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Crop and Soil Productivity Response to Corn Residue Removal: A Literature Review

W. W. Wilhelm,* J. M. F. Johnson, J. L. Hatfield, W. B. Voorhees, and D. R. Linden

ABSTRACT

Society is facing three related issues: overreliance on imported fuel, increasing levels of greenhouse gases in the atmosphere, and producing sufficient food for a growing world population. The U.S. Department of Energy and private enterprise are developing technology necessary to use high-cellulose feedstock, such as crop residues, for ethanol production. Corn (*Zea mays* L.) residue can provide about 1.7 times more C than barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), sorghum [*Sorghum bicolor* (L.) Moench], soybean [*Glycine max* (L.) Merr.], sunflower (*Helianthus annuus* L.), and wheat (*Triticum aestivum* L.) residues based on production levels. Removal of crop residue from the field must be balanced against impacting the environment (soil erosion), maintaining soil organic matter levels, and preserving or enhancing productivity. Our objective is to summarize published works for potential impacts of wide-scale, corn stover collection on corn production capacity in Corn Belt soils. We address the issue of crop yield (sustainability) and related soil processes directly. However, scarcity of data requires us to deal with the issue of greenhouse gases indirectly and by inference. All ramifications of new management practices and crop uses must be explored and evaluated fully before an industry is established. Our conclusion is that within limits, corn stover can be harvested for ethanol production to provide a renewable, domestic source of energy that reduces greenhouse gases. Recommendation for removal rates will vary based on regional yield, climatic conditions, and cultural practices. Agronomists are challenged to develop a procedure (tool) for recommending maximum permissible removal rates that ensure sustained soil productivity.

Three of the most pressing issues facing our society, in the midterm, are overreliance on imported fuels [U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, 2002], increasing levels of greenhouse gases in the atmosphere (IPCC, 2001), and ability of our agricultural systems to sustain production at rates needed to feed a growing world population (Cassman, 1999). Many papers have been written on these topics both individually and in the various combinations (Doran, 2002; Follett, 2001; Janzen et al., 1998a, 1998b; Lal et al., 1999). However, few authors have addressed all three topics together.

Recent developments in the energy industry and activity by entrepreneurs have prompted new strategies for addressing the first issue, overreliance on imported fuels (Hettenhaus et al., 2000). This strategy expands use of biomass for fuel production and is contingent on development of new organisms or enzymes to convert cellulosic (a high concentration of cellulose) biomass [opposed to grain (starchy) biomass] to ethanol for use as a motor vehicle fuel. The U.S. DOE, in concert with private enterprise, is making great strides toward developing enzymes and improving efficiency in fuel production from biomass (DiPardo, 2000; Hettenhaus et al., 2000).

Sources of cellulosic biomass are numerous (woody biomass crops and lumber industry wastes, forage crops, industrial and municipal wastes, animal manure, and crop residues); however, currently few sources are perceived to be available in sufficient quantity and quality to support development of an economically sized processing facility of about 1800 Mg dry matter d^{-1} (Hettenhaus et al., 2000), except crop residues (DiPardo, 2000). Bagasse [remaining after sap extraction from sugarcane (*Saccharum officinarum* L.)] in Louisiana and rice (*Oryza sativa* L.) straw in California are regional examples of crop residues collected in current culture and available for production of ethanol (DiPardo, 2000). Creating an acceptable use or disposal procedure for these residues represents a huge problem in the regions where they are produced although the total quantity is not sufficient to have a great impact on fuel needs for the nation (DiPardo, 2000). On the other hand, the quantity of corn stover is large, but corn stover is generally not

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Abbreviations: $\delta^{13}C$, change in ^{13}C atom percent; DOE, Department of Energy; HI, harvest index; SOC, soil organic carbon; SOM, soil organic matter.

Table 1. Grain production and estimated residue production for the four largest corn grain production states and the U.S. total for the 2000 crop year.

State	Grain yield†	Harvest index‡	Stover yield	Fraction of U.S. total
	Tg§		Tg	
Iowa	44.3	0.50	44.3	0.175
Illinois	42.5	0.50	42.5	0.168
Nebraska	25.8	0.50	25.8	0.102
Minnesota	24.4	0.50	24.4	0.096
Four state total	136.9	0.50	136.9	0.541
U.S. total	253.7	0.50	253.7	1.000

† Data from Natl. Agric. Stat. Serv. (2000).
‡ Harvest index = grain yield/(grain yield + stover yield).
§ Tg = 10^{12} g.

collected in the normal cultural practices employed for grain production in the Corn Belt.

Based on grain production for the 2000 crop year (National Agricultural Statistics Service, 2000) and a conservative harvest index [HI, grain yield/(grain yield + stover yield)] of 0.50 (Linden et al., 2000), total stover production for the four states with the greatest corn grain production (Iowa, Illinois, Nebraska, and Minnesota) was about 137 Tg (10^{12} g) (Table 1). Certainly, only a relatively small portion of this residue would be available as a feedstock; but if all were available, the residue in Iowa alone (44.3 Tg) could supply more than sixty 1800 Mg d^{-1} plants defined in DOE analyses (Hettenhaus et al., 2000). Using the ethanol yield (conversion efficiency) of 300 L Mg^{-1} stover (McAloon et al., 2000) gives a daily output of 540 kL industrial $plant^{-1}$ or an annual production potential from Iowa stover of 10.7 GL (10^9 L). Analyses by DOE assume an industrial plant will produce ethanol for 330 d yr^{-1} and be offline for maintenance during the other 35 d (McAloon et al., 2000). The actual amount of feedstock (stover) that could be removed has been estimated from 20% (Nelson, 2002) to about 30% (McAloon et al., 2000) of the total based on the need for adequate soil cover to control soil erosion. If 30% of the feedstock is used, Iowa has the potential to supply 3.57 GL of ethanol. This is slightly less than the 4.21 GL of U.S. motor fuel ethanol consumption for 2000 (Energy Information Administration, 2002). With these facts and assumptions in mind, DOE has targeted development of biomass ethanol production based on corn stover as a feedstock.

The calculations outlined above indicate corn stover produced in Iowa may have the potential to meet current ethanol use for motor fuels, but this production capacity will have little impact in meeting total U.S. motor fuel needs (both ethanol and nonethanol consumption), estimated to be 617 GL in 2000 (Energy Information Administration, 2002). The 3.57 GL of potential production from Iowa corn residue represents only 0.6% of the 617 GL of motor fuel used in the USA in 2000. However, stover production in Iowa represents less than 20% of the total U.S. corn crop, and corn is only one of many crop residues that could be collected and used for biomass ethanol production. Nelson (2002) used agricultural statistics from 1995 to 1997 to estimate that 42 Tg of corn stover and 8 Tg of wheat straw could be removed in 37 states, without exceeding tolerable soil erosion levels. Ethanol production from agricultural residues has the potential to be a viable component in the plan to reduce U.S. reliance on imported fossil fuels.

The second issue, increasing levels of greenhouse gases in the atmosphere, has received extensive publicity in the popular press and scientific literature. The Kyoto Summit propelled discussions of greenhouse gas effects on global climate and the role various human activities play in producing or consuming these gases. Agricultural practices have been cited as both sources and sinks for greenhouse gases, especially CO_2 (Follett, 2001; Lal et al., 1999). Crop residues and soil organic matter (SOM) represent a significant portion of total terrestrial C. Many of our traditional crop cultural practices (i.e., tillage, fallow, etc.) have resulted in release of old (relic) soil C into the atmosphere by increasing the rate of SOM decomposition (Bauer and Black, 1981; Haas et al., 1957; Janzen et al., 1998b) or decreasing organic matter input. Over decades of crop production in the U.S. Corn Belt and Great Plains, organic matter originally contained in these soils was lost through accelerated decomposition and erosion (Doran et al., 1998; Follett, 2001). Lal et al. (1999) indicated that with appropriate changes in crop management practices such as conservation tillage and irrigation and reducing or eliminating fallow and increasing the amount of crop residue returned to the soil, SOM content could be increased. Implicit is that increasing SOM also decreases atmosphere C pools. In fact, efforts have been initiated to develop markets for crop producers using C-sequestering cultural practices to sell *C credits*.

The last issue, sustaining the ability of crop production systems to generate sufficient food for a growing world population, is extremely complex. Practices that reduce the productive potential of our soils undermine our efforts to provide food and fiber for an expanding world population. Continued crop production potential of soils has a direct relationship to its organic matter content (Doran et al., 1994; Lal, 1998; Mann et al., 2002). Within limits, productivity is positively related to the SOM content (Reicosky and Forcella, 1988).

Many of the characteristics of highly productive soils relate to the organic fraction of the soil (Doran et al., 1998; Doran, 2002; Janzen et al., 1998a). Organic matter imparts numerous positive characteristics to soil. Some relate to soil physical and chemical properties, but all revolve around the dynamics of organic matter decomposition by soil organisms (Albrecht, 1938; Franzluebbers, 2002). The primary physical characteristic influenced by SOM is soil structure through soil aggregation and aggregate stability (Tisdall and Oades, 1982; Six et al., 1999). In turn, aggregates and their stability have tremendous influence on infiltration of water, soil water-holding capacity, and aeration as well as bulk density and penetration resistance and the more ill-defined characteristic, soil tilth (Carter, 2002). Chemical properties that at least partly depend on SOM include pH, nutrient availability and cycling, ion exchange capacity, and buffering capacity (Tisdall et al., 1986). Follett (2001) indicated that if all other factors are constant, SOM content is dictated by the quantity of residue returned to the

soil. Therefore, it is logical to deduce that if residue is removed, SOM will decline if other cultural practices are not modified simultaneously to reduce decomposition and other losses to offset the change in organic matter entering the system.

Crop residues are important in the formation of SOM. In addition, residue buffers soil against the forces of raindrop impact and wind shear. Crop residues on the soil surface strongly influence radiation balance and energy fluxes and reduce the rate of evaporation from the soil. Therefore, they traditionally have been used as a soil amendment for erosion control (Gilley et al., 1986; Gregorich et al., 1998, Soil Conserv. Soc. of Am., 1979). Erosion decreases productivity by removing the organic-matter–rich topsoil. Any removal of crop residue must be limited by the need to retain sufficient soil cover to keep soil loss by erosion within tolerable limits established by NRCS (Larson, 1979; Nelson, 2002). The *T* values currently used for erosion tolerance do not necessarily provide an adequate level of protection to prevent environmental degradation and yield loss (Mann et al., 2002).

Distribution of corn production either as continuous corn or in rotation with soybean for the Midwest is shown in Fig. 1. Intense corn production is centered in the central United States. When these data are coupled with land resource data on which this corn is produced (Fig. 2), it is obvious that a large amount of the land in the intense production area is classified as highly erodible. Crop production on highly erodible land must occur while maintaining adequate crop or residue cover to protect the soil resource against erosion. In the 2000 crop residue survey gathered by the Conservation Technology Information Center, 36% of the land in corn production in the Midwest was farmed with some form of conservation tillage (Conserv. Technol. Inf. Cent., 2002). The collection of corn stover for use as a bioethanol feedstock must be limited to accommodate the other objectives for residue within the production system and consider the current soil conservation measures used on a site-by-site basis. One of the most important, but certainly not the only need, is erosion protection.

Use of corn residue for production of ethanol has the advantages of reducing dependence on imported fossil fuel and developing a renewable energy source (as discussed above). Others include reducing the release of greenhouse gases from fossil fuels, stimulating the farm economy and rural communities, and removing or minimizing obstacles to crop production such as reducing insects and diseases in future crops through elimination of overwintering sites and sources of infection. Research from the central and northern Corn Belt (Kaspar et al., 1990; Swan et al., 1994) indicated that removing residue in total, or only moving it away from the planted row, could increase grain yield.

Our objective for this paper is to summarize our previous work in combination with other published works on the impacts that wide-scale collection of corn stover may have on corn production capacity of Corn Belt soils. We address the issue of crop yield (sustainability) and related soil processes directly, but the issue of greenhouse gases will largely be dealt with indirectly and by inference. We emphasize at the outset that we neither support nor oppose use of corn stover for production of ethanol as a matter of principal but rather think it absolutely essential that all ramifications of new management practices and crop uses be explored and evaluated fully before an industry is established. As researchers directly associated with agricultural producers, we are keenly aware of the need for growers to have new sources of income if they are to sustain their enterprises. However, as a society concerned about the sustainability

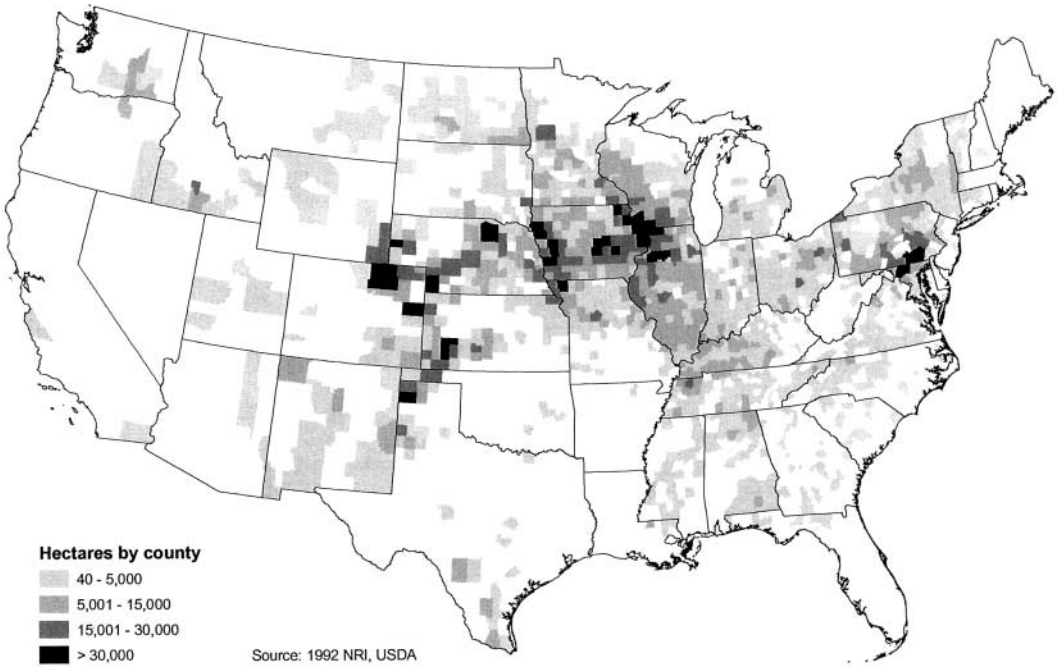

Fig. 1. Corn production in the United States (USDA, 1995).

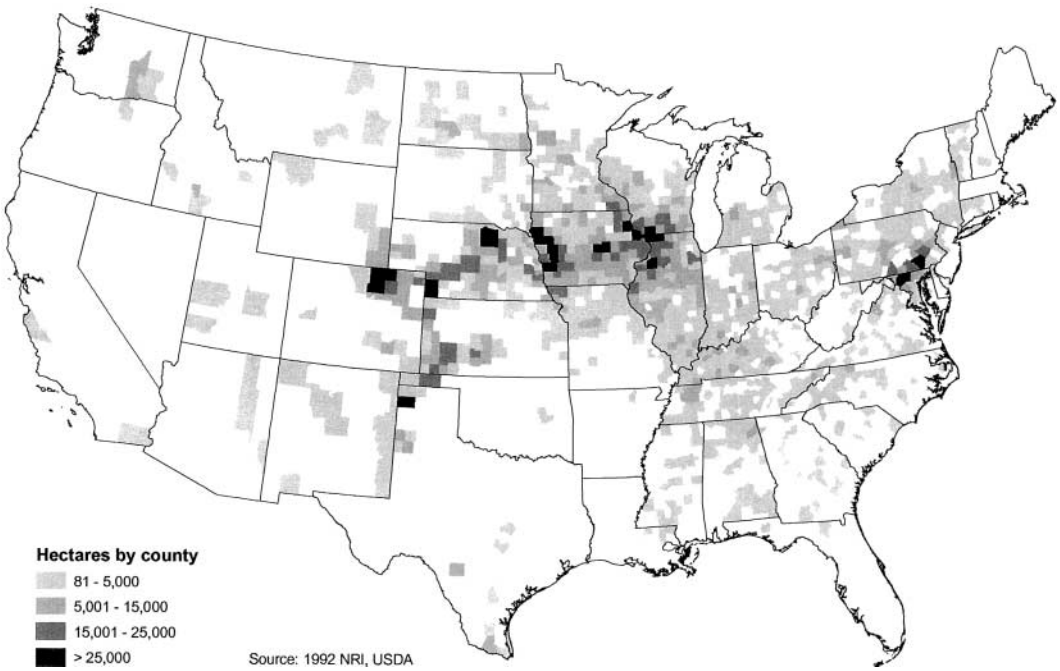

Fig. 2. Corn production on land classified as *highly erodible land* by NRCS (USDA, 1995).

of food, feed, and fiber production capacity and the quality of our environment, we must guard against public policy and industrial decisions based on partial information. The worst action for society would be for actions on the part of government or industry to address near-term problems (overreliance on imported fossil fuels and low farm incomes) that may only aggravate long-term problems (reduction in production capacity of our farmland soils).

In this paper, we use the terms SOM and soil organic C (SOC) frequently. In many cases, the terms can be interchanged without loss of meaning, such as the statement that SOM is positively related to the amount of residue returned to the soil (Maskina et al., 1993). This general relationship is very likely true for SOC, too. However, since the authors measured and reported SOM, we use SOM in this paper. In other cases, authors may have measured and reported only SOC. In this latter case, we report only SOC. In some cases, authors may have used the terms interchangeably. The term SOC is more specific than SOM because it discriminates between organic and inorganic C in the soil and includes only the mass of C in the material, not O, H, N, P, S, etc., that may also be part of SOM. We apologize for any confusion the similarity in terms may cause the reader but feel it necessary to report data and conclusions as they appear in the literature.

We use three terms to describe all, or part, of the aboveground, nongrain part of a corn plant: cornstalk, stover, and residue. In this paper, we define cornstalk as the mature central axis of the plant (i.e., the culm), which is composed of nodes and internodes. Stover and residue are both terms that include all of the aboveground parts of the corn plant (stalk, leaves, cobs, and husk) that remain in the field after grain harvest. The crown and surface (brace) roots are not included in our definition of stover. As we use these terms, stover is this aboveground material before it has weathered or been incorporated into the soil by vehicle or animal traffic or natural action of wind, rain, ice, and snow. Residue is the aboveground, nongrain parts of the corn plant that have been weathered and/or partly incorporated into the soil surface by natural events or human or animal activity.

RESIDUE MANAGEMENT IMPACT ON CROP YIELD

Crop residues clearly influence crop production. In an experiment conducted over 3 yr under rainfed conditions in eastern Nebraska, 0, 50, 100, or 150% (dry weight basis) of the residue produced by the previous crop was returned to the soil. A portion of the residue from the 0 and 50% rates was added to achieve the 150% rate. For each megagram per hectare of the previous corn crop's residue removed, grain yield of the current crop was reduced 0.13 Mg ha^{-1}, and biomass yield was reduced 0.29 Mg ha^{-1} (Wilhelm et al., 1986). These relationships were essentially the same for soybean residue removal: Soybean grain yield was reduced 0.09 Mg ha^{-1}, and grain yield was reduced 0.30 Mg ha^{-1}. The reduction in yield was attributed to reduced water availability and increased soil temperature.

In a 3-yr follow-on study to Wilhelm et al. (1986), Maskina et al. (1993) reported that returning 0, 50, 100, and 150% of the residue produced by the previous crop to the soil resulted in SOM contents (to 30 cm) of 24.7, 25.3, 26.2, and 27.4 g kg^{-1}, respectively. In addition, during the latter 3-yr study (when residue treatments had been discontinued; that is, all crop residues were returned to the plots where they were produced), corn grain and residue yields still differed between the 0 and 150% rates by about 750 kg ha^{-1} (Maskina et al., 1993). Again, the authors attributed the greater production in the plots previously treated with 150% residue rate to

improved water relations in the soil for both plant growth and microbial activity, which enhanced nutrient cycling. Power et al. (1998) indicated that the positive yield response to differential residue applications received 10 yr earlier in the Wilhelm et al. (1986) study was still apparent, with no evidence of decline. Power et al. (1998) suggested that the positive influence of residue applications was caused by changes in soil properties, such as SOM and N cycling. Barber (1979) reported that SOM levels (11 yr after initiation of treatments) were similar for the fallow and residue removal treatment, which were both less than the SOM level for the residue-returned treatment, which, in turn, was less than the SOM in the double-residue treatment. In contrast to the work reported in the series of papers by Wilhelm and coworkers (Wilhelm et al., 1986; Maskina et al., 1993; Power et al., 1998), Barber (1979), working in Indiana, reported no change in corn yield as a result of 6 yr of fallow, residue removal, all residue returned, or double residue returned. Wilts et al. (unpublished, 2004), averaging yields over a 29-yr period from a site in Minnesota, reported no differences in biomass production between plots where silage was removed annually compared with plots where only grain was harvested. This apparent contradiction in yield response may be a result of contrasting tillage practices employed among experiments as suggested by Allmaras et al. (2000) and the different environments characterizing the eastern and western Corn Belt. In the work by Wilhelm and coworkers (Wilhelm et al., 1986; Maskina et al., 1993; Power et al., 1998), corn was grown without tillage or irrigation in Nebraska while Barber (1979) used a moldboard plow for primary tillage and in-season cultivation as part of the weed control regime in his study in Indiana and Wilts et al. (unpublished, 2004), in Minnesota, also used a moldboard plow for primary tillage. As the data in this paragraph and logic would suggest, changes in SOC are proportional to the amount of crop residue returned to the soil (Larson et al., 1972), but tillage system influences SOC retention (Linden et al., unpublished, 2004). Current SOC content is a result of the balance between inputs and output (decomposition and other loss processes). The value of SOM lies in its dynamics. Soil is more productive if SOM is regularly added and subsequently decomposed. In these processes, nutrients and C are cycled and structure maintained or enhanced (Albrecht, 1938).

Parton and Rasmussen (1994) also showed a linear relationship between aboveground input of C and the change in soil C over time. This was expressed as Δsoil C (g m^{-2} yr^{-1}) = $-0.34 + 0.18$ aboveground C input (g m^{-2} yr^{-1}) for their observed data points. Paustian et al. (1992), using the CENTURY model, showed there was a positive, linear relationship across a range of different soil treatments between C input and change in SOC using 30 yr of data. Results of this modeling exercise are consistent with field observations on wheat by Rasmussen et al. (1980) and Parton and Rasmussen (1994) and on corn by Maskina et al. (1993), Barber (1979), and Larson et al. (1972).

Recently, Linden et al. (2000) reported results of a 13-yr study of the influence of tillage, N fertilization, and residue removal on corn grain and biomass production. During 8 of the 13 yr, residue treatment (removed or returned to the soil) affected yield. Over the course of the study, stover yield averaged 4.80 Mg ha^{-1} for the residue-removed treatment compared with 5.24 Mg ha^{-1} for the residue-returned treatment. They also reported that HI did not differ among treatments and averaged 0.56 for their study but was sensitive to weather differences among years. Harvest index was low when total biomass (grain plus stover) yield was low. Computing grain yield from the stover yield and HI data, the residue-removed treatment produced an average of 6.10 Mg grain ha^{-1}, and the residue-returned treatment produced 6.67 Mg grain ha^{-1}. Production was lower with no tillage than with the tilled treatments. When residue was returned and N fertilizer applied, differences among tillage treatments were reduced but not eliminated. In a companion study, Clapp et al. (2000) reported that 13 yr of stover harvest did not affect SOC in the surface 0 to 15 cm compared with the residue-returned treatment if the plots were tilled annually (moldboard or chisel-plowed) and had low N input. In contrast, when stover was returned on no-till plots, the SOC in the surface 30 cm increased 14%. When fertilizer N was applied and the residue returned, the soil consistently had more SOC compared with the residue-harvested treatments regardless of tillage. Clapp et al. (2000) also reported that the combination of returning stover and adding N fertilizer slowed decomposition of relic SOC while the combination of removing stover and adding N increased the decomposition of relic SOC.

Tillage and crop residue management effects on corn yield and soil quality (SOC) has been studied extensively over many years. Unfortunately, most of these reports have been from short-term studies that only suggest what would occur over the course of 1 or 2 yr (Cassel et al., 1995; Karlen et al., 1984) but fall short of indicating what might happen under long-term continuation of these management practices (Dick et al., 1998). Short-term studies also do not account for variation in weather conditions over extended periods nor are they long enough for measurable changes in SOC to occur (Karlen et al., 1994; Linden et al., unpublished, 2004; Wilts et al., unpublished, 2004). Reports of results from long-term studies have been published recently by Angers et al. (1995), Dick et al. (1998), and West and Post (2002). Dick et al. (1998) and West and Post (2002) reported that tillage was an important factor in determining change in SOC, but Angers et al. (1995) found that incorporation of corn-derived C into SOM was not affected by tillage. Dick et al. (1998) and West and Post (2002) indicated that rotations impacted C sequestration mainly through changing C input. Dick et al. (1998) stated that residue removal was less important than tillage or rotation for changing C sequestration.

Tillage and residue management variations create a complex association of soil and surface conditions that both directly and indirectly influence the performance of a crop such as corn. For example, crop residue coverage has been observed to decrease yields because of poor weed control, excessively wet and cold soils, and poor seed placement and stand (Swan et al., 1994). On the

plus side, residues are credited with improving yields through retention of essential nutrients, protection from raindrop crusting (Blevins et al., 1983), and conservation of soil water (Doran et al., 1984). Under most USA Corn Belt conditions, the benefits and risks vary depending on weather and climate. These benefits and risks may also change with time as management practices are continued year after year (Griffith et al., 1988; Linden et al., 2000).

TILLAGE AND RESIDUE IMPACTS ON SOIL ORGANIC MATTER

Tillage has a major influence on SOC, controlling residue placement on the surface and where the residue is buried (Staricka et al., 1991, 1992; Allmaras et al., 1996). Tillage buries residue, but the residue is not distributed uniformly throughout the depth of tillage (Staricka et al., 1991); rather, the incorporated residue tends to be concentrated into relatively narrow bands. Angers et al. (1995) also found differences in the vertical distribution of SOM but not the rate of SOM turnover among tillage depths. Residue burial patterns are characteristic of the tillage tool used (Allmaras et al., 2000).

Allmaras et al. (2000) proposed that the choice of tillage tool was the overriding determining factor for SOC storage. Storage of SOC in shallow soil depths (<7.5 cm) is usually greater with no-tillage than in annually tilled systems where sweep (<10 cm), chisel (15 cm), disk, or moldboard plow (15–30 cm) are the primary tillage tools. However, SOC storage below 7.5 cm can be greater in annually tilled systems (Jastrow, 1996). Allmaras et al. (2000) concluded that no-tillage stored more SOC than non–moldboard plow while moldboard plow stored the least SOC. In recent studies on change in ^{13}C atom percent ($\delta^{13}C$), SOC and $\delta^{13}C$ distribution were dominated by tillage (Layese et al., 2002). Tillage also affects soil bulk density, aeration, and other physical factors, which in turn can affect SOC storage (Angers et al., 1995; Reeves et al., 1997; Dao, 1998; Needelman et al., 1999; Clapp et al., 2000). Numerous factors, such as soil type, sampling depth (Ellert and Bettany, 1995), time since treatments were initiated (Liang et al., 1998), and N fertilizer rate and placement (Gregorich et al., 1995, 1996; Wanniarachchi et al., 1999), interact with tillage to influence SOC storage.

Moldboard plow tillage increased C loss compared with less disruptive tillage practices that are shallow and do not invert the soil (Reicosky et al., 1995; Paustian et al., 1997; Dao, 1998; Allmaras et al., 2000). Conversion from moldboard plowing to no-tillage increases the amount of SOC from 0.13 Mg C ha^{-1} yr^{-1} to as high as 0.60 Mg C ha^{-1} yr^{-1} (Paustian et al., 1997; Janzen et al., 1998b; Bruce et al., 1999; Lal et al., 1999; Smith et al., 2001). Analyzing C sequestration rates from 67 long-term studies consisting of 276 paired treatments, West and Post (2002) showed that across all cropping systems, except wheat–fallow, changing from conventional tillage to no-tillage could result in sequestration of 0.57 ± 0.14 Mg C ha^{-1} yr^{-1}. Most of this increase in sequestration likely occurs in the first 10 yr after changing tillage practice, and a new equilibrium would be approached within 20 yr. Climate plays a role in C sequestration potential for conversion from moldboard tillage to no tillage. The potentials ranged from 0.10 to 0.50 Mg ha^{-1} yr^{-1} for humid temperate regions and from 0.05 to 0.20 Mg ha^{-1} yr^{-1} for semiarid and tropical regions (Lal et al., 1999). Presumably, if there were less C released from soil (output) with reduced tillage or no-till, the amount of C inputs needed to maintain or increase SOC could decrease, thus increasing the biomass available for ethanol production. However, in a 13-yr continuous corn study on Waukegan silt loam, no-tillage and chisel tillage were able to increase or maintain SOC in the surface 30 cm only when the residue was returned (Clapp et al., 2000). The relic SOC decomposition increased when corn residue was removed from tilled treatments, especially when combined with high N application (Clapp et al., 2000). Changing from moldboard plowing to less disruptive forms of tillage (e.g., chisel or no-tillage) increases the amount of C incorporated into SOC (Dick et al., 1998; Clapp et al., 2000; Layese et al., 2002; Linden et al., unpublished, 2004; West and Post, 2002). Relying only on no-tillage and unharvestable C inputs (crown, roots, and root exudates) was insufficient to prevent C loss in these studies.

Larson et al. (1972) estimate, under clean cultivation (moldboard plow), a soil with an initial organic C content of 18 g kg^{-1} would require 6 Mg residue ha^{-1} yr^{-1} to maintain the SOC level (Table 2). Similarly, 5 Mg

Table 2. Reported estimates on the amount of annual C inputs required for maintaining soil organic C levels.

Source	C†	Residue	Initial organic C	Soil type	Location	Crop	Primary tillage
	– Mg ha^{-1} yr^{-1} –		g kg^{-1}				
Black (1973)	0.3	0.8	11–18	sandy loam	Montana	wheat	V-blade 9–12 cm
Rasmussen et al. (1980)‡	1.2	3.0	8.7	–	Washington	wheat	–
Paustian et al. (1992)	1.5	3.8	15	sandy clay loam	Uppsala, Sweden	wheat or barley§	hand tillage
Rasmussen et al. (1980)¶	2.0	5.0	10–16	–	Kansas	wheat	–
Rasmussen et al. (1980)	2.1	5.3	12.5	coarse-silty, mixed mesic Typic Haploxeroll	Oregon	wheat	moldboard plow
Larson et al. (1972)	2.4	6.0	18	clay loam	Iowa	corn	moldboard plow
Barber (1979)	>4.0	10.0	19	silt loam	Indiana	corn	moldboard plow
Huggins et al. (1998)	5.6#	14.0	26–35††	clay loam	Minnesota	corn/soybean	moldboard plow

† Assuming 0.4 g C g residue^{-1}, and only aboveground residue values included, except Huggins et al. (1998), which includes above- and belowground C.
‡ Values based on data originally published by Horner et al. (1960).
§ Before 1973, root crops were grown on five occasions.
¶ Values based on data originally published by Hobbs and Brown (1965).
# The amount of needed input based on only aboveground material would be about 3.7 Mg C ha^{-1} yr^{-1} and 9.25 Mg residue ha^{-1} yr^{-1} assuming belowground inputs contribute 1.5 times more C to soil organic C than aboveground inputs.
†† Crookston et al. (1991).

mature residue ha^{-1} yr^{-1} was required in a wheat–fallow system to maintain SOC (Rasmussen et al., 1980; Table 2). The amount of residue required per year to maintain SOC ranged from <1 Mg ha^{-1} yr^{-1} in Montana to >9.25 Mg ha^{-1} yr in Minnesota (Table 2). Returning more residue increased SOC, returning less resulted in loss of SOC. When the study by Larson et al. (1972) was conducted, average cornstalk (note, only cornstalks) production for continuous corn was 4.7 Mg ha^{-1} (grain yield at 8.2 Mg ha^{-1}), a mass insufficient to maintain SOC. Allmaras et al. (2000) estimated stover yields at 7.3 Mg ha^{-1} yr^{-1} for practices and hybrids used in 1990.

Robinson et al. (1996) reported a positive linear relationship between the amount of corn residue added in moldboard-plowed fields and the increase in SOC in the surface 15 cm. They also reported that current SOC levels were influenced by N fertilizer application rate, initial SOC level, and crop management practices (such as tillage and crop rotation). The slope of the residue application rate–SOC relationship ranged from 0.26 to 0.57 g C kg $soil^{-1}$ (Mg $ha^{-1})^{-1}$ of annual residue addition. Maskina et al. (1993) reported increased SOM with increased amounts of corn stover returned to the soil under no-tillage culture. In contrast, there was no measurable difference in SOC between returning aboveground corn stover and removing silage after 30 yr with moldboard plowing (Reicosky et al., 2002). Incorporation or removal of wheat straw cropped in rotation with other small grains had no effect on soil respiration from soil aggregates on a clay soil (Dexter et al., 2000). Other researchers have also reported little or no effect of retention of cereal crop residues on increasing SOM (Dexter et al., 1982; Johnson and Chamber, 1996; Nicholson et al., 1997). The amount of SOM was the same where winter wheat residue was removed and retained for 30 yr in a fallow–wheat–wheat rotation (Campbell et al., 1991b).

Recent studies on SOC storage and turnover have employed ^{13}C natural abundance ($\delta^{13}C$) as an in situ marker of relic and recent SOC pools. Mass concentrations of SOC and the $\delta^{13}C$ are sufficient to calculate the amount of SOC coming from a C_4 (e.g., corn) or C_3 (e.g., soybean) crop when the initial SOC has a different signature than the current crop (Balesdent et al., 1987). The natural abundance ^{13}C technique has been used to show differences in the depth distribution of SOC (Angers et al., 1995), storage of SOC (Balesdent et al., 1990), and respiration loses of residue C (Rochette et al., 1999) as affected by tillage. Gregorich et al. (1996) reported significant SOC turnover as influenced by long-term N fertilization of continuous corn. A positive interaction between N application and return of corn residue was found, indicating that N fertilization was insufficient to sustain SOC without the return of corn residue (Layese et al., 2002). In addition, removal of stover increased relic SOC decomposition (Clapp et al., 2000). Total organic C and ^{13}C measurements indicated that fertilized soils had more SOC from recent crops than nonfertilized soils; C_4–derived C accounted for the difference in fertilized soils (Gregorich et al., 1996). From 22 to 30% of SOC in the Ap layer was derived from corn in the fertilized soils but only 15 to 20% in an unfertilized soil during a 30-yr study (Gregorich et al., 1996). After 13 yr of continuous corn, a no-tillage system retained 24% of available source C in the SOC pool in the top 30 cm of soil while chisel plow retained 14% and moldboard plow retained 11% (Linden et al., unpublished, 2004).

BELOWGROUND INPUTS AND SOIL ORGANIC MATTER

One problem in defining the importance of stover to the dynamics of SOC is our inability to quantify and describe the total input of C to the soil during and following the active photosynthetic life of a crop. Photosynthetic products enter the soil via rhizodeposition, root material, and shoot residue. Carbon outputs include plant and soil respiration, soil C displacement by erosion, and leaching of soluble C. Belowground C inputs are difficult to measure and, therefore, seldom available. The literature presents many attempts to quantify belowground C inputs (Sauerbeck and Johnen, 1977; Balabane and Balesdent, 1992; Bolinder et al., 1999; Bottner et al., 1999; Flessa et al., 2000). Measured or modeled root mass has been used to estimate C input, but it often fails to account for total C because considerable C may come from root exudates or from decomposed roots that are not measurable with common techniques for assessing root biomass (Balesdent and Balabane, 1996; Sauerbeck and Johnen, 1977). Recently, $\delta^{13}C$ and total C, measured in paired (stover harvest and stover returned) corn plots, were used to estimate corn-derived SOC and the contribution of the unharvestable material (Linden et al., unpublished, 2004; Wilts et al., unpublished, 2004).

Photosynthetically fixed C can be translocated below ground. Kuzyakov (2001) recently reviewed tracer studies on the translocation of C from the atmosphere to the soil. Agricultural cereals (e.g., wheat and barley) translocate 20 to 30% of photosynthetic C below ground. About half of the translocated C was used for root growth, a third of translocated C was respired by the root or was readily decomposable root exudates, and the balance was incorporated into SOC or microbial biomass. Results from a recent modeling exercise by Molina et al. (2001) predicted that 24% of the net C fixed photosynthetically by corn became rhizodeposition. Roots retained less photosynthetic C than was released from roots to the rhizosphere during the growing season, but because roots are more difficult to decompose (relative to rhizodeposition), root debris contributed more C to SOM (Molina et al., 2001).

Root exudates and rhizodeposition are easily decomposable C sources, which appear to retard decomposition of other plant debris and native SOM matter (Goudrain and De Ruiter, 1983; Lekkerkerk et al., 1990; Torbert et al., 2000). In contrast, Bottner et al. (1999) found that after labile material was depleted, the presence of living roots stimulated the mineralization of recalcitrant root material and SOC. The length of exposure to living roots can impact the decomposition of SOC (Kuzyakov and Cheng, 2001). During the growing season, the contribution of living roots changes; early in the season, plant roots have high exudation rates stimulating microbial activity, but as the season prog-

Table 3. Reported estimates of the unharvestable C input relative to the aboveground C input. The amount of biomass retained in the soil, the ratio of root to shoot contribution, total C input including stover, crown, and roots, except from silage or stover-removed experiments.

Source	Root/shoot contribution	Total C input	Soil	Crop	Fertilizer	Tillage†
		Mg ha^{-1} yr^{-1}			kg ha^{-1}yr^{-1}	
Barber (1979)	0.8	4.8	silt loam	corn	280 N, 50 P, 90 K	MBP
Balesdent and Balabane (1996)	1.5	5.0	17% clay	corn	not reported	NR
Bolinder et al. (1999)	1.4	4.5	silty loam	silage corn	150 N	NR
Molina et al. (2001)	1.8	4.6	silt loam	stover removed	0 N	CP
Linden et al. (unpublished, 2004)	2.6	5.9	silt loam	corn	200 N	MBP
Linden et al. (unpublished, 2004)	2.0	3.4	silt loam	corn	0	MBP
Linden et al. (unpublished, 2004)	2.6	5.9	silt loam	corn	200 N	CP
Linden et al. (unpublished, 2004)	2.0	3.2	silt loam	corn	0	CP
Linden et al. (unpublished, 2004)	2.6	5.9	silt loam	corn	200 N	NT
Linden et al. (unpublished, 2004)	2.0	3.2	silt loam	corn	0	NT
Wilts et al. (unpublished, 2004)	1.8	8.2	clay loam, silt loam, silty clay loam	corn	166 N, 46 P, 90 K	MBP
Wilts et al. (unpublished, 2004)	1.9	7.7	clay loam, silt loam, silty clay loam	corn	83 N, 23 P, 45 K	MBP

† CP, chisel plow; MBP, moldboard plow; NR, not reported; NT, no tillage; RT, ridge tillage.

resses, the exudation rates decrease, and late in the season, the primary root inputs are senescing root material and shoot input (Kuzyakov and Cheng, 2001).

Roots contribute more C to SOM than aboveground residue. For example, Gale and Cambardella, (2000) using ^{14}C found that 75% of the new C entering soil was root-derived while a large portion of the surface-residue–derived C was released as CO_2. Five months after incorporation of ^{13}C-labeled hairy vetch (*Vicia villosa* Roth subsp. *villosa*), about 50% of root-derived C was still in the soil while only about 13% of shoot-derived C was retained (Puget and Drinkwater, 2001). Barber and Martin (1976) estimated 37% of corn root C was incorporated into SOM, but only about 11% of aboveground corn residue was retained as SOM. Similar values have been reported by Angers et al. (1995) and Flessa et al. (2000). A slower rate of root decomposition, relative to shoots, increases the residence time of root-derived C in the soil (Huggins et al., 1998; Balesdent and Balabane, 1996).

There are relatively few studies that allow direct comparison of C originating from unharvestable tissues (roots, crown, and exudates) compared with stover (Table 3). The relative contribution of unharvestable tissues compared with shoots averages 1.9, ranging from 0.8 to 2.6 (Table 3). Some of the differences may reflect the different methods used to estimate the retention time. Although different methods were employed, the literature provides evidence that roots contribute more C to SOC than does aboveground residue. This is intriguing since corn averages 5.5 times more aboveground material compared with root material (Bolinder et al., 1999). It is important to stress that although roots contribute more C to SOC, this does not imply that aboveground residue is not an important contributor. As noted in the sections "Residue Management Impact on Crop Yield" and "Tillage and Residue Impacts on Soil Organic Matter," removal of aboveground residue can result in a substantial decrease in SOC.

RETENTION OF CROP-DERIVED SOIL ORGANIC MATTER

Retention of crop residue C as SOM involves complex biochemical reactions within the dynamic soil environment. Literature abounds with information about factors that influence the quantity of C retained. The list includes mass of C inputs (Huggins et al., 1998; Follett, 2001), initial SOC content (Campbell et al., 1991a), soil texture (Needelman et al., 1999), temperature and water regime (Gregorich and Janzen, 2000), soil N content and fertilizer applications (Balabane and Balesdent, 1992; Green et al., 1995), residue contact with soil (Clapp et al., 2000), proximity of N fertilizer and fresh source of C (Clapp et al., 2000), tillage tool (Allmaras et al., 2000), and the chemical composition of the residue (Berg and Matzner, 1997). The major influences of C retention are not defined clearly because of uncertainties in our ability to sample and measure both C inputs and SOC changes. Mann et al. (2002) noted the continued inability to accurately model short-term C dynamics. Some of the uncertainties are associated with conversion from measured mass concentrations to field-area basis, which may involve unequal sampling masses (i.e., incomplete sampling depth; Ellert and Bettany, 1995), lack of precision in instrumentation (Veldkamp and Weitz, 1994), unspecified spatial and temporal sampling variability (Veldkamp and Weitz, 1994), and failure to report SOC on a volumetric basis that allows accurate comparisons of SOC change across treatments and time.

Only a small portion of the plant residue added to soil is converted to stable SOM. It is estimated that only one-third of the C derived from plant residues remains in the soil after 1 yr (Angers and Chenu, 1997) and only 10 to 20% remains after 2 yr (Broder and Wagner, 1988; Buyanovsky and Wagner, 1997; Stott and Martin, 1990). Maintenance of SOM requires that efflux does not exceed influx. The small amount of new C converted to stable SOM implies that a large influx is needed to provide substrate in excess of respiratory demand of soil fauna.

The half-life of SOM ranges over several orders of magnitude, from weeks to more than 1000 yr (Allmaras et al., 2000; Carter, 2002). Studies using $\delta^{13}C$ have estimated the SOC half-lives from 47 to 176 yr (Balesdent et al., 1990; Gregorich et al., 1995; Gregorich et al., 1996; Huggins et al., 1998; Clapp et al., 2000). The overall decomposition rate of residue or SOM reflects the inte-

grated decomposition rates and relative amounts of soluble C (e.g., carbohydrates, amino acids), hemicellulose, cellulose, lignin, and N (Kumar and Goh, 2000; Parr and Papendick, 1978). Dissolved organic C (carbohydrates, amino acids, and other organic molecules) is labile with a half-life of only several hours (Kumar and Goh, 2000; Uselman et al., 2000), hemicellulose and cellulose have half-lives on the order of days, and the half-life of lignin is about 1 yr (Kumar and Goh, 2000; Eiland et al., 2001). The protection of SOC via physical and chemical means causes a portion of the SOC to have an effective half-life that is much greater than that characteristic of the chemical components of new residue. Corn stover has 6 to 11% lignin (Broder and Wagner, 1988; Martens, 2000; Masoero et al., 1999; Parr and Papendick, 1978), 28 to 30% cellulose (Broder and Wagner, 1988; Parr and Papendick, 1978), 18 to 24% hemicellulose (Broder and Wagner, 1988; Parr and Papendick, 1978), and 0.4 to 1% total N (Martens, 2000; Parr and Papendick, 1978). Corn roots have 8% lignin, 0.97% total N, and a C/N ratio of 48 (Iritani and Arnold, 1960). The greater contribution of roots to SOM has been attributed to roots having greater lignin and lesser soluble C compared with shoots (Bolinder et al., 1999; Iritani and Arnold, 1960; Torbert et al., 2000; Trinsoutrot et al., 2000b). Initial decomposition of crop residue correlated with amount of soluble C, but later decomposition correlated with the concentration of cellulose, hemicellulose, and lignin (Gregorich and Janzen, 2000; Trinsoutrot et al., 2000a).

WEATHER AND CLIMATE EFFECT ON SOIL ORGANIC MATTER

Regardless of the quantity or quality of crop residue on or in the soil, at an ecosystem scale, environmental conditions, especially temperature and water availability, are the factors that ultimately control changes in SOM. Parton et al. (1996) presented the following equation to describe the dynamics of SOM within agricultural systems,

$$dC/dt = hA - kC \quad [1]$$

where C is the soil C level (g C m^{-2}), h the C storage constant, k the decomposition rate of C in the soil (yr^{-1}), t time (years), and A the addition of organic C to the soil (g C m^{-2} yr^{-1}). This equation serves as a model for assessing the impact of weather and climate on SOM. Changes in the soil microclimate determine k. Changes in weather and climate determine A through their effect on plant biomass produced and subsequent return to the soil. This formulation is a result of earlier work by Parton et al. (1987) that described the change in C within soils from the following relationships:

$$dC_i/dt = K_i \times M_d \times T_d \times C_i \quad [2]$$

where i represents the different state variables (structural and metabolic soil surface litter; structural and metabolic soil litter; active, slow, and passive soil fractions) describing the various C pools (C_i), K_i is the maximum decomposition rate for the different state variables,

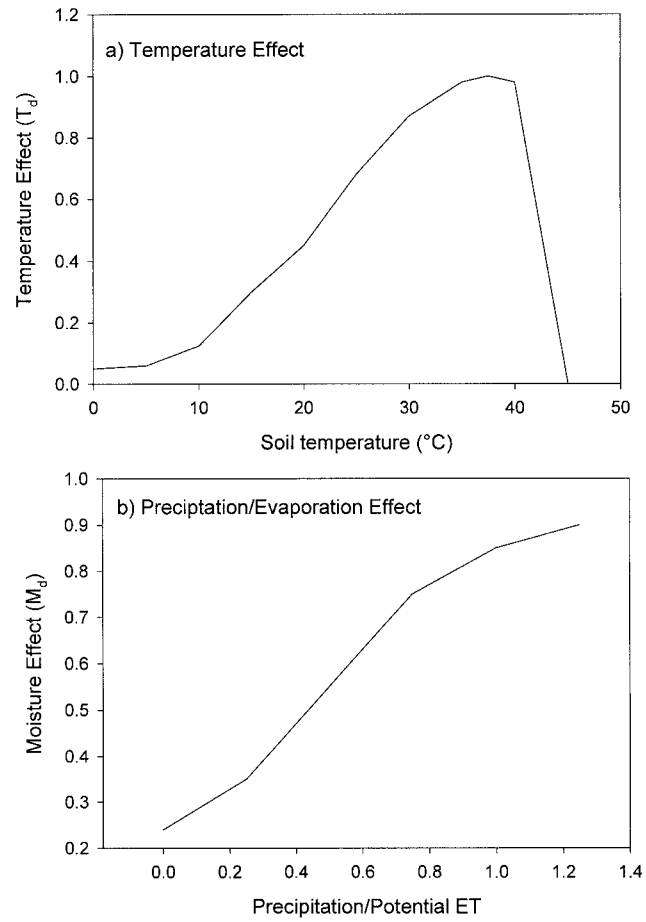

Fig. 3. (a) Temperature effect and (b) moisture effect for the CENTURY model used to quantify the change in soil organic matter pools (redrawn from Parton et al., 1987). ET, evapotranspiration.

M_d is the effect of the ratio of monthly precipitation to potential evapotranspiration rate on decomposition, and T_d is the effect of monthly average soil temperature on decomposition (Parton et al., 1987). The relationships for the effect of soil temperature and precipitation/potential evapotranspiration ratios are shown in Fig. 3. The vast difference in the shapes of the relationships between the moisture and temperature functions show the dissimilarity in impacts of these two weather/climate factors on SOM changes. Both Eq. [1] and [2] indicate that SOM changes are sensitive to deviations in temperature and moisture that are mediated by changes in crop residue additions.

Changes in the soil microclimate alter both the M and T terms in Eq. [2]. There have been comprehensive studies on the combined effects of crop residue on soil temperature and moisture (e.g., Allmaras et al., 1972; Van Doren and Allmaras, 1978; Cruse et al., 1982). The effects of crop residue on the surface energy balance were summarized by Horton et al. (1994). They showed that the energy balance of the soil surface is dominated more by soil water content near the surface regardless of the type of residue or the configuration of the residue on the soil surface. Bristow (1988) showed that under wet conditions at the soil surface, there was no difference in the soil temperature profiles for bare soil or

soil covered with either vertical or horizontal mulch. In contrast, under dry surface conditions, the maximum temperature at the 2.5-cm depth was 6°C warmer with bare soil than with residue covering the surface; however, no detectable difference was observed between the bare and residue-covered surface for minimum temperatures. Sauer et al. (1996) showed that evaporation amounts were reduced by 0.4 mm d^{-1} when corn residue was placed on the soil surface. The reduction in evaporation rates increases the time the soil surface remains wet. Presence of the residue layer increases the resistance of water vapor transfer through the layer and, consequently, decreases the evaporation rate. This creates a discontinuity in the microclimate at two locations: (i) at the interface between surface of the residue and the atmosphere and (ii) at the soil surface at the underside of the residue layer. It is common to observe temperature differences as large as 20°C across a 10-cm residue layer. Sauer et al. (1996) observed that the effectiveness of corn residue to act as a water vapor barrier changed as the residue weathered over the winter. In the fall, with fresh residue, there was a larger effect on soil water evaporation than in the spring with aged residue. Hatfield and Prueger (1996) confirmed these findings, reporting that soil temperature differences between bare plowed and residue-covered nontilled fields in the fall were 2°C while in the spring, the differences were less than 0.5°C. Residue had a greater effect on the amplitude of the diurnal temperature patterns than on mean temperature.

Presence of crop residues changes the soil energy balance over the winter. Reflectivity of corn residues decreased over the winter to the point where residues were difficult to distinguish from bare soil in central Iowa (Sauer et al., 1997). Sauer et al. (1998b) showed that adding corn residue to the soil surface altered the energy balance. However, in cases when the soil surface was dry and the residue was wet due to small rainfall events, the evaporation rate remains near the potential evaporation rates as long as the water supply in the residue persists. The degradation of the cornstalk cuticle over the winter causes the residue layer to have a larger water storage capacity compared with fresh residue. Evaporation rates in the fall, with the fresh residue, never exceeded 0.8 mm d^{-1} but ranged between 0.6 to 2.0 mm d^{-1} in the spring under similar environmental conditions (Sauer et al., 1998b). When residue dries, the vapor barrier established between the soil surface and the atmosphere reduces the evaporation rate at the soil surface. This creates a condition in which the residue layer preserves soil water and produces the *mulch* effect. Steiner (1994) provided a detailed review of the effect of residue on the evaporation process and the effect of residue on reducing soil water evaporation rates.

Another change that occurred over the winter in the central Corn Belt was the smoothing action of the snow and wind on the corn residue layer. Sauer et al. (1998a) showed that the roughness of the surface, and therefore the drag coefficient, decreased over the winter. This creates a condition in the spring that reduces the energy exchange process with the atmosphere and further reduces the rate of water evaporation from the soil surface. As the surface becomes smoother, the energy exchange through turbulence is decreased. The changes in configuration of the residue layer over the winter affect energy exchanges, and through it, the soil temperature and water status, and in turn, the rate of SOM change.

If field observations are combined with the temperature and moisture effects shown in Fig. 3, the impact surface crop residue has on SOM through changes in soil microclimatic factors can be assessed. From Fig. 3., increasing soil temperature (to about 40°C) will increase SOM decomposition (Eq. [2]). The dampening of the temperature extremes, due to the presence of residue, may slow the turnover of SOM pools, depending on the average temperature regime of the site. Generally, residue on the soil surface reduces the rate of water evaporation from the soil surface. Maintaining soil water content increases residue decomposition rate at the underside of the residue layer and in the surface soil layer. These assessments of change in the temperature and soil water content under residue do not account for all of the effects that altered microclimate has on soil microbiology. Biederbeck and Campbell (1971) found that increased temperature extremes generally had a negative impact on microbial populations. Soil microclimate conditions, within tilled soils with no residue cover, show the largest diurnal temperatures extremes during the period when growing plants are not present (Hatfield and Prueger, 1996; Rickman et al., 2001). The relationships shown here (Fig. 3) provide a basic framework for assessing impacts of residues on the soil surface, at least qualitatively. The challenge remains to verify the quantitative effects described by relationships.

The other major factor in both Eq. [1] and [2] determining the effect of weather and climate on SOM is the amount of biomass produced. Although biomass yield has been discussed in earlier sections of this paper, we will summarize it briefly here in the context of Eq. [1] and [2]. Factor A in Eq. [1] and factor C_i in Eq. [2] represent the amount of biomass added to the soil surface. Favorable weather increases the crop residue produced during the growing season. Variations in production among years due to weather changes, mostly precipitation differences, cause large differences in biomass production (Wilhelm et al., 1987). These yearly differences can be as great as 7 Mg ha^{-1} for the central Corn Belt if irrigation is not part of the cultural system. Generally, annual fluctuations in stover production are less under irrigated production. Biomass yield for wheat in eastern Colorado is typically 2 Mg ha^{-1} while yield for corn in central Iowa is 12 Mg ha^{-1}. This difference has a dramatic impact on the ability of a production system to sustain or create SOM. Carbon input will change with crop, year, and management practice. Suitability of different crops to different climates changes the amount of residue produced.

SOIL COMPACTION IMPLICATIONS OF STOVER COLLECTION

Soil compaction is defined as the process whereby soil particles are pushed closer together with an accom-

panying decrease of total pore space in the bulk soil mass. The main source of soil compaction induced by human activity under modern agriculture is from the forces applied to the soil surface by wheels (for simplicity, the word wheels implies both wheels and tracks on farm equipment unless otherwise stated) of farm equipment used during farming operations. The extent to which wheel traffic causes soils to compact depends on several factors, the two most important being soil water content and force applied to the soil. Several studies, conducted on a range of soils, suggest that the force applied to the soil surface should not exceed 0.70 kg cm^{-2} to prevent compaction that would negatively impact plant root growth (Vermeulen and Perdock, 1994). Under many situations, it is possible to keep loads below this limit, even on large four-wheel drive tractors, if tracks, low-inflation-pressure tires, or multiple wheels per axle are used. Nevertheless, if the soil is near field capacity, even very low pressures can cause deformation of the soil surface structure to the point of decreasing water infiltration and causing soil erosion.

The removal of corn stover impacts soil compaction in two ways: (i) removal of organic matter on or near the soil surface and (ii) increased field traffic during collection and removal. Soil organic matter can help soil resist the huge compactive forces of modern tillage and harvest equipment. The impacts of organic matter on soil compactibility are important but difficult to quantify as reviewed by Soane (1990). Generally, there is a direct relationship between soil-incorporated organic matter content and the stability of soil structure and an opposite relationship with soil bulk density. However, the ability of surface residue (e.g., corn stover on the soil surface) to overcome the compactive force of wheel traffic may be limited (Gupta et al., 1987). In field studies, water infiltration rates were slower in the wheel-tracked areas of no-till even though corn stover was left on the soil surface. With the heavy wheel loads commonly applied during corn harvest, it seems unlikely that the compactive forces of the wheel can be mediated by corn stover on the soil surface. However, to whatever extent corn stover on the soil surface eventually increases SOM, compaction from wheel traffic should decrease.

The removal of corn stover for energy production normally requires at least three additional field operations: (i) concentrating stover into rows, (ii) consolidating loose fluffy material, and (iii) transporting across/from the field. The increased wheel traffic over a field to collect and remove corn stover is perhaps more definitive. As discussed previously, the weight being carried by the wheel and the soil water content are two very important factors governing the extent a soil is compacted by traffic. Another important factor is preconsolidation; that is, the history of compaction on the unit of land. A field that has a high bulk density due to previous heavy wheel traffic can withstand another pass of a heavily weighted wheel better than a field that has a low bulk density. However, the field with a history of heavy wheel traffic will likely be more compacted and less productive than a field with little or no history of heavy wheel traffic.

Theoretically, harvest equipment can be modified so that stover is collected as it emerges from the harvesting machine and deposited (in either consolidated or loose form) at the edges of the field, thus eliminating the need for the three additional field operations mentioned above. However, a machine capable of harvesting corn grain and collecting and transporting corn stover in one operation will almost surely have increased weight compared with current harvest equipment. Depending on the size and weight of the equipment and on the soil characteristics, this wheel traffic and the ensuing soil compaction can have significant practical consequences. The practical implications of soil compaction, with respect to stover removal for energy production, can best be understood by delineating the effects of surface compaction from that of subsoil compaction.

Surface Compaction

For purposes of this discussion, surface compaction refers to the normally tilled layer of soil, or roughly the surface 20 to 30 cm of soil. The physical structure of this layer, especially at the poorly defined interface between soil surface and atmosphere, is critical in determining the rate of water movement into the soil profile and therefore soil erosion (Onstad and Voorhees, 1987). Compaction not only decreases the total amount of soil pore space available to store water, but also generally decreases the mean pore diameter, which in turn decreases the infiltration rate of precipitation or irrigation water. Bauder et al. (1981) reported that continuous no-till of a clay loam soil in southern Minnesota resulted in greater levels of mechanical impedance (important for water infiltration and root growth). Lindstrom and Voorhees (1980) reported lower infiltration rates on no-till compared with conventional tillage, and wheel traffic compaction tended to eliminate difference between tillage methods.

Voorhees et al. (1979) reviewed the various ways in which wheel-induced surface soil compaction can impact water runoff and soil erosion. In field research conducted in Minnesota, Young and Voorhees (1982) showed that about 50% of the total soil moved in the erosion process came from the wheel-tracked area even though the wheel tracks covered only 25% of the surface. One winter of freezing and thawing cycles in clay loam soil in southwestern Minnesota is relatively ineffective in ameliorating surface soil compaction while moldboard plowing was very effective; conservation tillage was intermediate (Voorhees, 1983). Collectively, these data suggest normal wheel traffic in a no-till system, even in soils that are subjected to annual freeze-thaw, will result in soil with a greater density (greater level of compaction) than soils subjected to annual tillage. The greater density will decrease water infiltration rate and increase water runoff and soil erosion. This could be offset in some soils by increased earthworm activity and greater number of macropores under no-till. But, the assumption that no-till will improve soil tilth and decrease soil erosion, thus allowing removal of corn stover for energy production, must be tempered with

the fact that increased field operations to collect and remove the stover will add more wheel traffic (and compaction) to the field and could exacerbate a problem.

The extent to which corn stover can be harvested without negatively impacting soil structure may also depend on the extent to which corn roots contribute to total SOM in the surface 30 cm of soil. Wheel-induced compaction in the surface 30 cm of soil interacts with tillage systems to create a very complex environment for root growth. For example, there was a 40% decrease in root growth in the surface 30 cm of soil under a conservation tillage system compared with a conventional plow system. However, surface compaction from interrow wheel traffic had little effect on root growth in a conservation tillage system but reduced root growth by 24% under the moldboard plow system (Voorhees, 1992).

Subsoil Compaction

Because farming is being done by a decreasing number of farmers, it is necessary to use larger-capacity farm machinery to conduct field operations in a timely manner. These larger machines generally also carry more weight. Equipment commonly used during corn harvest carries weights ranging between 10 and 40 Mg axle^{-1} (Voorhees et al., 1986). Compare this to maximum axle load limits of 10 to 12 Mg axle^{-1} on public hard-surfaced highways.

Results from an international study on subsoil compaction from high-axle-load wheel traffic on a range of soil types, climatic conditions, and crop species clearly show that axle loads in excess of 10 Mg axle^{-1} can cause significant deep-soil compaction with negative effects on plant growth (Hakansson et al., 1987). Soil compaction deeper than 30 cm can be considered *permanent* under normal farming operations where heavy wheel traffic is applied every season. Voorhees et al. (1986) showed that in Minnesota, axle loads of 10 and 20 Mg axle^{-1}, typical for corn harvest operations, increased compaction and decreased saturated hydraulic conductivity to depths of at least 60 cm. These loads subsequently decreased corn grain and stover yield by up to 30%, depending on soil water content at time of trafficking, soil type, and growing season conditions (Voorhees et al., 1989). In Ohio and southern Ontario, under wetter soil environments, corn yields were decreased as much as 50% (Voorhees, 2000). Assuming a grain/stover ratio of 1 (i.e., HI = 0.50), this also means a potential 50% decrease in harvestable corn stover. Can limits be established whereby soil conditions can be identified and quantified as to their susceptibility to being compacted by a given wheel trafficking? The answer is a qualified yes. A major effort is underway in Europe to do just that (Anonymous, 2000). Coupled with similar but less intensive efforts in the USA, it should be possible to specify the axle load or tire/track–soil contact pressure beyond which field operations to harvest corn stover can be expected to cause detrimental soil compaction. Conversely, one could also estimate the soil water content below which it is safe to use stover-harvesting equipment on a particular field without causing compaction.

A serious limitation to these guidelines is that they do not account for the timeline of field operations. For example, if a field is judged to be too wet (from the standpoint of causing compaction), the choices are either (i) waiting until the soil dries sufficiently (or freezes) to support the heavy equipment or (ii) using smaller, lighter-weight equipment or hauling smaller loads to reduce gross vehicle weight. Both options require more time, which is normally not available during corn harvest. The option of waiting until the soil dries or freezes to support heavy equipment may be compromised by snowfall and loss of stover quantity and quality. A third option of equipping machinery with more or wider tires should decrease compactive pressure per unit area but will also increase the portion of field being trafficked.

BY-PRODUCT OF ETHANOL PRODUCTION FROM CORN STOVER AS A SOIL AMENDMENT

Biomass ethanol production plans usually state that the highly ligneous fermentation by-product will be burnt to produce heat needed for ethanol distillation and generation of electricity to operate the production plant and sell to other users (McAloon et al., 2000). As an alternative, the by-product could be returned to the field as a soil amendment. The by-product would provide a source of C for SOM. The composition of the by-product is considerably different from the original corn stover in that most of the readily available C is consumed during the fermentation process. After the production of ethanol from corn stover, the resulting by-product has 62% lignin, 13% cellulose, 3% hemicellulose, and 2% N according to the National Renewable Energy Laboratory, Golden, CO (J. McMillan, personal communication, 2002). Baled corn stover is about 20% lignin, 36% cellulose, 23% hemicellulose, and <1% N (NREL, 2002). The lignin and N concentration are increased in the by-product while hemicellulose and cellulose concentrations are decreased compared with corn stover. The change in composition would make the by-product more resistant to decomposition as the half-life of lignin is much longer than the half-life of hemicellulose, cellulose, and sugars (Kumar and Goh, 2000; Parr and Papendick, 1978; Uselman et al., 2000). Laboratory trials support these hypotheses (Johnson et al., 2004). After amending soil cores with either corn stover or the by-product of biomass ethanol production, the equivalent of 56% C from corn stover was released as CO_2 but only 18 to 36% of the C from the by-product (Johnson et al., 2004).

Johnson et al. (2004) hypothesized that due to the delay in decomposition, the by-product may serve as a viable precursor to SOM. The addition of the by-product to soil with about 20 g organic C kg^{-1} soil had little effect on soil properties such as aggregate stability, aggregate size distribution, and humic acid concentration. However, when applied to a soil with less than 5 g organic C kg^{-1} soil, the concentrations of humic acid and aggregate stability were increased proportionately to the amount of by-product added (Johnson et al.,

2004). Returning the lignin-rich by-product may be especially beneficial on soils with low organic matter and could be used on a site-specific basis on eroded or degraded soil to improve organic C content. After fermentation, there is 0.2 to 0.3 kg of by-product per kg of initial corn stover (J. McMillian, personal communication, 2002). Applying the by-product to the field may be a viable disposal method, but it would not entirely replace the C removed.

HARVESTABLE RESIDUE

Corn exceeds other leading global cereal crops (rice and wheat) in biomass production (Wright et al., 2001). The amount of potentially available C from corn stover (leaves, stalks, and roots) was at least 1.7 times more than the amount estimated for barley, oat, sorghum, soybean, sunflower, and wheat (Allmaras et al., 2000). Thus, of the grain crops, corn provides the largest potential pool of biomass for ethanol production. In the introduction, estimates were made on how much stover would be available on a regional and national level. The estimates presented by Nelson (2002) are more conservative compared with those of Hettenhaus et al. (2000). The recent review by Mann et al. (2002) does not give recommendation of harvestable residue, recognizing research is still needed to project long-term effects of stover harvest on soil and water quality, SOC dynamics and storage, and interactions among cropping systems and management issues.

Most management and C input studies have focused on aboveground biomass (Table 2), but as was discussed above, roots contribute more than half the C inputs. In addition, most of the studies conducted were done using moldboard plow tillage. Best management practices and aboveground residue harvest rates need to be established for minimum amount of stover that must be retained on the soil to maintain and/or increase SOM, minimizing erosion and protecting soil quality and productivity. This very complex issue must be addressed regionally if not on a field or even subfield basis. Current estimates on the annual residue inputs range more than an order of magnitude, from 0.8 to 14 Mg ha^{-1} (Table 2). Rotation, tillage, and fertilization management; soil properties; and climate will all play major roles in determining the amount of stover that can be removed in a sustainable system.

Producers and biomass users also need to determine if stover harvest is economical if only 20 to 30% of the biomass produced can be harvested. A soil management tool such as the Soil-Conditioning Index (USDA-NCRS, 2001) based on a model developed by Austin (1964) provides a field-level aid to delineate the amount of residue required to maintain SOM. This model allows comparison of tillage operations, yields, and residue removal rates on the SOM levels. For example, a clay loam soil in Lincoln, NE, in a corn–soybean rotation with annual tillage using a chisel plow would have insufficient average biomass production to recommend removal of stover. Currently, the model is not configured to predict the amount of stover that can be removed on a large scale. The question remains: How much stover can be removed without negatively impacting SOC, erosion, and long-term yield potential? The interaction among tillage, compaction, and other management issues needs to be addressed by both field and modeling studies.

THE CHALLENGE

As agronomists with expertise in all of the varied aspects of crop production and soil management, we have, or can acquire, the knowledge needed to assist the bioenergy industry to create a truly sustainable fuel and energy supply. We are challenged to go beyond the normal process for dissemination of scientific results by authoring journal papers; we must engage the key movers in the fledgling industry to make them aware that crop residues have had, and continue to have, critical and legitimate uses in land management. Through this review, we are making the initial steps in this process. In addition, and more difficult, we have the responsibility and challenge of making realistic recommendation on how much stover or crop residue can be removed from the land as a biofuel feedstock or feedstock for other industries. By making realistic recommendations, we foster several products for society on a sustainable basis. We provide farmers and rural communities the advantage of a new source of income. We befriend and cooperate with an industry that may otherwise be perceived as an adversary because it competes for a resource (stover) that has not been useful to outside industry in the past. Lastly, we fulfill our societal mandate to develop the technology to SAFELY and SUSTAINABLY address three important societal issues—overdependence on imported fuels, increasing greenhouse gas concentrations in the atmosphere, and feeding the growing world population.

SUMMARY

Three of the most pressing societal problems, in the midterm, are overreliance on imported fuels, increasing levels of greenhouse gases in the atmosphere, and ability of our agricultural systems to sustain food production at rates needed to feed a growing world population. Collection of crop residues as a feedstock for biomass ethanol production is an appropriate solution for the first two problems. However, these residues are necessary to protect soil from erosion and contribute to SOC levels, a key factor in most desirable characteristics of soil quality, and are positively related to soil and crop productivity. The impact of crop residue removal on soil quality and crop productivity must be assessed before prudent decisions and policy can be developed to guide this emerging industry. As with most agronomic practices, results from studies reported in the literature do not provide consistent conclusions on the impact of residue removal on soil characteristics and crop yield. Reasons for the contrasting results are related to factors such as existing SOC levels, climate and weather, soil characteristics, and crop management practices. Difficulties in accurately measuring changes, especially in the short

term, in SOC level also contributed to the apparent conflicting conclusions.

From many studies, it is apparent that weather and climate not only impact how and at what pace crop residue becomes SOC, but crop residues strongly impact the microclimate under which the crop residues decompose to form SOM and conditions under which the crop grows and develops. The presence of surface crop residue has a greater impact on the amplitude of diurnal soil temperature than the mean. This impact is greatest when residue is fresh and diminishes as the residue weathers. Soil temperature effects of residues are involved in a complex set of processes that result in reduced evaporation of water from soil when it is covered with residue.

Collection and transport of corn stover from a field will involve wheel traffic, which can cause soil compaction, leading to water runoff, soil erosion, and decreased dry matter production in following years. Parameters of equipment weight and soil factors can be quantified to set *safe weight limits* to minimize soil compaction but must be evaluated against the constraints of timely, efficient residue harvest.

Within limits, corn stover can be harvested for ethanol production and provide the USA with a renewable, domestic source of energy that recycles greenhouse gases. Recommendation for removal rates must to be based on regional yield, climatic conditions, and cultural practices. The challenge for agronomists and soil scientists is to gather, summarize, and report data on which stover removal recommendations can be based so that a SUSTAINABLE domestic biomass energy industry can be developed. In establishing recommendations, the current problems of overreliance on imported fuels, increasing levels of greenhouse gases, and agriculture's long-term ability to provide food, feed, and fiber for a growing world population must be addressed.

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