover management treatments involved retaining or removing stover. When removed, stover was chopped, raked, and baled. While this methodology did not fully remove all cellulosic material, it was used to emulate probable removal rates by producers using field-scale equipment. Stover was not chopped in plots where retained. Tillage was then performed within 5 d of stover management. The three tillage system treatments were chisel-till (CT), strip-till (ST), and no-till (NT). Chisel-till was a chisel operation to a depth of 20 cm in the fall, followed by field cultivation to a depth of 9 cm in the spring prior to planting. Strip-tillage occurred between the previous year's corn rows in the fall with an Orthman 1tRIPr (Orthman Manufacturing, Inc., Lexington, NE) at Lamberton and a Redball strip-till unit (Will-Rich, LLC, Wahpeton, ND) at Waseca. These units were equipped with mole knives that tilled a 20-cm wide band to a depth of 20 cm and created a berm 8 cm in height.

Plots at both sites were planted in late April to early May in 76-cm rows to a depth of 5 cm at 84,000 seeds ha^{-1} with a planter equipped with row cleaners. Corn within the NT and ST treatments was planted 38 cm away from the previous year's rows. DEKALB DKC52-59, a 102-d relative maturity hybrid with transgenic resistance to glyphosate [potassium *N*-(phosphonomethyl)glycine], European corn borer (*Ostrinia nubilalis* [Hübner]), and corn rootworm (*Diabrotica spp.*), was used in all site-years. Starter N and P were applied as starter fertilizer at planting using ammonium polyphosphate $[(NH_4)_3HP_2O_7 + NH_4H_2PO_4]$ at 6.5 kg N ha^{-1} and 9.6 kg P ha^{-1}.

Fertilizer N treatments were broadcast applied by hand without incorporation as ammonium nitrate (NH_4NO_3) within 5 d after planting. Fertilizer N rates were 0, 45, 89, 134, 179, and 224 kg N ha^{-1}. Soil P and K were high or very high according to soil tests and were amended according to University of Minnesota guidelines with triple superphosphate $[Ca(H_2PO_4)_2{\bullet}H_2O]$ and potash (KCl) (Kaiser et al., 2011). Sulfur was applied as gypsum ($CaSO_4{\bullet}2H_20$) at 17 kg S ha^{-1} because S fertilization is recommended in continuous corn and reduced tillage systems in Minnesota (Kaiser et al., 2011).

Plant biomass samples were collected after physiological maturity within 7 d of grain harvest by randomly selecting six plants from non-grain harvest, non-border rows. Plants were cut at the crown, partitioned between the ear and stover (leaves, stalk, and tassel) fractions, and the stover fraction was chopped using a mechanical chipper. Stover will refer to these plant fractions throughout the chapter. Stover and intact ears were then dried at 60°C in a forced-air dryer to a constant weight. Dry ears were shelled and the cobs were retained, while the grain was discarded. Stover and cob fractions were weighed and then ground using a Thomas-Wiley Laboratory Mill (Thomas Scientific, Swedesboro, NJ) equipped with a 2-mm screen and subsampled. Subsamples were analyzed for C concentration with an Elementar Variomax CN analyzer (Elementar, Hanau, Germany). The C content of stover and cob was then calculated using the respective weights and C concentrations.

Polysaccharide component sugars were estimated by near infrared reflectance spectroscopy (NIRS) using prediction equations developed at the University of Minnesota. Dried and ground samples were scanned using a Perten DA 7200 NIR Analyzer (Perten Instruments, Hägersten, Sweden). Analysis of the calibration sample set for cell wall polysaccharide component sugars was performed using the Uppsala Dietary Fiber method (Theander et al., 1995) as described by Lewis et al. (2010). Calibration statistics are available in Table 4.1. Potential cellulosic ethanol yields of stover and cobs were calculated from these polysaccharide component sugar estimates using the U.S. Department of Energy’s theoretical ethanol yield calculator (2009), shown in Eq. 4.1:

$$\text{Theoretical ethanol yield } [(\text{L Mg}^{-1} \text{ dry matter (DM)}] = \qquad [4.1]$$

$$[(\%\ \text{Arabinose} + \%\ \text{Xylose}) \times 737.55] +$$

$$[\%\ \text{Glucose} + \%\ \text{Galactose} + \%\ \text{Mannose}) \times 720.66]$$

where conversion efficiency is assumed to be 100%. Following calculation, theoretical ethanol yields were multiplied by the respective stover or cob biomass yield to determine ethanol yield potential on a per-hectare basis.

Prior to statistical analysis, residuals were evaluated for normality using the UNIVARIATE procedure of SAS (SAS Institute, 2005) and for common variance using scatterplots of residuals vs. predicted values (Kutner et al., 2004). Data were analyzed using the MIXED procedure of SAS at $\alpha = 0.05$. Site, tillage system, stover management, fertilizer N rate, and their interactions were fixed effects. Random effects included year, block (nested within site), and all interactions associated with these effects. Data from Lamberton in 2009 was excluded from the analysis because the weak crop responses to fertilizer N and high residual NO_3-N levels in the fall of 2009 in this site-year indicated considerable residual NO_3-N carryover from the 2008 to 2009 growing seasons. This decreased certainty that responses in this site year were a result of treatment effects. The amount of total random variation associated with year and its interactions with fixed effects was determined from covariance parameter estimates. When the main effect of fertilizer N rate or its interactions with fixed effects were significant, regression analysis was performed. Linear and quadratic regression was performed using the MIXED procedure of SAS at $\alpha = 0.05$ (SAS Institute, 2005). Quadratic-plateau regression was performed using the NLIN procedure of SAS at $\alpha = 0.05$ (SAS Institute, 2005). The best-fit regression model was selected based on its ability to produce the smallest model-fit residuals when compared to the other regression models. Differences between predicted estimates from different regression models for a given response variable were determined by comparing 95% confidence intervals, when applicable.

RESULTS AND DISCUSSION

Stover Biomass Yield

The main effect of year and its interactions with fixed effects individually accounted for less than 10% of the total random variation associated with stover biomass yield (SBY). This indicates response of SBY to stover management, tillage system, and fertilizer N rate was relatively consistent across years. The response of SBY to fertilizer N rate differed between stover management treatments, as indicated by the significant interaction, but was not affected by tillage system (Table 4.2). The response of SBY to fertilizer N rate was best described by quadratic-plateau regression (Fig 4.1). Removal of stover increased SBY at fertilizer N rates ≤90 kg N ha^{-1} (Fig. 4.1). In the unfertilized control, removing stover increased SBY by 15%. When fertilizer N rates of 45 and 90 kg N ha^{-1} were used with stover removal, SBY increased by 13 and 11%, respectively. No differences in SBY existed between stover management treatments at fertilizer N rates >90 kg N ha^{-1}. The increased SBY with stover removal at fertilizer N rates ≤90 kg N ha^{-1} suggests that plant-available N is greater when stover is removed. This is likely related to increased net N mineralization by either decreased N immobilization (Rice and Smith, 1984; Power et al., 1986b) or increased N mineralization rates (McCarthy et al., 1995; Andraski and Bundy, 2008).

Since the response of SBY to fertilizer N rate differed (Table 4.2), the agronomically optimum N rate (AONR) for SBY maximization decreased from 219 to 158 kg N ha^{-1} with stover removal (Fig 4.1). Depending on tillage system (Chapter 2), SBY maximization required 47 to 63 kg N ha^{-1} less fertilizer N than the EONR for grain yield when stover was removed. Also, >5 kg N ha^{-1} fertilizer N less fertilizer N was needed when stover was retained. This coincides with Sindelar et al. (2012), who found that fertilizer N rates that maximize SBY were lower than the AONRs for grain yield across several environments in Minnesota.

Stover biomass yield at the AONRs, as predicted by the regression equations, were similar between stover management treatments (6.92 and 6.94 Mg ha^{-1} when retained and removed, respectively). These SBY estimates are lower than those reported by Shinners and Binversie (2007) in Wisconsin (7.6 to 11.2 Mg ha^{-1}) and Sindelar et al. (2012) in several environments in Minnesota (5.8 to 9.8 Mg ha^{-1}). However, they were greater than those reported by Avila-Segura et al. (2011) in Wisconsin (7.2 Mg ha^{-1}), and were within the range reported by Wilhelm et al. (2011) across several states (5.3 to 7.6 Mg ha^{-1}). This demonstrates that SBY can vary across the Corn Belt and is likely dependent upon several agronomic factors such as water availability, air temperature, hybrid genetics, and various soil characteristics (e.g., organic matter content, soil texture).

Cob Biomass Yield

The main effect of year and its interaction with site accounted for 34 and 19% of the total random variation associated with cob biomass yield (CBY). The cumulative amount of variation in CBY among all other interactions with year was only 12%. This indicates the response of CBY to tillage system, stover management, and fertilizer N rate was relatively consistent among years. Cob biomass yield was affected by fertilizer N rate, but not by tillage system, stover management, or their interactions (Table 4.2). Significant quadratic increases of CBY occurred with increasing fertilizer N across sites

(Fig. 4.2). This response agrees with Varvel and Wilhelm (2008a), Halvorson and Johnson (2009), and Sindelar et al. (2012). Cob biomass yield was 0.83 Mg ha^{-1} with no fertilizer N, but increased by 69% to 1.41 Mg ha^{-1} with 224 kg N ha^{-1} fertilization. These yields are generally lower than those reported by Halvorson and Johnson (2009) in Colorado and Sindelar et al. (2012) in Minnesota, but are similar to those reported by Varvel and Wilhelm (2008a) at a rain-fed site in Nebraska, by Wilhelm et al. (2011) across several states, and by Avila-Segura et al. (2011) in Wisconsin. Unlike SBY, CBY was not maximized within the range of fertilizer N rates used in this study. While not quantified, it is probable that more fertilizer N was needed to maximize CBY in this study when compared to the EONRs for grain yield (Chapter 2). This is supported by Sindelar et al. (2012), who observed that the AONRs for CBY were greater than the AONRs for grain yield in five of seven N-responsive environments.

Cob/Stover Ratio

The main effect of year accounted for 48% of the total random variation associated with the cob/stover ratio (CSR). All interactions among year and the fixed effects accounted for only 10% of the total random variation in CSR. The CSR was affected by fertilizer N rate, and the response was consistent across tillage systems and stover management treatments (Table 4.2). The CSR increased linearly as fertilizer N rate increased (Fig. 4.3); and the increase of CSR agrees with Halvorson and Johnson (2009) in Colorado and Texas. A weak linear relationship between fertilizer N rate and CSR did exist ($r^2 = 0.13$; $P = 0.008$), likely because of the large amount of random variation among years. The CSR was 0.177 with no fertilizer N application, but was 0.208 at 224 kg N ha^{-1} application. These CSRs generally fall within the range of those calculated from data reported by Shinners and Binversie (2007) and Sindelar et al. (2012), but are lower than the CSRs calculated from data from Avila-Segura et al. (2011) and Wilhelm et al. (2011). Cobs exhibited a greater response to fertilizer N rate than stover (Fig. 4.3). Thus, it is likely inaccurate to assume that cobs represent a constant proportion of aboveground cellulosic, particularly if using this type of ratio for estimating the amount of cobs available for removal for cellulosic ethanol production.

Stover Carbon

The main effect of year accounted for 36% of the total random variation associated with stover carbon concentration (SCC). Interactions among year and the fixed effects accounted for less than 7% of the total random variation in SCC. Thus, the response of SCC to tillage system, stover management, and fertilizer N rate was relatively consistent among years. Stover carbon concentration increased as fertilizer N rate increased, but the response to fertilizer N rate differed between sites (Table 4.2; Fig 4.4). At Lamberton, SCC increased quadratically as fertilizer N rate increased to 204 kg N ha^{-1}, and was 430 and 447 g kg^{-1} at fertilizer N rates of 0 and ≥204 kg N ha^{-1}, respectively. At Waseca, SCC increased quadratically from 426 g kg^{-1} with no fertilizer N and was not maximized within the range fertilizer N rates used in this study. The range of these concentrations parallels those from Duguid et al. (2009), who reported that C concentration of stover components (husks, leaves, and stalks) ranged from 433 to 447 g kg^{-1}. Similarly, Johnson et al. (2010) reported C concentrations of 428 and 435 g kg^{-1} for stover above and below the ear, respectively, across several states.

For stover carbon content (SCT), year and its interaction with site accounted for 9 and 14% of the total random variation, respectively. Like SCC, SCT increased as fertilizer N rate increased, but the response of SCT to fertilizer N rate differed between stover management treatments (Table 4.2; Fig. 4.5). Regardless of stover management, quadratic-plateau regression best described the response of SCT to fertilizer N rate. This response was relatively similar to the responses observed for SBY (Fig. 4.l), as SCT was greater with stover removal at fertilizer N rates ≤45 kg N ha^{-1} (Fig. 4.5). With no fertilizer N, SCT was 24% greater with stover removal. However, no differences existed between stover management treatments at fertilizer N rates >90 kg N ha^{-1}.

Removal of stover decreased the fertilizer N rate needed to maximize SCT by 20 kg N ha^{-1} (Fig. 4.5). Also, the AONRs for SCT were less than the EONRs for grain yield by 32 to 49 kg N ha^{-1} and >31 kg N ha^{-1} in systems where stover was removed and retained, respectively (Chapter 2). At these fertilizer N rates, SCT was predicted to be 3.01 and 2.95 Mg ha^{-1} when stover was retained and removed, respectively. In comparison, SCT ranged from 1.9 to 2.4 kg C ha^{-1} with no fertilizer N. These responses indicated that SBY had a more dominant impact on SCT than SCC, since the responses of SBY and SCT to fertilizer N rate were both dependent upon stover management, while SCC was not.

Cob Carbon

The main effect of year and its interaction with site accounted for 48 and 14% of the total random variation associated with cob C concentration (CCC), while the cumulative variation of the remaining interactions between the fixed effects and year was

<3%. For cob C content (CCT), the main effect of year and its interaction with site accounted for 44 and 18% of the random variation, respectively, while the remaining cumulative variation of the other interactions among fixed effects and year was 8%. While CCC and CCT varied slightly among years, their responses to tillage system, stover management, and fertilizer N rate were relatively consistent across years.

Cob C concentration increased quadratically as fertilizer N rate increased, but this response differed among tillage systems (Table 4.2, Fig. 4.6). This increase in CCC with fertilizer N agrees with results from Halvorson and Johnson (2009) at two sites in Colorado. Neither the main effect of stover management nor its interactions affected CCC (Table 4.2). Cob C concentration decreased as tillage intensity decreased, but differences among tillage systems diminished as fertilizer N rate increased (Fig. 4.6). With no fertilizer N, CCC was 464.8, 463.2, and 462.8 g C kg^{-1} DM in CT, ST, and NT, respectively. However, as fertilizer N rate increased, differences among tillage systems decreased and were nonexistent with a fertilizer N rate of 224 kg N ha^{-1}. The increased CCC with CT at fertilizer N rates <224 kg N ha^{-1} may have been related to greater net N mineralization. However, as cobs likely relied less on indigenous N as fertilizer N availability increased, these differences among tillage systems decreased.

Cob C content increased quadratically as fertilizer N rate increased (Fig. 4.7). Increases in CCC with increasing fertilizer N rate were also observed by Halvorson and Johnson (2009). Unlike CCC, CCT was not affected by tillage system or its interactions with fertilizer N rate or stover management (Table 4.2). Cob C content was 0.39 Mg C ha^{-1} with no fertilizer N, but increased by 54% to 0.64 Mg C ha^{-1} with 224 kg N ha^{-1} application. Unlike SCT, CCT was not affected by stover management. These results demonstrate that stover management has a more profound effect on the C dynamics of stover than cobs.

Stover Ethanol Yield

The interaction between year and site accounted for 10% of the total random variation associated with stover ethanol yield (SEY), while the remaining interactions between year and the fixed effects accounted for 15%. This indicates the response of SEY to tillage system, stover management, and fertilizer N rate was relatively consistent among years. The quadratic response of stover ethanol yield to fertilizer N rate differed between stover management treatments (Table 4.2; Fig. 4.8). Similar to SBY and SCT, SEY was greater when stover was removed at fertilizer N rates ≤45 kg N ha^{-1}. This response of SEY to fertilizer N rate is similar to that observed for SBY because stover theoretical ethanol yield (STEY) was not affected by any fixed main effect or interaction in this study, and averaged 407 L Mg^{-1} DM. Without fertilizer N, SEY increased by 19% when stover was removed. Differences between stover management treatments decreased as fertilizer N rate increased. At the AONRs, SEY was 2740 and 2829 L ha^{-1} when stover was retained and removed, respectively. These ethanol yields fell within the lower range of those reported across several environments in Minnesota by Sindelar et al. (2012).

When stover was removed, 13 kg N ha^{-1} more fertilizer N was necessary to maximize SEY when compared to where stover was retained (Fig 4.8). More importantly, 10 to 27 kg N ha^{-1} and >42 kg N ha^{-1} less N was needed to maximize SEY compared to the EONRs for grain yield when stover was removed and retained, respectively. Sindelar et al. (2012) also observed that the AONRs for SEY were similar or less than those for grain yield in several environments across Minnesota. It is likely that SEY will simultaneously be maximized in similar environments when fertilizer N rates that economically optimum grain yield are used.

Cob Ethanol Yield

The main effect of year and its interaction with site accounted for 37 and 15% of the random variation associated with cob ethanol yield (CEY). Random variation among all other interactions between fixed effects and year were less than 6%. Cob ethanol yield was affected by fertilizer N rate, but not by tillage system or stover management (Table 4.2). No fixed effects or interactions affected cob theoretical ethanol yield (CTEY), which averaged 489 L Mg^{-1} DM across all sites, tillage systems, stover management treatments, and fertilizer N rates.

Cob ethanol yield increased quadratically as fertilizer N rate increased (Fig. 4.8). This is similar to reported responses from across Minnesota by Sindelar et al. (2012). The response of CEY to fertilizer N rate was substantial. When no fertilizer N was applied, CEY was 410 L ha^{-1}, but increased to 662 L ha^{-1} with 224 kg N ha^{-1} application. Although CEY was agronomically maximized within the range of fertilizer N rates used in the study (223 kg N ha^{-1}), CEY may not consistently be maximized when the EONRs for grain yield are used. In this study, EONRs for grain yield ranged from 205 to 222 kg N ha^{-1} when stover was removed (Chapter 2). However, CEY at these EONRs for grain yield would still be within ≤10 L ha^{-1} of cellulosic ethanol at to the AONR for CEY.

CONCLUSIONS

Stover and cob biomass, C, and ethanol yields all increased as fertilizer N rate increased. However, the magnitude of their responses and their interaction with stover management or tillage system were dependent on the plant fraction. In general, the responses of stover biomass, C, and ethanol yields to fertilizer N rate differed with stover management. Carbon concentration was the only cob property affected by an interaction. This shows that stover properties are more sensitive to stover management than cob properties. This may be related to the time of the growing season where the majority of the growth and development of these fractions occurs. Corn stover production generally begins earlier in the growing season than cob production (Abendroth et al., 2011), and is thus potentially affected more by soil temperature. This timing can limit growth and biomass production when low temperatures occur (Fortin and Pierce, 1990; Stone et al., 1999). These relationships between growth and time of growing season may explain the differing responses.

Since the amount of biomass and C produced by stover depends on fertilizer N rate and whether stover is retained or removed, recommendations for removing specific rates of cellulosic material (e.g., 50%) may not be appropriate across all field scenarios. Based on estimates of C inputs needed to maintain soil organic C (SOC) from 24 sites, mostly in the U.S., , an average of 2.2 Mg C ha^{-1} of aboveground C would need to be returned to the soil to maintain SOC across a range of cropping systems (Johnson et al., 2006). For example, if stover and/or cobs were to be removed from a cropping system that was solely relying on indigenous N and stover was not previously harvested, less than 5% of cellulosic material could theoretically be removed. In comparison, if stover removal occurred in a similar field with a fertilizer N rate of 180 kg N ha^{-1}, 40% of cellulosic material could theoretically be removed without jeopardizing SOC. These results and comparisons indicate the amount of C produced by stover is fluid and depends on crop management decisions, particularly fertilizer N rate. It also emphasizes that stover removal recommendations should account for the amount of C that needs to be retained to maintain SOC and the amount that is contained in stover and cobs. However, the results from this study suggest that removal of only cobs was appropriate across all fertilizer N rates without endangering SOC in any tillage system at either site, based on estimates from Johnson et al. (2006).

Finally, these results suggest that SEY, which is the dominant fraction of total cellulosic ethanol, can be maximized at fertilizer N rates that are less than the EONRs for grain yield. This is important because fertilizer N rates will not require adjustment to maximize theoretical cellulosic ethanol yield potential. While CEY may not be consistently maximized at the EONRs for grain yield, CEY potentially lost when the EONRs for grain yield are used under these soil and climatic conditions should be relatively minor (<10 L ha^{-1}).

Table 4.1. Calibration statistics from near infrared reflectance spectroscopy (NIRS) for corn stover and cob cell wall components.

Cell wall component	Mean	Range	SE_{cv}†	*R*
	-------- g kg^{-1} dry matter --------			
Klason lignin	116	32-179	13.6	0.76
Arabinose	32	16-50	3.8	0.54
Xylose	213	131-314	11.9	0.92
Rhamnose	0.91	0.30-1.50	0.25	0.33
Glucose	294	200-361	11.9	0.87
Galactose	11	6-21	1.4	0.76
Mannose	5.9	3.0-11	0.55	0.85
Uronic acids	23	16-29	1.7	0.52

†SE_c: Standard error of cross validation.

Table 4.2. Tests of fixed effects for stover biomass yield (SBY), cob biomass yield (CBY), cob-stover ratio (CSR), stover C concentration (SCC), stover C content (SCT), cob C concentration (CCC), cob C content (CCT), stover theoretical ethanol yield (STEY), stover ethanol yield (SEY), cob theoretical ethanol yield (CTEY), and cob ethanol yield (CEY).

Fixed source of variation	SBY	CBY	CSR	SCC	SCT	CCC	CCT	STEY	SEY	CTEY	CEY
Site (S)	0.88	0.46	0.29	0.21	0.88	0.72	0.41	0.22	0.67	0.27	0.48
Tillage system (T)	0.19	0.47	0.21	0.54	0.21	0.19	0.41	0.98	0.25	0.25	0.45
Stover management (R)	0.24	0.28	0.51	0.19	0.23	0.27	0.32	0.31	0.24	0.36	0.33
Fertilizer N rate (N)	0.002	<0.001	0.003	0.001	<0.001	0.01	<0.001	0.88	0.001	0.07	<0.001
S × T	0.43	0.33	0.89	0.54	0.39	0.92	0.30	0.65	0.55	0.97	0.36
S × R	0.47	0.74	0.77	0.46	0.61	0.62	0.84	0.95	0.53	0.69	0.89
S × N	0.96	0.33	0.39	0.01	0.64	0.81	0.68	0.60	0.98	0.71	0.77
T × R	0.11	0.19	0.36	0.58	0.17	0.86	0.33	0.48	0.12	0.30	0.31
T × N	0.30	0.19	0.31	0.20	0.29	0.04	0.13	0.39	0.26	0.25	0.25
R × N	0.05	0.83	0.16	0.15	0.04	0.61	0.94	0.20	0.04	0.68	0.99
S × T × R	0.18	0.17	0.18	0.25	0.14	0.36	0.24	0.44	0.16	0.87	0.25
S × T × N	0.37	0.14	0.27	0.16	0.45	0.24	0.11	0.77	0.42	0.24	0.16
S × R × N	0.29	0.79	0.35	0.69	0.30	0.44	0.63	0.75	0.36	0.43	0.77
T × R × N	0.65	0.53	0.95	0.40	0.74	0.35	0.69	0.81	0.84	0.38	0.77
S × T × R × N	0.63	0.36	0.76	0.19	0.69	0.59	0.20	0.22	0.56	0.58	0.27

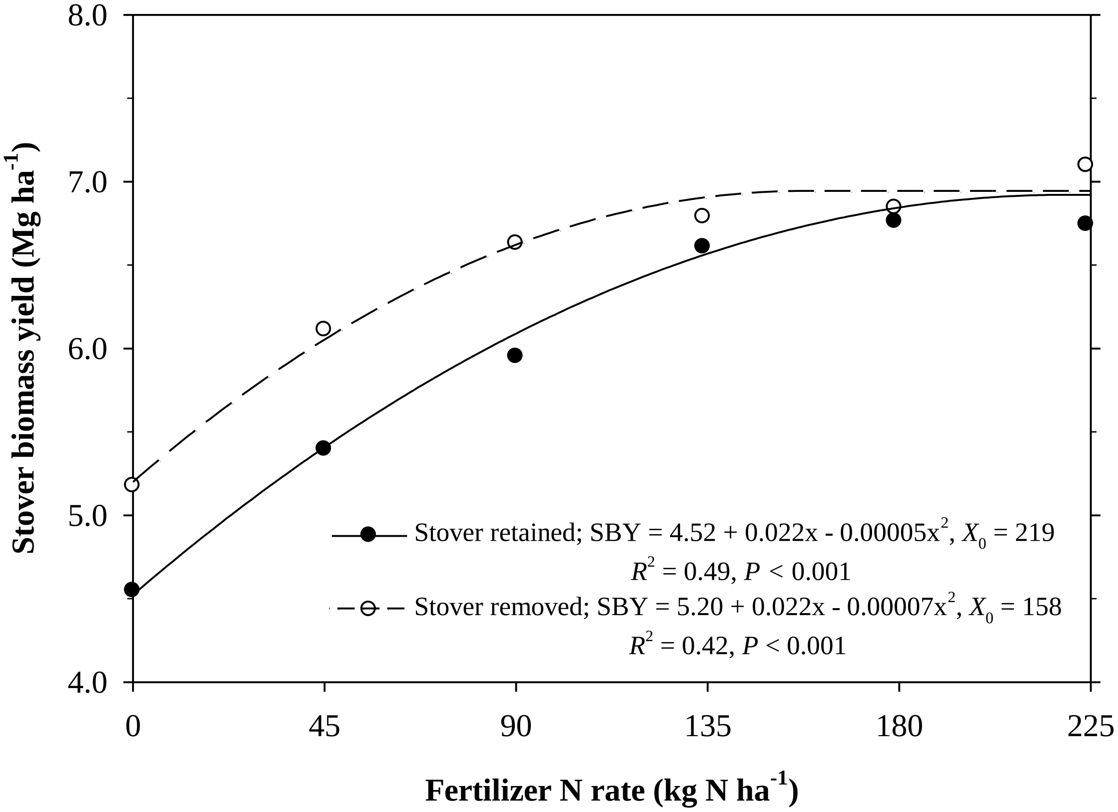

Fig. 4.1. Response of stover biomass yield (SBY) to fertilizer N rate as affected by stover management, averaged across sites and tillage systems.

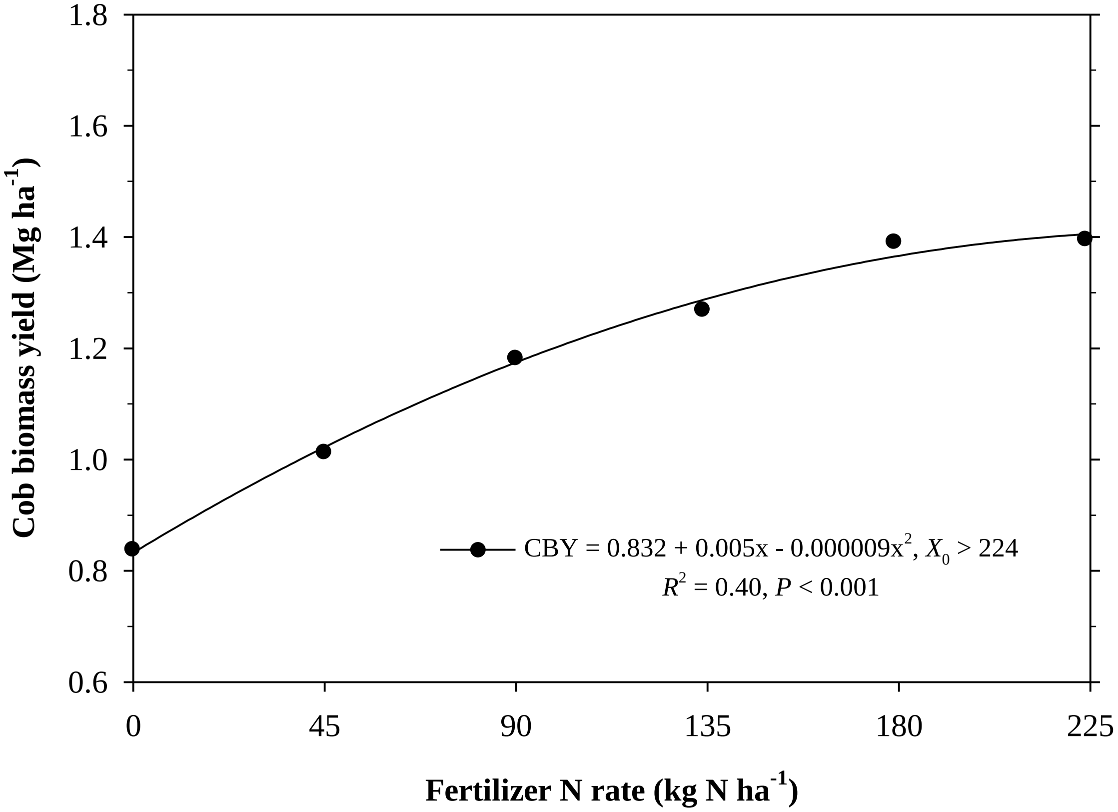

Fig. 4.2. Response of cob biomass yield (CBY) to fertilizer N rate, averaged across sites, stover management treatments, and tillage systems.

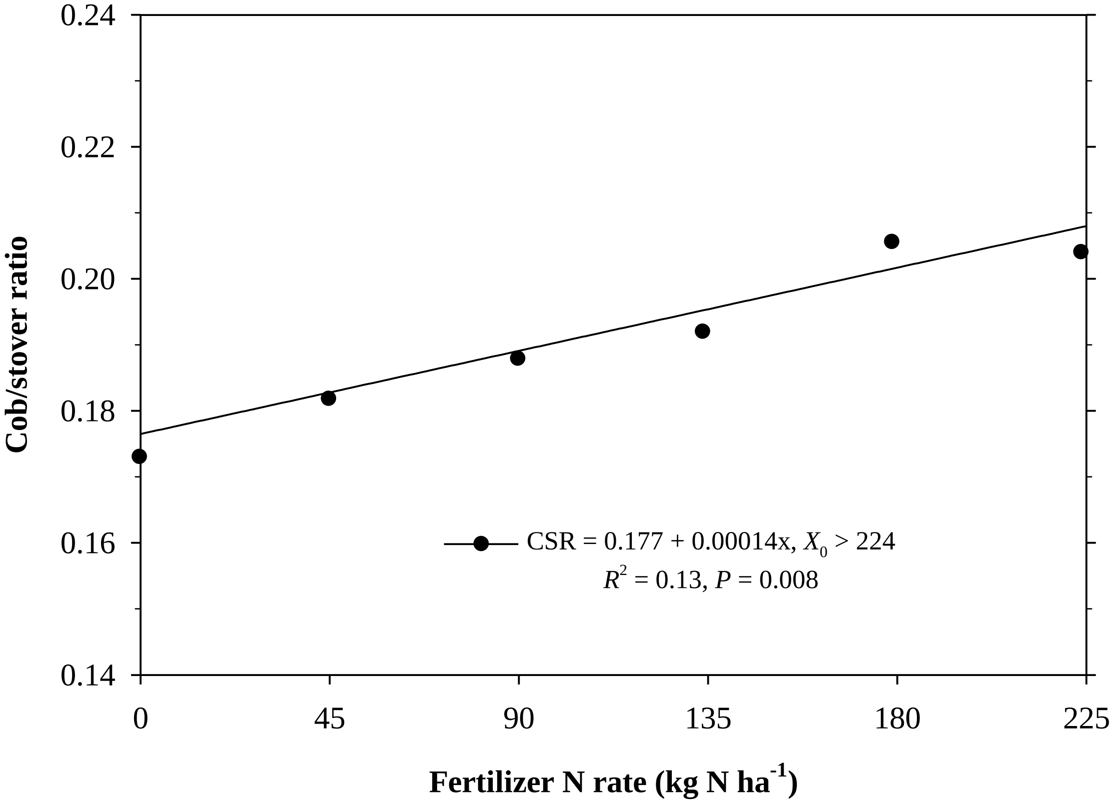

Fig. 4.3. Response of cob/stover ratio (CSR) to fertilizer N rate, averaged across sites, stover management treatments, and tillage systems.

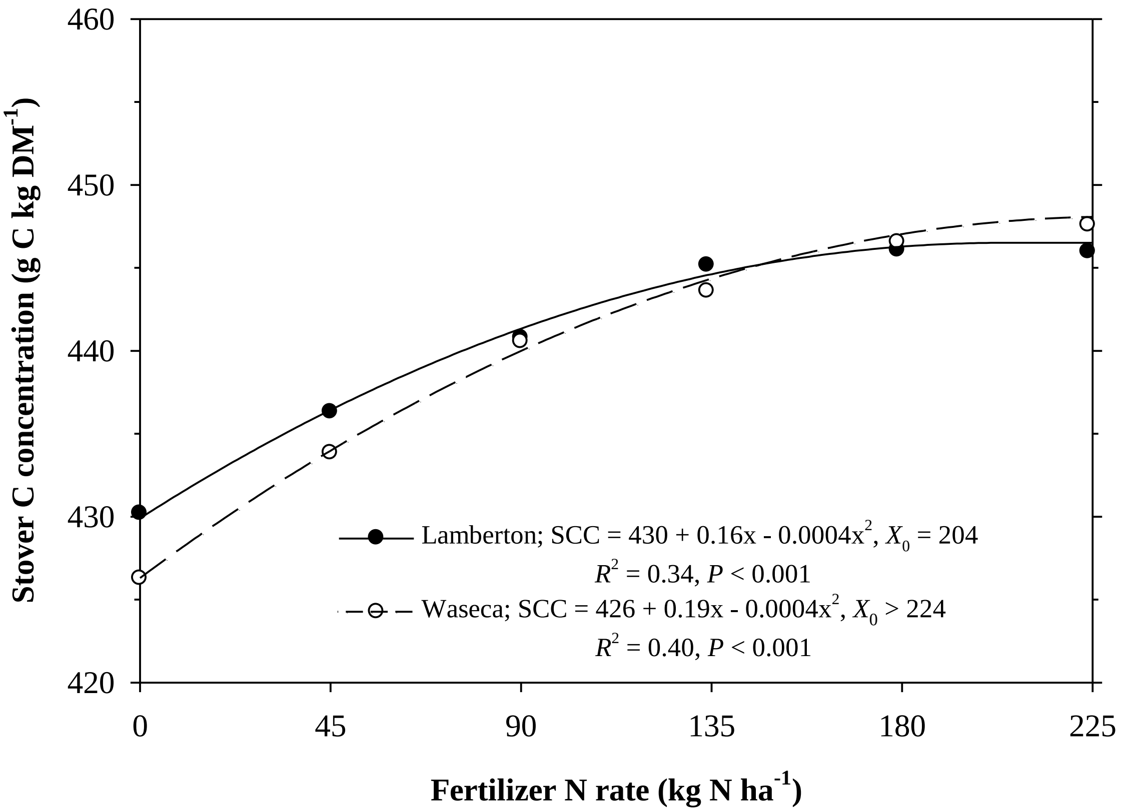

Fig. 4.4. Response of stover C concentration (SCC) to fertilizer N rate as affected by stover management, averaged across sites and tillage systems.

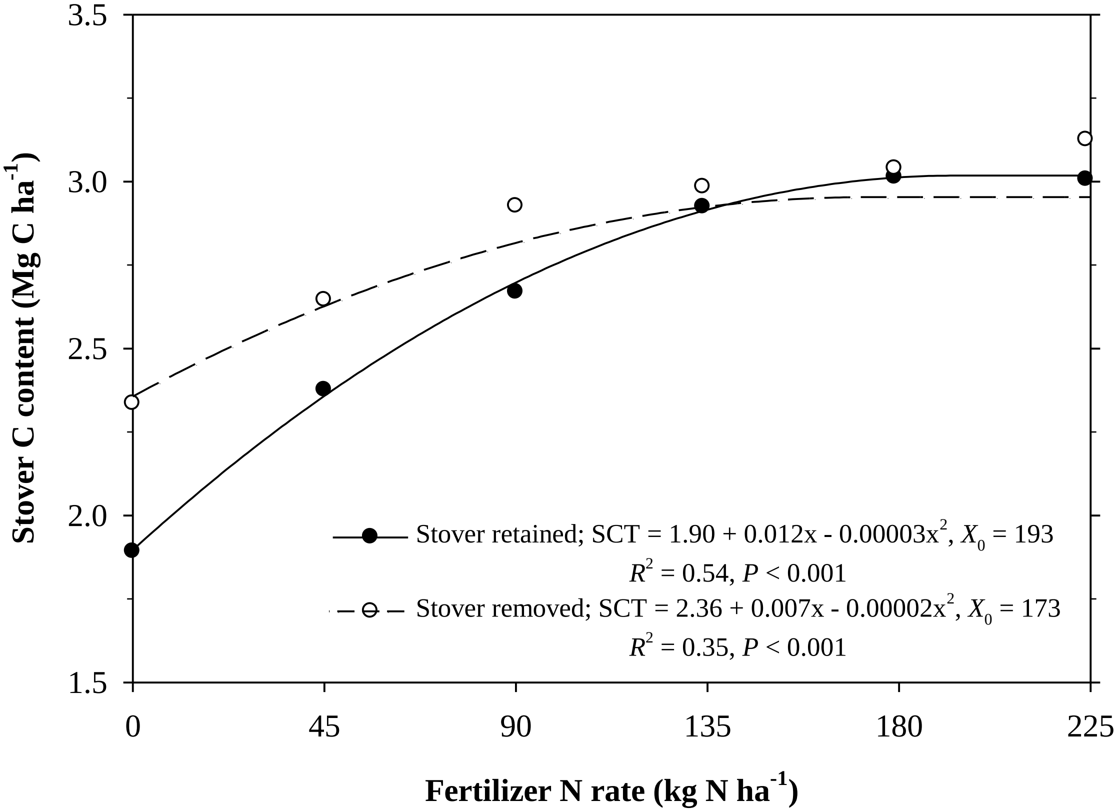

Fig. 4.5. Response of stover C content (SCT) to fertilizer N rate as affected by stover management, averaged across sites and tillage systems.

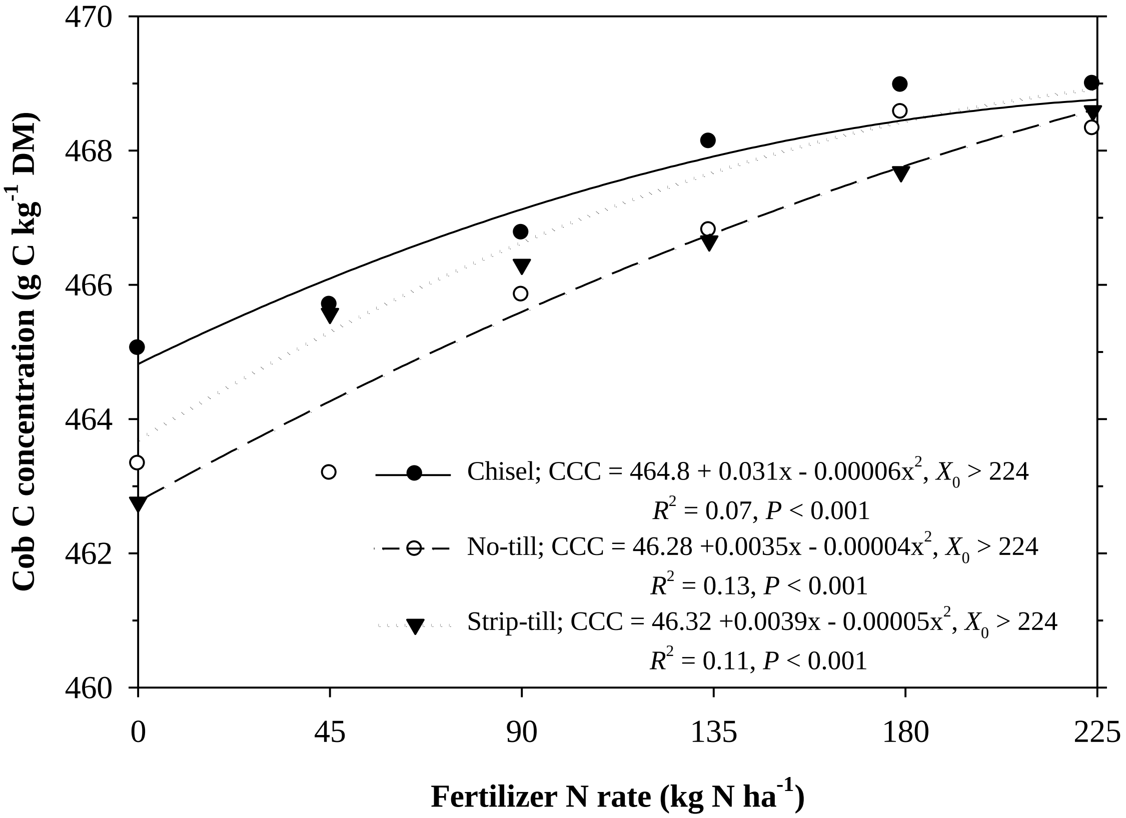

Fig. 4.6. Response of cob C concentration (CCC) to fertilizer N rate as affected by tillage system, averaged across sites and stover management treatments.

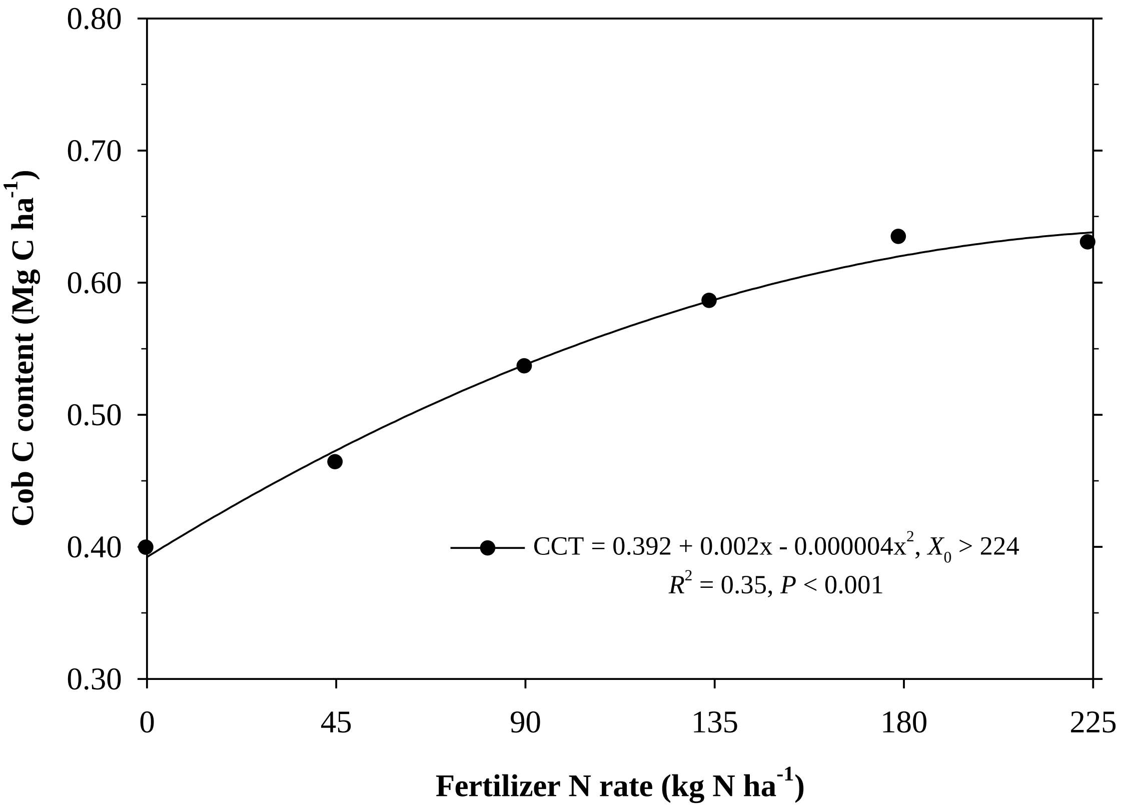

Fig. 4.7. Response of cob C content (CCT) to fertilizer N rate, averaged across sites, stover management treatments, and tillage systems.

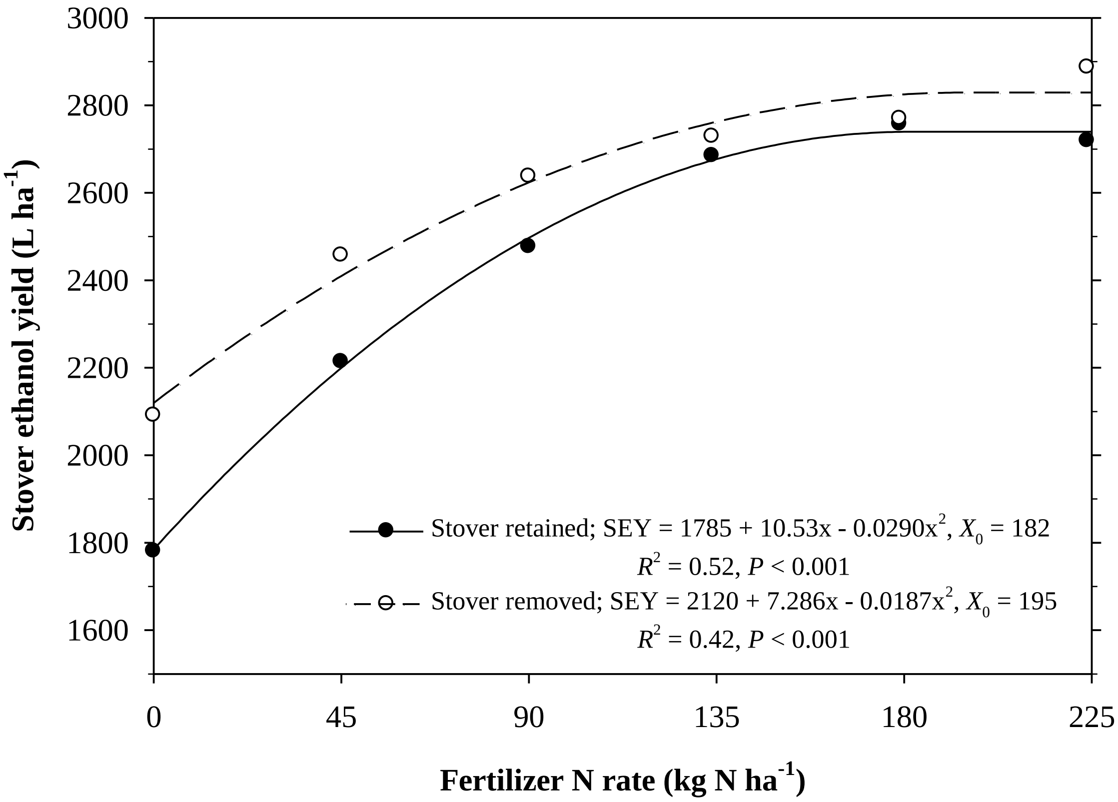

Fig. 4.8. Response of stover ethanol yield (SEY) to fertilizer N rate as affected by stover management, averaged across sites and tillage systems.

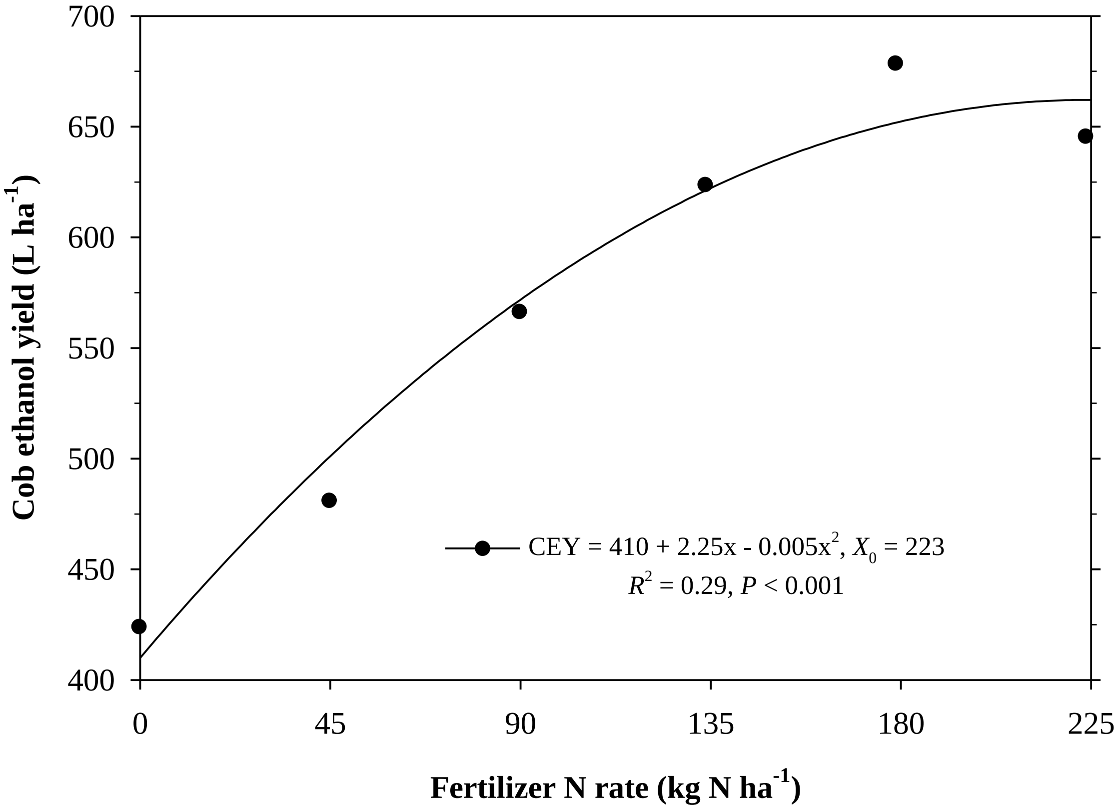

Fig. 4.9. Response of cob ethanol yield (CEY) to fertilizer N rate, averaged across sites, stover management treatments, and tillage systems.

CHAPTER 5: EFFECT OF STOVER, TILLAGE, AND NITROGEN MANAGEMENT ON TOTAL AND LABILE SOIL ORGANIC MATTER

MATERIALS AND METHODS

Research plots were established in the fall of 2008 in a continuous corn (CC) cropping system on a subsurface tile drained Nicollet-Webster clay loam soil complex (fine-loamy, mixed superactive, mesic Aquic Hapludolls and fine-loamy, mixed, superactive, mesic Typic Endoaquolls) at the University of Minnesota Southern Research and Outreach Center near Waseca, MN (44°3′ N, 93°31′ W). Prior to the establishment of the study, the site was a 2-yr corn-soybean [*Glycine max* (L.) Merr] (CS) rotation managed with either or moldboard plow or chisel tillage (CT) for >50 yr. The experimental design was a split plot arrangement in a randomized complete block design with four replications. Plots remained in the same location throughout the study. Main plots were a factorial arrangement of stover management (retained or removed) and tillage system [CT, no-till (NT), and strip-till (ST)]. Split plots were fertilizer N rate (0 and 224 kg N ha^{-1}) and were 6.1 m wide (eight 76-cm rows) and 7.0 m long.

Research protocol was consistent throughout the duration of the study. Stover management and tillage was performed annually following grain harvest. In plots where stover was removed, standing stalks were chopped with a stalk chopper, raked, and baled with field-scale equipment in order to emulate probable removal rates by producers. Stalks were not chopped in plots where stover was retained. Tillage then occurred within 5 d after stover treatments. The CT treatment was a chisel operation to a depth of 20 cm in the fall, followed by spring field cultivation to a depth of 9 cm in the spring prior to planting. Strip-tillage consisted of tilling a 20-cm wide band to a depth of 20 cm with an Orthman 1tRIPr (Orthman Manufacturing, Inc., Lexington, NE), which created a berm 8 cm in height. DEKALB DKC-5259, a 102-d relative maturity hybrid, was planted 7 cm deep at 84,000 seeds ha^{-1} in late April or early May with a commercial planter equipped with row cleaners. Corn in NT and ST was planted 38 cm away from the previous year's rows. Starter N and P fertilizer as ammonium polyphosphate [$(NH_4)_3HP_2O_7$ + $NH_4H_2PO_4$] was applied in the furrow simultaneously with the seed at planting at 6.5 kg N ha^{-1} and 9.6 kg P ha^{-1}, respectively. Fertilizer N treatments were broadcast applied by hand without incorporation within 5 d after planting using ammonium nitrate (NH_4NO_3). Soil-test P and K levels were generally high or very high, and were amended with triple superphosphate [$Ca(H_2PO_4)_2{\bullet}H_2O$] and potash (KCl) as needed according to University of Minnesota guidelines (Kaiser et al., 2011). Sulfur was broadcast applied annually before planting at 17 kg S ha^{-1} using gypsum ($CaSO_4{\bullet}2H_2O$).

Baseline soil samples for soil bulk density (BD), soil organic C (SOC) and N (TN), and particulate organic matter C (POM-C) and N (POM-N) were collected in the fall of 2008 prior to stover management and tillage treatments. Three cores that were 3.8 cm in diameter were sampled from non-trafficked interrows with a hydraulic probe to a depth of 60 cm from all main plots. Cores were divided into 0- to 5-, 5- to 15-, 15- to 30-, and 30- to 60-cm depth increments and stored at 4°C to limit microbial activity until processed. Following grain harvest in 2011, soil samples were collected from subplots through the same procedure as baseline sampling, but instead two cores were sampled from each subplot.

Following soil sampling, whole samples were weighed and homogenized. Approximately 30 g of soil was obtained from each sample, weighed, and dried at 105°C for 24 h to determine gravimetric water content. These water contents were used to calculate BD through the core method (Grossman and Reinsch, 2002). Samples were then manually sieved through 8 and 4.75 mm sieves. Organic matter fragments unable to pass through the respective sieve were removed by hand. Samples were air dried for 1 wk, processed with a mortar and pestle to pass through a 2-mm screen, and analyzed for SOC and TN using the dry combustion procedure (Nelson and Sommers, 1996) with an Elementar variomax CN analyzer (Elementar, Hanau, Germany). Carbon estimates obtained from this procedure were assumed to be equal to total C because soil pH of baseline samples was below 7.1 (Al-Kaisi et al., 2005a). Particulate organic matter was fractionated as soil organic matter (SOM) between 53 and 2000 μm. The upper limit of this size range was achieved through the sieving procedure previously mentioned. The lower limit was achieved using the wet sieving method with 5 g L^{-1} sodium hexametaphosphate and water described by Marriott and Wander (2006), except deionized water was substituted for tap water. After sieving, POM samples were dried at 50°C for 24 h, weighed, ground with a mortar and pestle to a powdery consistency, and analyzed for C and N by combustion with an Elementar variomax CN analyzer.

Total mass of soil and POM C and N pools was determined from respective concentrations and soil BD values. Changes in respective soil properties were then calculated and analyzed through a repeated measures analysis with the MIXED procedure in SAS at $\alpha = 0.10$, with depth serving as the repeated measurement. Stover management, tillage system, fertilizer N rate, depth, and their interactions were fixed effects. Block and its interactions were random effects. Since the improper selection of a covariance structure can negatively affect estimates and pairwise comparisons (Littell et al., 1998), several structures were analyzed, and the structure that produced the smallest criterion estimates was selected (Littell et al., 2006). Mean comparisons were made using Fisher's protected LSD test, $\alpha = 0.10$.

RESULTS AND DISCUSSION

Soil Bulk Density

Following 3 yr of management, Δ soil BD was positive in most stover management × tillage system × depth combinations (Table 5.1; Fig. 5.1). While adoption of reduced or NT systems has been shown to increase soil BD (Mahboubi et al., 1993; Dam et al., 2005; Christopher et al., 2009), the positive Δ soil BD within CT in this study was somewhat unexpected. Sustained management with field-scale equipment over the duration of the study may have contributed to these increases (Soane, 1990). Interactions among stover management, tillage system, and depth were significant for the Δ soil BD (Table 5.2). The Δ of soil BD was not affected by fertilizer N rate. This is supported by Clapp et al. (2000), Liebig et al. (2002), and Dolan et al. (2006). Removal of stover only influenced Δ soil BD within NT and its effects were solely within the surface 15 cm depths, as no differences existed in the 15- to 30- and 30- to 60- cm depths (Fig. 5.1). The stratification in differences was not unexpected because others have reported that the greatest response of soil BD to stover or tillage management is often in near-surface measurements. This is because significant decomposition and incorporation is usually necessary in order to cause differences at lower depths (Skidmore et al., 1986). Within NT, stover removal increased Δ soil BD by 0.26 and 0.14 Mg m^{-3} in the 0- to 5- and 5-15-cm depths, respectively. This agrees with Blanco-Canqui et al. (2006a), who reported effects of stover removal on soil BD within NT were detectable as soon as two months following removal. Clapp et al (2000) and Dolan et al. (2006) observed decreases in soil BD with stover removal in the 0- to 5-cm depth within NT after 13 and 23 years, respectively, in Minnesota. These results differ from findings by Karlen et al. (1994), who reported no soil BD changes with stover removal in Iowa.

The response of Δ soil BD to tillage system depended on depth and stover management (Table 5.1). When retained, differences in Δ soil BD were only in the 0- to 5-cm depth, as Δ soil BD was greater within NT than within CT (Fig. 5.1). The Δ of soil BD within ST was similar to Δ soil BD within CT and NT in the 0- to 5-cm depth when stover was retained. No differences in Δ soil BD existed among tillage systems for any depths below 5 cm. This is consistent with other reported findings in cereal grain cropping systems (Christopher et al., 2009; Presley et al., 2012). When stover was removed, tillage effects on Δ soil BD were more evident. Removal of stover within ST and NT resulted in Δ soil BDs that were greater than CT in the 0- to 5-cm depth. This may have been caused by the soil surface’s increased susceptibility to particle disruption/detachment and surface compaction since surface stover coverage and subsequent soil protection is greatly reduced when stover is removed (Wilhelm et al. 2004; Blanco-Canqui et al., 2006a). Blanco-Canqui et al. (2006a) reported that stover removal also increases cone index, an indicator of surface compaction. In the 5- to 15-cm depth, Δ soil BD only differed between CT and NT with stover removal. This was the only instance where stover or tillage management affected soil BD below the 0- to 5-cm depth. This suggests that the cumulative transition from a CT system without stover removal to NT with stover removal may result in soil BD increases below 5 cm in as soon as 3 yr.

Soil Organic Carbon

The effect of stover management on ΔSOC was dependent upon depth, but not tillage system or fertilizer N rate (Table 5.2). A positive ΔSOC occurred following 3 yr of management by 10 and 2% in the 0- to 5- and 5- to 15-cm depths, respectively, from baseline measurements of 18.3 and 36.7 Mg C ha^{-1}, respectively (Table 5.1; Fig. 5.2). The positive ΔSOC supports the hypothesis by Clay et al. (2012) that C is sequestered in surface depths of Upper Midwest soils when corn is grown. These positive changes after short-term management also suggest this soil C sink is not saturated. This means it has the potential to store C until equilibrium with the atmosphere is reached (Six et al., 2002). No Δ in SOC with stover removal occurred in the 15- to 30- or 30- to 60-cm depths. This is supported by other studies that have reported the lack of management effects on SOC beyond 15 cm (Dick, 1983; Dick et al., 1997). The sequestration of SOC associated with retaining stover was not unexpected, as the quantity and type of crop-derived organic material returned to the soil has been shown to influence SOC dynamics (Larson et al., 1972; Varvel, 1994; Halvorson et al., 1999). In comparison, a negative ΔSOC by 14 and 4% occurred with stover removal in the 0- to 5- and 5- to 15-cm depths, respectively. These responses coincide with findings by Allmaras et al. (2004). They observed losses of SOC in the 0- to 30-cm depth by 15 and 9% within CT and NT, respectively, with 200 kg N ha^{-1} fertilization following 13 yr of stover removal, while retaining stover maintained or increased SOC (2 to 5% greater than baseline measurements). Additional studies by Clapp et al. (2000) and Dolan et al. (2006) also reported a reduction of SOC in treatments with stover removal following 13 and 23 yr of CC management.

Tillage system did not affect ΔSOC (Table 5.2). While the lack of response to tillage system agrees with Angers et al. (1995, 1997) and Liang et al. (1998), reviews of tillage studies by Kern and Johnson (1993), Paustian et al. (1997b), and West and Post (2002) concluded that adopting NT sequesters more SOC. The lack of a tillage system effects on ΔSOC in this study may be attributed to the combination of the short duration of the study and high SOC levels at the onset of treatment initiation. West and Post (2002) concluded that observable increases of SOC resulting from a reduced tillage, specifically NT, may not occur for 5 to 10 yr. This hypothesis is supported by Franzluebbers and Arshad (1996). They did not observe differences in SOC with reduced tillage in Canada until 6 yr following adoption and attributed the lack of response within the initial 5 yr to high SOC levels. Another possible reason for the lack of tillage system effects could be related to the fine-textured nature of this soil. It is understood that clay particles physically protect SOC from microbial degradation through either aggregation or mineral/SOM associations (Tisdall and Oades, 1982; Van Veen and Kuikman, 1990; Hassink, 1997; Six et al., 2002). Despite the destructive force of tillage on soil aggregates (Tisdall and Oades, 1982; Balesdent et al., 2000), it does not seem that its short-term usage could overcome this physical protection at levels to invoke detectable differences. Further research would be necessary to understand how soil aggregation is affected by tillage through time under these soil/climatic conditions.

Neither the main effect of fertilizer N rate nor its interactions affected ΔSOC (Table 5.2). The lack of response of ΔSOC to fertilizer N rate agrees with Coulter et al. (2009), but disagrees with Gregorich et al. (1996), Wilts et al. (2004), and Jagadamma et al. (2007, 2008). It should be noted that measurements in the studies where SOC was affected by fertilizer N rate occurred after long-term management (23 to 35 yr). This suggests that the short-term duration of this study (3 yr) may have contributed to the lack of differences in SOC between fertilizer N rates. However, it is hypothesized that differences in SOC between fertilizer N rates will appear with continued N management. Regardless, the responses in this study suggest the increased amount of C input by retaining corn stover has a greater effect on short-term (≤3 yr) SOC dynamics compared to tillage system and fertilizer N rate.

Total Nitrogen

Interactions of depth with the main effects of stover management, tillage system, and fertilizer N rate were observed for ΔTN (Table 5.2). As a result of stover removal, a negative ΔTN by 14% relative to the baseline measurement of 1.44 Mg N ha^{-1} was observed in the 0- to 5-cm depth (Table 5.1; Fig. 5.3A). In contrast, a positive ΔTN by 12% in the 0- to 5-cm depth occurred when stover was retained. Differing TN in the 0- to 5-cm depth with stover management is supported by Karlen et al. (1994) and Dolan et al. (2006). Blanco-Canqui and Lal (2009) observed decreased TN with stover removal in the 0- to 10-cm depth. The change in TN was similar between stover management treatments at depths below 5 cm. While the lack of differences between stover management treatments at depths beyond 5 cm was expected and is documented in the literature, the positive ΔTN in the 5- to 15-cm depth with stover removal was somewhat unexpected. Since corn roots are an important contributor to soil C and N pools (Balesdent and Balbane, 1996; Johnson et al., 2006) and decomposition rates of roots are less than leaves and stems (Johnson et al., 2005), root-derived N may be contributing to the increase. Also, residual NO_3-N increased with stover removal and when fertilizer N rates approached the economically optimum N rates (Chapter 3). This suggests the increase could also be related to greater NO_3-N in the soil profile. It is hypothesized that this positive ΔTN is unsustainable and that TN at these depths will decrease as the duration of stover removal increases.

The effect of tillage on ΔTN was strongly dependent upon depth (Table 5.2). In the 0- to 5-cm depth, use of NT or ST maintained TN while a negative ΔTN by 6% occurred within CT (Fig. 5.3B). In the 5- to 15-cm depth, TN within CT was similar to the baseline measurement. A positive ΔTN by 8 and 15% occurred in the 5- to 15-cm depth within NT and ST, respectively. This coincides with Al-Kaisi et al. (2005b), Dolan et al. (2006), and Blanco-Canqui and Lal (2008). They all observed greater TN within NT compared to other tillage systems. These increases with reduced tillage can probably be attributed to slower SOM decomposition rates resulting from less soil disturbance (Doran, 1987). In the 15- to 30-cm and 30- to 60-cm depths, ΔTN did not differ among tillage systems. This is likely related to the high degree of variability observed within each treatment at each depth, particularly in the 30- to 60-cm depth. The lack of differences in ΔTN agrees with Al-Kaisi et al. (2005a, b). They observed no differences in TN among tillage systems at all depths below 15 cm. However, this differs from findings by Dolan et al. (2006), who observed differences in TN at several depth increments between 15 and 45 cm. Results from this study and others suggests that the effects of tillage system on TN can vary and be soil and climatic dependent (Doran, 1987; Blanco-Canqui and Lal, 2008).

The response of ΔTN to fertilizer N rate differed by depth (Table 5.2). In the 0- to 5-cm depth, ΔTN was similar among stover management treatments, and TN after 3 yr of fertilizer N application was similar to the baseline measurement (Table 5.1; Fig. 5.3C). The lack of response of ΔTN to fertilizer N rate is supported by Dolan et al. (2006) and Coulter et al. (2009). In the 5- to 15-cm depth, a positive ΔTN by 10% occurred with the addition of 224 kg N ha^{-1}. Total N in the 5- to 15-cm depth did not change from the baseline measurement when no fertilizer N was applied. Though Jagadamma et al. (2007) also observed an increase in TN as a function of fertilizer N rate in the 10- to 20-cm and 20- to 30-cm depths, it is unclear why increases occurred in the 5- to 15-cm depth but not in the 0- to 5-cm depth, since soil properties in the surface depth are often the most responsive to management (Blanco-Canqui et al., 2006a; Presley et al., 2012). In the 15- to 30-cm and 30- to 60-cm depths, no ΔTN occurred, and the response was similar between fertilizer N rates. Therefore, despite the interaction with depth, these results suggest that fertilizer N rate does not have a negative effect on TN following 3 yr of CC.

Soil Carbon/Nitrogen Ratio

The reported soil C/N ratios represent the ratios after 3 yr of management. The response of soil C/N ratio to stover management was dependent on depth, as the ratio differed between stover management treatments in the 0- to 5-cm depth, but not in the 5- to 15-cm, 15- to 30-, and 30- to 60-cm depths (Tables 5.2 and 5.3). In the 0- to 5-cm depth, the soil C/N ratio increased from a baseline of 12.7 to 13.4 when stover was retained. The soil C/N ratio did not change from the baseline measurement when stover was removed. These results are similar to findings by Clapp et al. (2000), where soil C/N ratios in the 0- to 15-cm depth within CT and moldboard tillage generally exhibited a greater increase in relation to baseline measurements when stover was retained following 13 yr of CC.

The soil C/N ratio was not affected by tillage system, fertilizer N rate, or their interactions (Table 5.2). The lack of tillage effects on the soil C/N ratio is consistent with Angers et al. (1997) and Al-Kaisi et al. (2005a), but differs from Cambardella and Elliot (1992). Blanco-Canqui and Lal (2008) observed greater soil C/N ratios with NT and attributed the differences to slower mineralization of residues. The lack of a fertilizer N rate effect on the soil C/N ratio coincides with findings by Liang and MacKenzie (1992) and Coulter et al. (2009), but disagrees with Jagadamma et al. (2007, 2008). It should be noted that measurements in Jagadamma et al. (2007, 2008) were after 23 yr of management, while measurements from this study, Liang and MacKenzie (1992), and Coulter et al. (2009) were after no more than 8 yr of management. This suggests the length of fertilizer N management may have an effect on the soil C/N ratio.

Particulate Organic Matter Carbon

In general, ΔPOM-C was more responsive to management than ΔSOC, as changes in POM-C were observed to depths of 30 cm. The response of ΔPOM-C to stover management was dependent upon fertilizer N rate and depth (Table 5.2). With the 0 kg N ha^{-1} treatment, negative ΔPOM-C with stover removal was observed in the 15- to 30-cm depth but not in the 0- to 5-cm, 5- to 15-cm, and 30- to 60-cm depths (Fig 5.4). Positive ΔPOM-C occurred when stover was retained and no fertilizer N was applied at all depths except the 30- to 60-cm depth. With the 224 kg N ha^{-1} treatment, ΔPOM-C was positive in the 0- to 5-cm and 5- to 15-cm depths when stover was retained. A negative ΔPOM-C occurred only in the 0- to 5-cm depth with stover removal. Measurements of POM-C at depths below 15 cm after 3 yr of CC did not differ from baseline measurements and were similar between stover management treatments.

The effect of fertilizer N rate on ΔPOM-C varied and was dependent upon depth and stover management (Table 5.2). When retained, a positive ΔPOM-C was 63% greater with fertilizer N in the 0 to 5-cm depth (0.378 and 0.616 Mg ha^{-1} at 0 and 224 kg N ha^{-1} fertilization, respectively). ΔPOM-C did not differ between fertilizer N rates with stover removal (Fig 5.4). No differences in ΔPOM-C between fertilizer N rates were observed in the 5- to 15-cm, 15- to 30-cm, and 30- to 60-cm depths, regardless of stover management. While the responses of ΔPOM-C to fertilizer N rate were only in the 0- to 5-cm depth, differing reports exist in the literature regarding the response of POM-C to fertilizer N rate. Liebig et al. (2002) reported increases in POM-C with fertilizer N in the 0- to 7.6-cm depth, regardless of crop rotation. However, no increases in POM-C as a function of fertilizer N rate were observed in the 0- to 15-cm depth in a rice (*Oryza sativa* L.)-wheat (*Triticum* aetivum L.)-jute (*Corchorus olitorius* L.) rotation with residue removal (Manna et al., 2006), or in the 0- to 15-cm and 15- to 30-cm depths in CC and CS rotations (Coulter et al., 2008). The comparison of the results of this study to these studies suggests that factors such as crop management or climatic conditions may influence the response of POM-C to fertilizer N rate. These results do suggest that ΔPOM-C is positively affected by fertilizer N, perhaps because of greater stover and root production with fertilizer N.

The majority of studies on crop management effects on POM-C have involved tillage (e.g. Cambardella and Elliot, 1992; Six et al., 1999; Fabrizzi et al. 2003), yet no collective consensus exists regarding its effects on POM-C. In this study, tillage system did not influence ΔPOM-C on a clay loam soil. This lack of response was consistent across depths. This agrees with Needelman et al. (1999) across a range of soils in Illinois, Yoo and Wander (2008) on a silt loam and silty clay loam in Illinois, and Sequeira and Alley (2011) on a silt loam in Virginia. They all observed no changes within the surface 15 cm. Studies that have reported responses to tillage have often observed depth stratification. Hussain et al. (1999) and Wander and Bidart (2000) observed increased POM-C as tillage intensity decreased in the 0- to 5-cm depth in Illinois, but no differences at deeper depths. Furthermore, Wander and Bidart (2000) did not observe any tillage effects on POM-C in the 0- to 5-cm depth at two other sites in their study. Franzluebbers and Stuedemann (2008) reported greater POM-C in the 0- to 5-cm depth as a result of NT adoption, but observed no tillage effects when the 0- to 30-cm depth was considered. In contrast, Six et al. (1999) observed greater POM-C in the 0- to 20-cm depth with NT in Kentucky, Nebraska, and Ohio. Despite the inconsistent results from these studies, they do suggest that factors such as the length of NT adoption and latitude are possibly contributing to the variation in reported responses.

Particulate Organic Matter Nitrogen

Following 3 yr of management, ΔPOM-N was affected by stover management, and the response was dependent upon tillage system and depth (Table 5.2). Within CT, no change in POM-N occurred with stover removal (Fig 5.5). In comparison, a positive ΔPOM-N by 28 and 39% occurred in the 0- to 5-cm and 5- to 15-cm depths, respectively, when stover was retained within CT. For ST, a positive ΔPOM-N by 49, 36, and 42% occurred when stover was retained in the 0- to 5-, 5- to 15-, and 15- to 30-cm depths, respectively. In comparison, a negative ΔPOM-N by 45% occurred with stover removal in the 0- to 5-cm depth, but did not change at depths below 5 cm. Similar to ST, a positive ΔPOM-N occurred at all depths to 30 cm within NT when stover was retained, as a positive ΔPOM-N by 91, 29, and 59% occurred in the 0- to 5-, 5- to 15-, and 15- to 30-cm depths, respectively. In comparison, a negative ΔPOM-N by 32% occurred with stover removal in the 0- to 5-cm depth. Similar to ST, POM-N did not change from baseline measurements at other depths.

The response of ΔPOM-N to tillage system differed between stover management treatments (Table 5.2). When stover was retained, ΔPOM-N in the 0- to 5-cm depth within NT was 321% greater than ΔPOM-N within CT (0.106 and 0.033 Mg ha^{-1} within NT and ST, respectively) and similar to ΔPOM-N within ST (Fig. 5.5). This is supported by results by Hussain et al. (1999) and Wander and Bidart (2000). They observed greater POM-N in the 0- to 5-cm depth as tillage intensity decreased. It should be noted that POM-N in this depth at two other sites reported by Wander and Bidart (2000) was not affected by tillage. Despite no differences among tillage systems in the 5- to 15-cm depth, adoption of NT and retaining stover increased POM-N in the 15- to 30-cm depth when compared to CT after 3 yr of management. This was not expected since tillage studies investigating POM-N below 5 cm have reported no differences (Hussain et al., 1999; Needelman et al., 1999; Wander and Bidart, 2000). When stover was removed, POM-N was similar among tillage systems at all depths.

Neither fertilizer N rate nor its interactions affected ΔPOM-N (Table 5.2), despite findings by Manna et al. (2005) and Coulter et al. (2009) reporting increases of POM-N with increasing fertilizer N rate. It was hypothesized that a response of ΔPOM-N to fertilizer N rate would occur since POM-C and -N are sensitive to changes caused by management (Cambardella and Elliot, 1992; Franzluebbers and Stuedemann, 2008). However, the lack of response in this study may be associated with its short-term length; measurements by Manna et al. (2005) and Coulter et al. (2009) were at least 8 yr after treatment establishment.

Particulate Organic Matter Carbon/Nitrogen Ratio

The POM C/N ratio represents the ratios following 3 yr of management. The POM C/N ratio only differed between stover management treatments in the 0- to 5-cm depth. Ratios were 9.3 and 13.9 in treatments with and without stover removal, respectively (Tables 5.2 and 5.3). The difference between these treatments appears to be more a function of retaining stover than removal. The POM C/N ratio in the 0- to 5-cm depth when stover was retained increased from a baseline measurement of 10.8 (Table 5.1). In comparison, the POM C/N ratio with stover removal was less than the baseline ratio. Since POM represents fine roots and sand-sized organic matter (Cambardella and Elliot, 1992; Carter, 2002), it is probable that the response of the POM C/N ratio without stover removal was primarily caused by the increase in POM-C, though an increase in POM-N also occurred in the 0- to 5-cm depth. Because of the high C/N ratio of corn stover (Johnson et al. 2006, 2007) and the association between POM and plant material, increases in the POM C/N ratio in CC cropping systems may occur. Though a decline of the POM C/N ratio from the baseline measurement with stover occurred, a greater decrease was hypothesized because plant-derived C inputs were greatly reduced. Since field-scale equipment was used to harvest stover, complete removal of all material was not achieved, meaning a small amount of aboveground stover remained (3.1 Mg of dry matter ha^{-1}) and was theoretically still available for SOM transformation. This remaining stover, the soil and climate characteristics of the site, and its CS cropping history prior to the initiation of this study may have contributed to this response.

The POM C/N ratio was not affected by tillage system, fertilizer N rate, or their interactions (Table 5.2). The lack of response to tillage system is consistent with results by Hussain et al. (1999) in the 0- to 5-cm depth and Sequeira and Alley (2011) in the 0- to 15-cm depth. While there was no tillage system effect on the POM C/N ratio in this study, it is possible that they may have been overshadowed by the dominant effect of stover removal. Research also suggests that differences may be detectable after long-term stover and tillage management. Hussain et al. (1999) observed differences between NT and moldboard plow tillage in the 5- to 15-cm depth following 8 yr of management.

Particulate Organic Matter Carbon/Soil Organic Carbon Ratio

The POM-C/SOC ratios discussed here represent the ratios following 3 yr of management. The ratio indicates how much of SOC is contained in the POM-C fraction.

This is important because the turnover rate of organic C differs among pools, and POM-C is known as a labile pool (Wander et al., 1998; Wander, 2004). Therefore, as the POM-C/SOC ratio increases, it is possible that the rate of organic C turnover may increase. The main effects of stover management, tillage system, and their interaction with depth were significant for the POM-C/SOC ratio (Table 5.2). Within CT, no differences existed between stover management treatments in the 0- to 5-cm and 30- to 60-cm depths, but the POM-C/SOC ratio was lower with stover removal in the 5- to 15-cm and 15- to 30-cm depths. This indicates POM-C is representing a smaller fraction of the SOC pool (Table 5.4). The POM-C/SOC ratio was smaller with stover removal in the 0- to 5-cm depth within NT and ST, but similar between treatments in the lower depths. This demonstrates the interaction of reduced tillage on the stratification of different C pools in the soil profile. The transformation of crop-derived organic C to POM-C, resulting in an increased proportion of labile C in relation to SOC, only occurred in the surface depth. In comparison, increases in the POM-C/SOC ratio within CT when stover was retained were observed at lower depths. This occurrence was likely caused by organic material incorporation through the tillage events.

While tillage system did affect the POM-C/SOC ratio, it was dependent upon stover management and depth (Table 5.2). When stover was removed, the POM-C/SOC ratio within NT was greater than within CT in the 5- to 15-cm depth (Table 5.4). This agrees with Cambardella and Elliot (1992). They observed that the POM-C/SOC ratio was greater with NT in the 0- to 20-cm depth. When stover was retained, the POM-C/SOC ratio was greater within CT than within NT and ST in the 30- to 60-cm depth. It did not differ among tillage systems at any other depth. Since differences in the ratio when stover was retained only occurred in the 30- to 60-cm depth and not in any upper depths, the validity of this response is in question. This is because differences in the POM-C/SOC ratio have not been reported at these depths. Also, no differences existed at surface depths, where they would be mostly likely to occur. Fertilizer N rate did not affect the POM-C/SOC ratio. This coincides with Liebig et al. (2002) and Coulter et al. (2009) and further indicates that fertilizer N rate likely does not influence the POM-C/SOC ratio.

Particulate Organic Matter Nitrogen/Total Nitrogen Ratio

The POM-N/TN ratios discussed here represent the ratios following 3 yr of management. The POM-N/TN ratio was affected by an interaction among stover management, tillage system, and depth, but not by fertilizer N rate (Table 5.2). Within CT, the POM-N/TN ratio was greater when stover was retained in the 5- to 15-cm depth, greater with stover removal in the 15- to 30-cm depth, and similar between stover management treatments in the 0- to 5-cm and 30- to 60-cm depths (Table 5.4). The response in the 5- to 15-cm depth is probably related to the return of N by organic material return and its incorporation. This would theoretically result in an increased addition to the POM-N pool. The POM-N/TN ratio was not affected by stover removal at any depth within NT or ST.

The effect of tillage system on the POM-N/TN ratio depended on stover management and depth (Table 5.2). When stover was retained, the POM-N/TN ratio was lower within CT than NT and ST in the 15- to 30-cm depth (Table 5.4). When stover was removed, the POM-N/TN ratio was lower within CT than NT and ST in the 5- to 15-cm depth. These responses were not expected, as it was hypothesized that the ratio within CT at these depths would be equal or greater than the ratios within NT and ST since organic material was incorporated within CT at these depths.

CONCLUSIONS

Removal of corn stover in CC rotations can negatively affect several near-surface soil properties in as soon as 3 yr in environments with fine-textured soils where physical SOM protection is high and microbial activity is often limited by cool soil temperatures. The negative effect of stover removal on soil BD was dependent upon soil disturbance. Soil BD in the 0- to 5-cm and 5- to 15-cm depths within NT was greater when stover was removed, but was similar between stover management treatments in all depths within CT. In general, retaining corn stover increased total C and N to depths of 15 cm and POM C and N to depths of 30 cm. In comparison, removal of stover often decreased the C and N content in these pools. These results indicate corn stover removal is the short-term management decision that has a larger impact on SOM dynamics on fine-textured soils than tillage system or fertilizer N rate. It also suggests labile and total C and N pools can be negatively affected by stover removal in as little as 3 yr. While effects of tillage system and fertilizer N rate on several soil properties were often secondary to the influence of stover removal, the response of these soil properties to stover management were often dependent upon these main effects. Since this was a short-term study, it is hypothesized that the effects of tillage system and fertilizer N rate would become more apparent as sustained management continues.

Based on these findings, sustained removal of corn stover, even short-term, will negatively affect several important properties related to soil quality. Thus, sustained removal will likely decrease soil productivity (Lal, 2004; Wilhelm et al., 2007). Despite this potential loss, this study also observed short-term net C and N increases when stover is retained. This indicates there is potential for SOC sequestration in fine-textured soils in the Upper Midwest when corn is grown continuously (Clay et al., 2012). These results underscore the necessity of monitoring SOM levels if sustained stover removal is employed. Even with diligent monitoring, organic amendments or cover crops may be necessary in order to offset large losses of organic C and N by complete stover removal. These results do suggest that a fraction of stover could be sustainably harvested from highly-productive CC cropping systems on clay loam soils in the Upper Midwest while properly maintaining soil quality, especially in systems implementing reduced tillage.

TABLES AND FIGURES

Table 5.1. Baseline soil bulk density (BD), pH, soil organic C (SOC) and N (TN), C/N ratio, particulate organic matter C (POM-C) and N (POM-N), POM C/N ratio, POM-C/SOC ratio, and POM-N/TN ratio.

Depth	Soil BD	Soil pH	SOC	TN	C/N ratio	POM-C	POM-N	POM C/N ratio	POM-C/SOC ratio	POM-N/TN ratio
cm	Mg m^{-3}		---Mg ha^{-1}---			----Mg ha^{-1}----				
0-5	1.22	5.7	18.3	1.44	12.7	1.26	0.116	10.8	0.069	0.081
5-15	1.30	5.8	36.7	2.85	12.9	1.72	0.107	16.0	0.047	0.038
15-30	1.29	6.2	45.1	3.40	13.3	1.52	0.088	17.3	0.337	0.026
30-60	1.32	6.9	31.3	2.23	14.0	1.92	0.069	27.8	0.613	0.031

Table 5.2. Tests of fixed effects for change in soil bulk density (ΔBD), change in total soil C (ΔSOC) and N (ΔTN), CN/ratio, change in particulate organic matter C (ΔPOM-C) and N (ΔPOM-N), POM C/N ratio, POM-C/SOC ratio, and POM-N/TN ratio.

Fixed source of variation	ΔBD	ΔSOC	ΔTN	C/N ratio	ΔPOM-C	ΔPOM-N	POM C/N ratio	POM-C/SOC	POM-N/TN
Depth (D)	<0.001	0.10	0.002	<0.001	0.48	0.49	<0.001	<0.001	<0.001
Tillage (T)	0.11	0.62	0.35	0.72	0.30	0.45	0.77	0.74	0.57
Stover management (R)	0.13	<0.001	0.28	0.01	<0.001	<0.001	0.33	0.005	0.15
Fertilizer N rate (N)	0.14	0.71	0.83	0.45	0.55	0.70	0.17	0.84	0.19
R × D	0.03	<0.001	0.02	0.08	0.007	0.01	0.003	0.05	0.51
T × R	0.84	0.59	0.88	0.86	0.74	0.36	0.54	0.22	0.59
T × D	<0.001	0.54	0.03	0.22	0.67	0.09	0.19	0.72	0.92
T × N	0.74	0.84	0.81	0.64	0.95	0.80	0.27	0.60	0.93
R × N	0.73	0.55	0.33	0.77	0.63	0.17	0.36	0.81	0.35
N × D	0.18	0.98	0.01	0.50	0.95	0.89	0.22	0.71	0.24
T × R × D	0.04	0.37	0.48	0.88	0.93	0.09	0.14	0.09	0.06
T × R × N	0.52	0.97	0.24	0.32	0.63	0.63	0.88	0.97	0.91
T × N × D	0.39	0.93	0.25	0.52	0.88	0.36	0.13	0.15	0.22
R × N × D	0.71	0.97	0.80	0.22	0.01	0.95	0.12	0.13	0.86
T × R × N × D	0.78	0.87	0.68	0.74	0.40	0.59	0.50	0.24	0.46

Table 5.3. Soil and POM C/N ratios as affected by stover management, averaged across tillage systems and fertilizer N rates.

Ratio	Depth (cm)	Stover retained	Stover removed
Soil C/N ratio	0-5	13.4 A†	12.5 B
	5-15	12.5 A	12.5 A
	15-30	13.9 A	13.4 A
	30-60	15.9 A	16.5 A
POM C/N ratio	0-5	13.9 A	9.3 B
	5-15	14.2 A	17.2 A
	15-30	17.3 A	15.0 A
	30-60	22.8 A	21.8 A

† Within a row for a given variable, means followed by the same uppercase letter are not significantly different, $\alpha = 0.10$.

Table 5.4. POM-C/SOC and POM-N/TN ratios as affected by stover management and tillage system in the 0- to 5-, 5- to 15-, 15- to 30-, and 30- to 60-cm depths, averaged across fertilizer N rates.

		Chisel		No-till		Strip-till	
Ratio	Depth	Stover retained	Stover removed	Stover retained	Stover removed	Stover retained	Stover removed
	cm	---------------------------------- Mg POM-C Mg SOC^{-1}	----------------------------------				
POM-C/SOC	0-5	0.087 Aa†	0.067 Aa	0.099 Aa	0.070 Ba	0.096 Aa	0.057 Ba
	5-15	0.057 Aa	0.035 Bb	0.047 Aa	0.054 Aa	0.054 Aa	0.043 Aab
	15-30	0.040 Aa	0.027 Ba	0.046 Aa	0.033 Aa	0.036 Aa	0.036 Aa
	30-60	0.065 Aa	0.041 Aa	0.032 Ab	0.051 Aa	0.037 Ab	0.046 Aa
		---------------------------------- Mg POM-N Mg TN^{-1}	----------------------------------				
POM-N/TN	0-5	0.103 Aa	0.095 Aa	0.111 Aa	0.093 Aa	0.105 Aa	0.092 Aa
	5-15	0.051 Aa	0.025 Bb	0.039 Aa	0.043 Aa	0.049 Aa	0.043 Aa
	15-30	0.022 Bb	0.033 Aa	0.036 Aa	0.030 Aa	0.039 Aa	0.031 Aa
	30-60	0.019 Aa	0.027 Aa	0.022 Aa	0.032 Aa	0.041 Aa	0.019 Aa

† Within a row for a given variable, stover management means followed by the same uppercase letter within each tillage system are not significantly different, $\alpha = 0.10$. Tillage system means followed by the same lowercase letter within each stover management treatment are not significantly different.

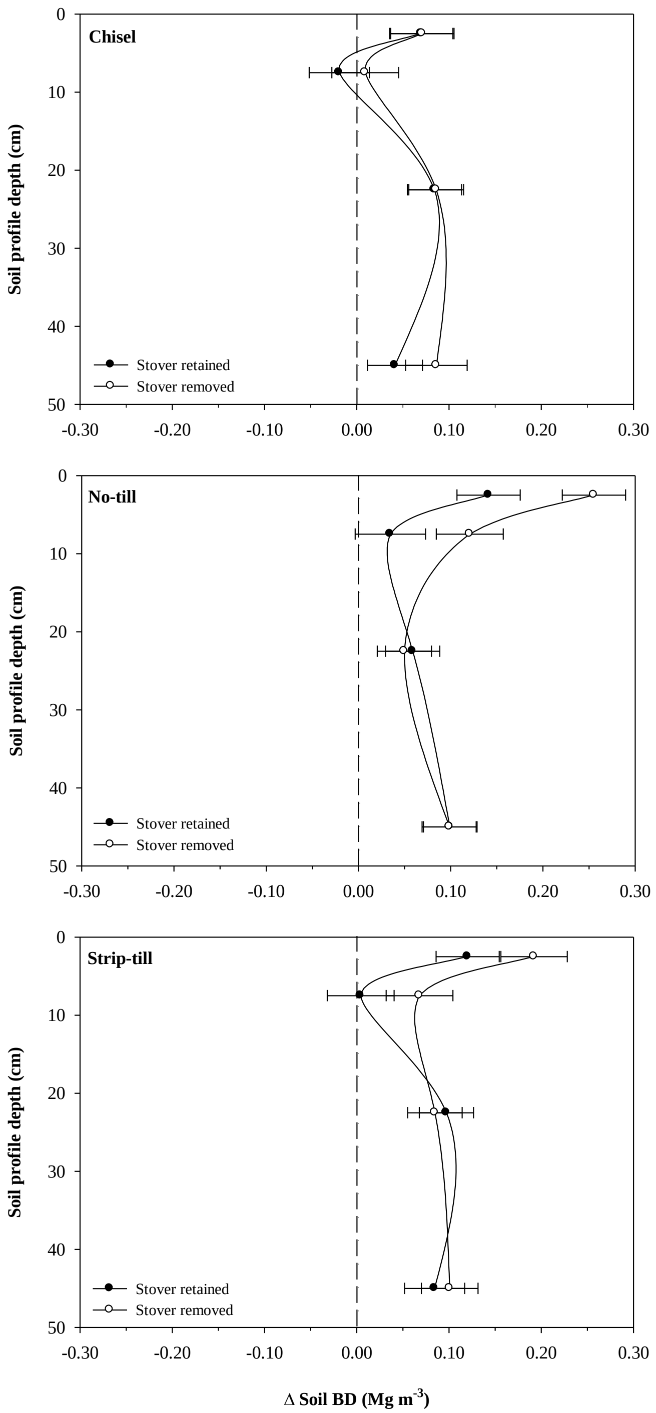

Fig 5.1. Changes (Δ) in soil bulk density (BD) from baseline measurements in the 0- to 5-, 5- to 15-, 15- to 30-, and 30- to 60-cm depths as affected by stover management and tillage system. Bars represent 90% confidence intervals around treatment means.

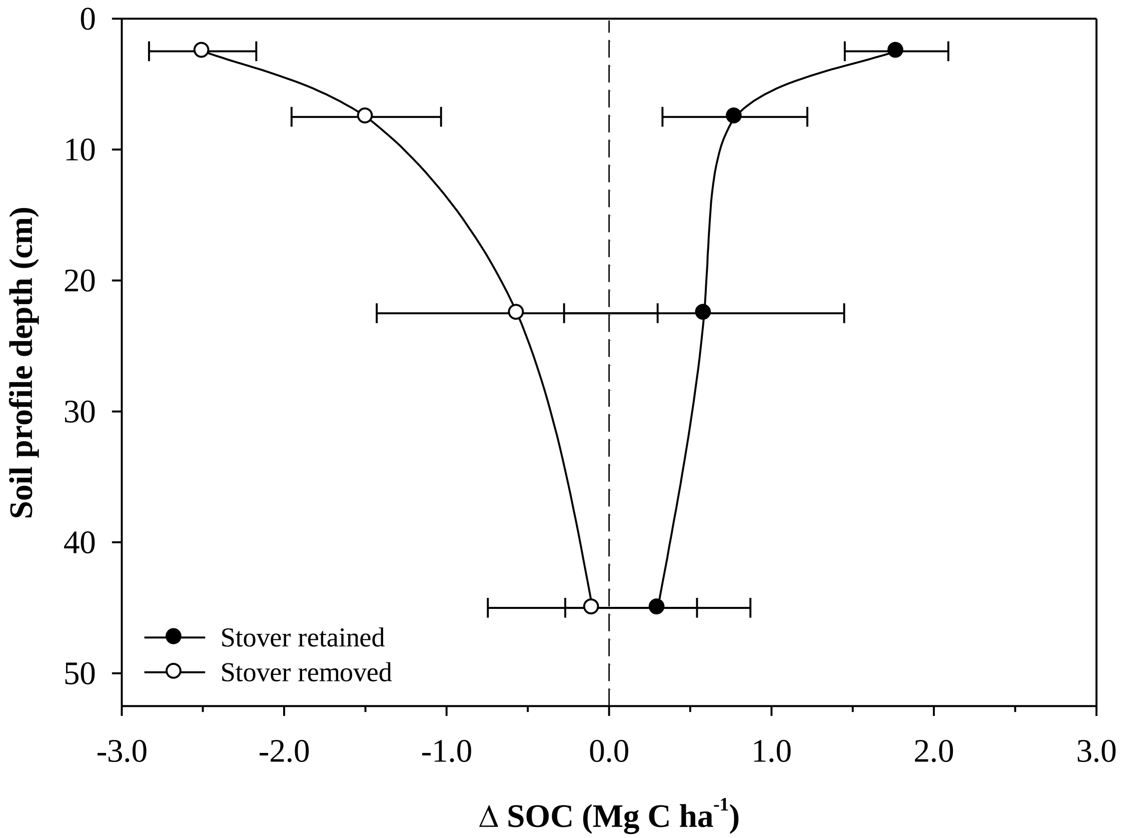

Fig. 5.2. Changes (Δ) in soil organic C (SOC) from baseline measurements in the 0- to 5-, 5- to 15-, 15- to 30-, and 30- to 60-cm depths as affected by stover management. Bars represent 90% confidence intervals around treatment means.

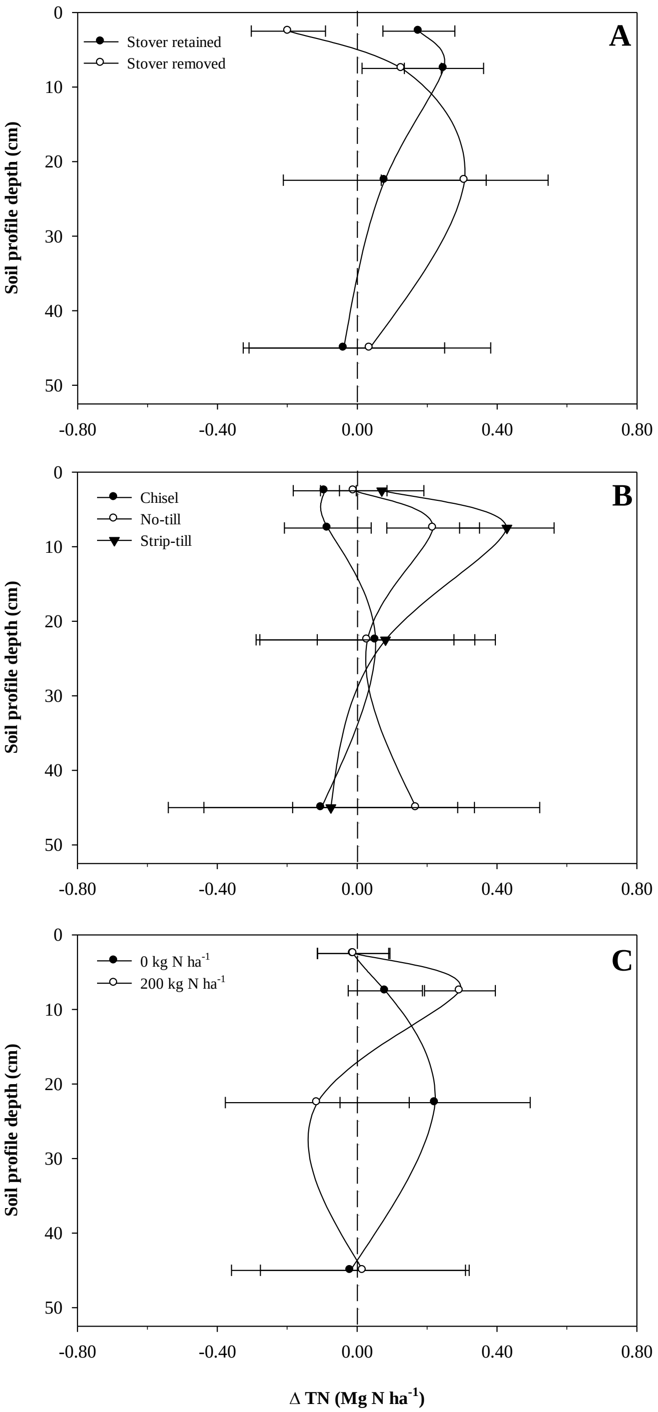

Fig. 5.3. Changes (Δ) in total N (TN) from baseline measurements in the 0- to 5-, 5- to 15-, 15- to 30-, and 30- to 60-cm depths as affected by stover management (A), tillage system (B), and fertilizer N rate (C). Bars represent 90% confidence intervals around treatment means.

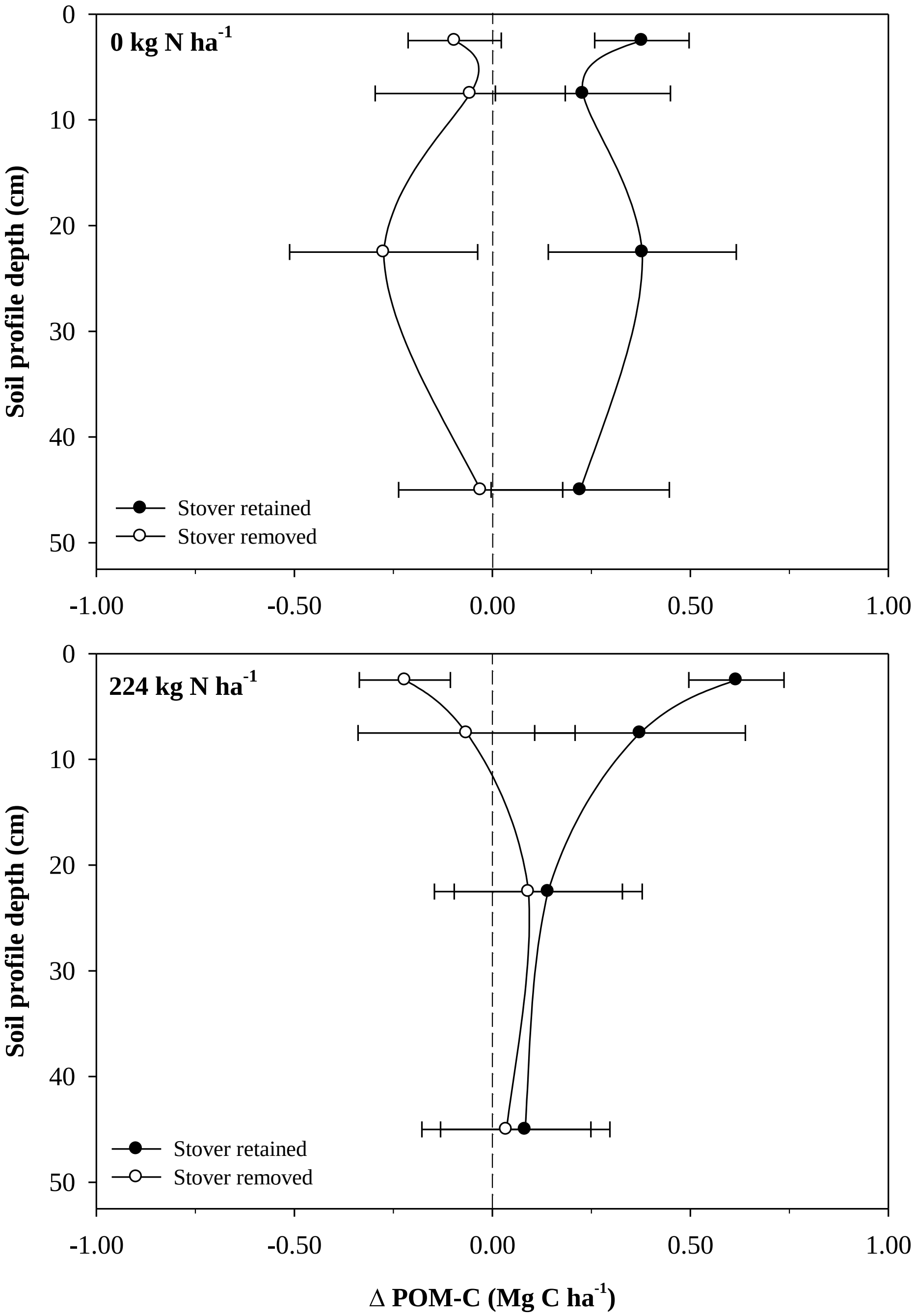

Fig. 5.4. Changes (Δ) in particulate organic matter C (POM-C) from baseline measurements in the 0- to 5-, 5- to 15-, 15- to 30-, and 30- to 60-cm depths as affected by stover management and fertilizer N rate. Bars represent 90% confidence intervals around treatment means.

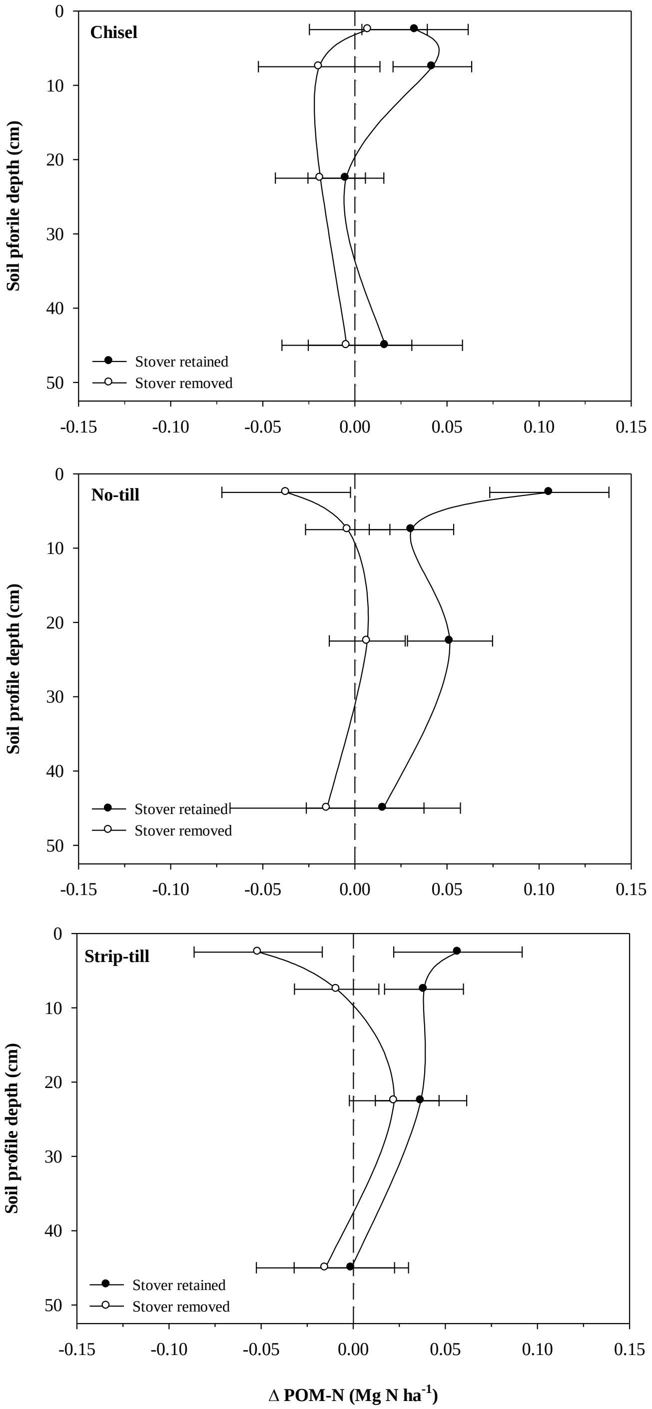

Fig 5.5. Changes (Δ) in particulate organic matter N (POM-N) from baseline measurements in the 0- to 5-, 5- to 15-, 15- to 30-, and 30- to 60-cm depths as affected by stover management and tillage system. Bars represent 90% confidence intervals around treatment means.

CHAPTER 6: CONCLUSIONS

This research was developed to address a range of questions related to the effects of stover removal on corn growth, productivity, and soil carbon dynamics. From an applied standpoint, this study determined if the amount of fertilizer N necessary to economically optimize (EONR) continuous corn grain production was affected by stover removal. This research indicated that less fertilizer N is necessary when stover is removed. This response was likely related to greater net N mineralization with stover removal. With this information, recommendations can be reported to stakeholders, namely producers, that less fertilizer N is required in continuous corn cropping systems when stover is removed. If these recommendations are not employed, economic return will not be maximized and potential for NO_3-N loss through leaching will likely increase since unutilized fertilizer N is being applied. While this research does indicate less fertilizer N is necessary when stover is removed, additional research is necessary to determine/validate how much EONRs should be reduced.

This research also shows that decreasing soil surface stover coverage by stover removal, tillage, or both has a positive effect on corn growth, yield, and N use efficiency in environments that are primarily limited by soil temperature and growing season length. This conclusion contradicts findings in Illinois, Nebraska, and Ohio (Wilhelm et al., 1986; Blanco-Canqui et al., 2006; Coulter and Nafziger, 2008). The differing response between those studies and this work can be explained by differences between study environments. In the previous studies, reductions in grain yield were attributed to lower water availability with stover removal. This indicates that the agronomic responses to stover removal are dependent on environment. Based on these results it can be expected that agronomic improvements will occur with stover removal when soil temperature and growing season length are the primary limiting factors of grain production. Where water availability is often the primary concern, it can be expected that decreased agronomic performance will occur with stover removal.

While agronomic performance was generally enhanced with stover removal, the results do indicate that sustained, short-term stover removal (≤3 yr) can potentially jeopardize soil and water quality. The research indicated residual soil NO_3-N (RSN) increased with stover removal at fertilizer N rates of 134, 179, 224 kg N ha^{-1} by 26, 34, and 40%, respectively. This is important because EONRs in this study fell within this range of fertilizer N rates. Since RSN is greater, NO_3-N leaching potential is elevated. This greater potential, in turn, further threatens water quality. Near-surface measurements of soil organic C (SOC) were also adversely affected by stover removal. When stover was removed for 3 yr, SOC in the 0- to 5-cm and 5- to 15-cm depths decreased by 2.50 and 1.49 Mg C ha^{-1}, respectively. In comparison, SOC in the same depths increased by 1.77 and 0.78 Mg C ha^{-1}, respectively, when stover was retained. While the absolute changes were greater than hypothesized, the responses indicate that sustained, short-term (≤3 yr) will result in declines in SOC.

In environments where soil temperature and growing season length are the primary yield limiting factors, this research indicates short-term stover removal has a positive influence on agronomic production, but adverse consequences on properties related to environmental and soil quality. This poses a great challenge as we strive to maximize food production while protecting natural resources. The hope of producing a sustainable fuel source further complicates this challenge. It is understood that we must produce more food from a smaller area of land. This research indicates that we can do this in these environments if stover is removed. However, it is also known that the soil carries the potential to sequester massive quantities of C, as we work towards mitigating the harmful effects of fossil fuel consumption. It is also known that SOC is the dominant characteristic in soil quality. This research shows that even short-term stover removal adversely affects the storage of C in the soil. If sustained stover removal is widely employed in the Upper Midwest in an effort to support the proposed cellulosic ethanol industry, we must identify and develop management strategies that maintain SOC levels. We need to explore and understand if the addition of cover crops or animal manure to cropping systems employing stover removal can offset cellulosic C losses. Finally, if stover removal is unavoidable, we must advocate sustainable removal levels that do not carry the risk of depleting SOC.

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APPENDIX A

SUPPLEMENTAL INFORMATION FOR CHAPTER 2

Table A1. Random variation associated with the response of surface stover coverage, plant emergence relative plant height (RPH), normalized difference vegetative index (NDVI), leaf area index (LAI), relative leaf chlorophyll (RLC), grain yield, and kernel number to year, site, and its interactions with fixed effects.

Source of variation	Surface stover coverage	Plant emergence	RPH	NDVI	LAI	RLC	Grain yield	Kernel number
	---			% Random variation				--
Blk(Site)	0.36	0.22	7.7	3.7	5.9	0	4.3	4.8
Year (Y)	0	0	34	26	24	18	0	26
Y × Site (S)	21	0	0.48	1.7	2.1	0	30	7.8
Y × Blk(Location)	0	1.0	0	3.1	0	9.4	1.1	0.41
Y × Tillage (T)	15	6.0	0	0	0	2.2	3.7	0
Y × S × T	4.8	3.4	0	0.24	0.73	0	0.51	4.9
Y × Stover removal (R)	11	0	0	0	0	0	0	0.27
Y × S × R	0.58	5.7	11	5.5	3.1	0	0.84	0
Y × T × R	0	0	1.6	1.8	1.2	0	0	0
Y × S × T × R	0	0	5.3	2.1	1.8	1.1	0	0
Y × T × S × Blk(Location)	32	4.3	7.6	10	14	25	7.2	2.7
Y × Fertilizer N rate (N)	-	0	0	1.2	2.6	8.5	6.7	4.7
Y × S × N	-	0	1.4	1.2	0	0	0	0
Y × T × N	-	0	0	0	0	0	0	0
Y × S × T × N	-	0	0	0	0	0	0	0
Y × R × N	-	0	0	0	0	0	0	0
Y × S × R × N	-	0	0.23	1.2	0.37	3.0	0	0
Y × S × T × N	-	0	0	0	0	0	0	0
Y × S × T × R × N	-	0	0	0	0	0	0	0

APPENDIX B

SUPPLEMENTAL INFORMATION FOR CHAPTER 3

Table B1. Random variation associated with the response of N uptake by grain (UG) and total aboveground plant (UT), recovery efficiency (RE), internal efficiency (IE), N harvest index (NHI), physiological efficiency (PE), partial factor productivity (PFP), agronomic efficiency (AE), and residual soil nitrate-N (RSN) to year, site, and its interactions with fixed effects.

Source of variation	UG	UT	RE	IE	PE	PFP	AE	RSN
	------------------------------ % Random variation -------------------------------							
Blk(Site)	0	0	0	0.83	0	0	0	0
Year (Y)	0	0	0	0	31	0	0	0
Y × Site (S)	48	30	26.1	42	38	22	3.8	21
Y × Blk(Location)	0.18	0	0	0.3	0	0	0	0
Y × Tillage (T)	1.4	1.2	0	0	0	2.3	2.6	0
Y × S × T	0.92	1.1	2.3	0	0.37	0	0.57	0
Y × Stover removal (R)	0	0	2.7	0.02	0	0	0	0
Y × S × R	0	0.21	0	0	0	0	0	0
Y × T × R	0	0	0	0	0	0	0	0
Y × S × R × S	0	0	0	0	0.57	0	0	0
Y × T × R × Blk(Site)	0	0	0	2.3	0	0	0	0
Y × Fertilizer N rate (N)	6.5	2.8	0	0	0	0	7.7	3.8
Y × S × N	0	2.5	1.9	5.7	0.65	15	0	0
Y × T × N	0	0	0	0.48	0.22	0	0	0
Y × S × T × N	0	0	0	0	0	0	0	0
Y × R × N	0	0	0	0	0	0	0	0
Y × S × R × N	3.7	4.4	6.5	1.2	0	0	0	0
Y × S × T × N	0	0	0	0	0	0	0	0
Y × S × T × R × N	0	0	0	0	1.5	0	0	0

APPENDIX C

SUPPLEMENTAL INFORMATION FOR CHAPTER 4

Table C1. Random variation associated with the response of stover biomass yield (SBY), cob biomass yield (CBY), cob-stover ratio (CSR), stover C concentration (SCC), stover C content (SCT), cob C concentration (CCC), cob C content (CCT), stover theoretical ethanol yield (STEY), stover ethanol yield (SEY), cob theoretical ethanol yield (CTEY), and cob ethanol yield (CEY) to year, site, and its interactions with fixed effects.

Source of variation	SBY	CBY	CSR	SCC	SCT	CCC	CCT	SEY	CEY
	-- % Random variation --								
Blk(Site)	1.5	2.4	0	0.39	0.72	1.3	1.9	0.93	0.09
Year (Y)	2.8	34	48	36	8.6	48	44	0.96	37
Y × Site (S)	9.8	19	7.4	1.4	14	14	18	9.7	15
Y × Blk(Site)	0	0	0	3.4	0	1.2	0	0	0
Y × Tillage (T)	0.16	3.6	0	0	0.04	0	0	0.47	0
Y × S × T	0	0	0	0	0	0	0	0	0
Y × Stover removal (R)	5.3	0	0	0	4.9	0	0	5.4	0
Y × S × R	0	3.9	0.77	0	0	0.91	3.6	0	1.9
Y × T × R	0	0	0	0.62	0	0	0	0	0
Y × S × R × S	0	0	0	0	0	0.51	0.55	0	0.33
Y × T × R × Blk(Site)	4.6	4.2	0	3.5	4	1.2	4.6	5.6	2.5
Y × Fertilizer N rate (N)	0	0	0	3.5	0	1.1	0	0	0
Y × S × N	9.2	2	0	0	7.6	0.27	2.4	7.7	2.5
Y × T × N	0	0	0	0.71	0	0	0	0	0
Y × S × T × N	0	1.5	0.64	0	0	0	0	0.38	0.11
Y × R × N	0	0	0	0	0	0	0	0	0
Y × S × R × N	0	1.3	0	0.11	0	0	1.1	0	0.44
Y × S × T × N	0	0	0	0.41	0	0	0	0	0
Y × S × T × R × N	0	0	0.51	0	0	0.03	0	0.27	0

APPENDIX D

SUPPLEMENTAL INFORMATION FOR CHAPTER 5

Table D1. Change (Δ) from baseline measurements and soil bulk density (BD) values after 3 yr of stover, tillage, and fertilizer N management.†

		Chisel		No-till		Strip-till	
Variable	Depth (cm)	Stover retained	Stover removed	Stover retained	Stover removed	Stover retained	Stover removed
		------------------------------------- Mg m^{-3} -------------------------------------					
ΔBD	0-5	0.070	0.071	0.141	0.255	0.134	0.192
	5-15	-0.019	0.009	0.035	0.121	0.004	0.068
	15-30	0.084	0.086	0.059	0.050	0.097	0.085
	30-60	0.041	0.086	0.099	0.099	0.085	0.101
Soil BD	0-5	1.29	1.29	1.36	1.48	1.34	1.41
	5-15	1.28	1.31	1.33	1.42	1.30	1.37
	15-30	1.37	1.38	1.35	1.34	1.39	1.37
	30-60	1.36	1.41	1.42	1.42	1.40	1.42

† Tillage system × stover management × depth interaction was significant.

Table D2. Change (Δ) from baseline measurements and soil organic carbon (SOC) contents after 3 yr of stover, tillage, and fertilizer N management.†

Variable	Depth (cm)	Stover retained	Stover removed
		--------- Mg ha^{-1} ---------	
ΔSOC	0-5	1.77	-2.50
	5-15	0.776	-1.494
	15-30	0.586	-0.565
	30-60	0.301	-0.102
SOC	0-5	20.1	15.8
	5-15	37.5	35.2
	15-30	45.7	44.5
	30-60	31.6	31.2

† Stover management × depth interaction was significant.

Table D3. Change (Δ) from baseline measurements and total nitrogen (TN) contents after 3 yr of stover, tillage, and fertilizer N management.†

		Stover management		Tillage system			Fertilizer N rate	
Variable	Depth (cm)	Retained	Removed	Chisel	No-till	Strip-till	0 kg N ha^{-1}	224 kg N ha^{-1}
		Mg ha^{-1}						
ΔTN	0-5	0.176	-0.197	-0.093	-0.010	0.071	-0.011	-0.010
	5-15	0.248	0.127	-0.084	0.218	0.428	0.081	0.294
	15-30	0.079	0.307	0.053	0.029	0.082	0.223	-0.114
	30-60	-0.038	0.036	-0.102	0.169	-0.075	-0.019	0.017
TN	0-5	1.62	1.24	1.35	1.43	1.51	1.43	1.43
	5-15	3.10	2.98	2.77	3.07	3.28	2.93	3.14
	15-30	3.48	3.71	3.45	3.43	3.48	3.62	3.29
	30-60	2.19	2.27	2.13	2.40	2.16	2.21	2.25

† Stover management × depth, tillage system × depth, and fertilizer N rate × depth interactions were significant.

Table D4. Change (Δ) from baseline measurements and particulate organic matter carbon (POM-C) values after 3 yr of stover, tillage, and fertilizer N management.†

		0 kg N ha^{-1}		224 kg N ha^{-1}	
Variable	Depth (cm)	Stover retained	Stover removed	Stover retained	Stover removed
		---------------------- Mg ha^{-1}	----------------------		
ΔPOM-C	0-5	0.378	-0.095	0.616	-0.221
	5-15	0.229	-0.056	0.373	-0.065
	15-30	0.379	-0.274	0.141	0.091
	30-60	0.222	-0.029	0.083	0.036
POM-C	0-5	1.64	1.17	1.88	1.04
	5-15	1.95	1.66	2.09	1.66
	15-30	1.90	1.25	1.66	1.61
	30-60	2.14	1.89	2.00	1.96

† Stover management × fertilizer N rate × depth interaction was significant.

Table D5. Change (Δ) from baseline measurements and particulate organic matter nitrogen (POM-N) values after 3 yr of stover, tillage, and fertilizer N management.†

		Chisel		No-till		Strip-till	
Variable	Depth (cm)	Stover retained	Stover removed	Stover retained	Stover removed	Stover retained	Stover removed
		---------------------------------- Mg ha^{-1} ----------------------------------					
ΔPOM-N	0-5	0.033	0.007	0.106	-0.037	0.057	-0.052
	5-15	0.042	-0.019	0.031	-0.004	0.039	-0.009
	15-30	-0.005	-0.019	0.052	-0.007	0.037	0.022
	30-60	0.017	-0.004	0.016	-0.015	-0.001	-0.015
POM-N	0-5	0.149	0.123	0.222	0.079	0.173	0.065
	5-15	0.149	0.088	0.138	0.103	0.146	0.098
	15-30	0.083	0.069	0.140	0.081	0.125	0.110
	30-60	0.086	0.065	0.085	0.054	0.068	0.054

† Tillage system × stover management × depth interaction was significant.