CHAPTER 6

Management Impacts on Carbon Storage and Gas Fluxes (CO_2, CH_4) in Mid-Latitude Cropland

Keith Paustian, G. Philip Robertson, and Edward T. Elliott

I. Introduction

Agricultural ecosystems comprise an estimated 11% of the land surface of the earth (Houghton et al., 1983) and include some of the most productive and carbon-rich soils. As a result they play a significant role in the storage and release of C within the terrestrial carbon cycle. At the same time these ecosystems are highly impacted through human activities and thus processes determining net carbon fluxes to the atmosphere are to a large degree influenced by land management practices.

In the context of global change, three major issues dealing with soil C balance and the emission of greenhouse gases from soil have come to the fore. These are (i) the potential for increased CO_2 emissions from soil under conditions of global warming, giving rise to a positive feedback on the greenhouse effect (Jenkinson et al., 1991), (ii) increased emission of other radiatively-active trace gases from soil as a consequence of land management practices [(e.g., greater N_2O emission and less CH_4 consumption with increased N fertilizer use (Bronson and Mosier, 1993; Robertson, 1993)], and (iii) the potential for increasing C storage in soils to explain what appears to be a contemporary mid-latitude CO_2 sink of 1.3-2.4 Pg yr^{-1} C (Tans et al., 1990) and to help ameliorate future increases of CO_2 in the atmosphere (Barnwell et al., 1992).

In this paper we will examine processes determining the carbon balance in agricultural soils, focusing in particular on the role of land management practices in influencing these processes. Our objectives are to provide a perspective on which practices are most likely to be important for shifting the balance towards greater storage of carbon in soils and reducing the net emission of CO_2 and maximizing the net capture of CH_4 in soil, and to examine the interactions between management and environmental controls on soil C under conditions of global climate change

II. Historical Perspective on Temperate Zone Agriculture and Soil C

Throughout most of the ~8,000 year history of agriculture, human use of the land for farming and grazing purposes probably had little effect on the global C cycle. This was due to low population densities, and consequently the relatively small area of land devoted to agriculture, and the extensive agricultural techniques used. However, locally and even regionally, some human-induced changes in amounts and distribution of soil carbon were likely significant, such as with deforestation and soil erosion occurring in the Mediterranean region during the Greek and Roman eras.

In temperate regions, early agriculture was primarily based on slash-and-burn methods. Carbon losses incurred by land clearing and cropping were largely restored upon abandonment of fields during a fallow period. As agriculture became more settled, with a permanent landbase, and as cultivation practices intensified, soil fertility and soil organic matter became more severely depleted. The 2- and 3-field farming

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systems, where one field was fallowed annually in rotation, typified European agriculture through the Middle Ages and into the 16th-17th centuries. However, replenishment of soil organic matter and plant nutrients through the addition of animal manure and with a brief fallow period in the rotation was generally insufficient, resulting in chronically low productivity and periodic cycles of famine and land abandonment (Seebomn, 1976).

By the late 17th and 18th centuries, land reform, the introduction of new crop rotations, including root and hay/legume crops, improved stock breeding and animal husbandry (hence greater manure production), and more efficient tillage methods gradually improved agricultural productivity in Europe and probably increased soil C stocks on historically tilled areas. By the mid 1850's these practices, typified by the famous Norfolk four-course rotation, were well established in western Europe and may have represented a near optimum situation for maintaining organic matter in agricultural soils (Steen, 1989).

Ironically, this same period also marks the beginning of a massive global loss of soil C associated with the rapid expansion of agriculture onto grassland and forest soils in North America, Australia, southern Africa and Eastern Europe (Wilson, 1978; Haas et al., 1957). While the intensive European-style of tillage based on the moldboard plow was widely adopted, the high native fertility of these newly cultivated soils as well as various economic and ecological constraints generally discouraged the use of crop rotations, manuring, ley cropping, and other practices beneficial to soil C maintenance (Cochrane, 1979). The net effect of this expansion of "exploitative" agriculture may have released as much as 110 Pg C from soils (Wilson, 1978), contributing to perhaps 25% of the ppm increase in atmospheric CO_2 prior to 1900.

The technological revolution in temperate zone agriculture during the 20th century, including farm mechanization and the use of industrially-produced fertilizers and pesticides, had major impacts on soil C. In the older, established agricultural areas of Europe and eastern North America these changes were mainly detrimental to soil C maintenance, with shifts towards more cereal-based monocultures relying on chemical fertilizers and away from animal-based production systems employing perennial hay crops, legumes, and manuring (Steen, 1989). In the more recently exploited lands, however, such as the former prairie soils of North America, the use of chemical fertilizers and introduction of higher yielding crop varieties greatly increased productivity and appears to have helped stabilize soil C levels (Cole et al., 1989). The current interest in sustainable agriculture, land use and global change issues, and the wider range of alternative tillage and cropping systems now available, together offer the potential for significant enhancements of soil C storage in temperate zone agroecosytems.

III. Management Links to Controls on Soil C Balance

The assimilation of CO_2 through photosynthesis and the release of CO_2 to the atmosphere through plant and heterotroph respiration ultimately determine the C balance of terrestrial ecosystems. In principle, a direct accounting of the various CO_2 fluxes involved in these processes (i.e., gross photosynthesis, photorespiration and dark respiration by plants, respiration by soil organisms) could be used to quantify fluxes and predict long-term changes in soil and vegetation C storage. In practice, such an approach is problematic due to the high spatial and temporal variability of these gas fluxes as well as methodological difficulties in performing large-scale gas exchange measurements. Furthermore, in most agroecosystems there is often little or no change in the long-term C storage in vegetation (e.g., annual crops) due to harvesting, and therefore the principle factors of interest are those affecting the amount of organic matter entering the soil and its rate of decomposition. Because of the long residence time of C in most soils, data from the long-term field experiments are invaluable in accessing how management practices, climate and edaphic factors interact in determining the C balance. Data from such experiments will be used to examine how management might be directed towards increasing C sequestration in soil.

Considering soil C change, in the simplest terms, as the net difference between C added to soil and the C mineralization from soil organic matter (Figure 1), there are three potential ways to increase C storage: (i) by increasing C inputs, (ii) by decreasing decomposition rates, and (iii) by reducing the amount of CO_2 produced per unit of organic matter decomposed. Each of these processes will be evaluated in turn as to how they may be influenced by management.

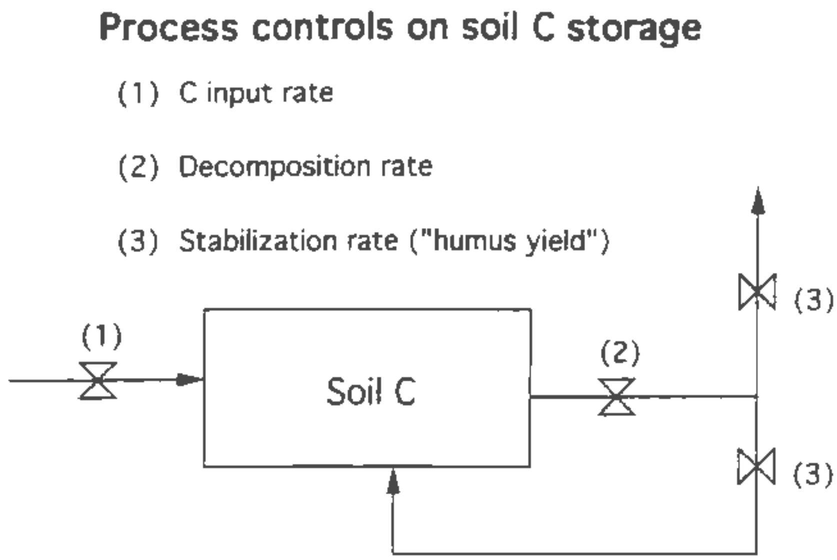

Figure 1. Characterization of control points at which management practices can influence soil C storage.

A. Controls on C Inputs

The main objective of agroecosystem management is to produce dry matter (as food and fiber) which, in turn, affects the amount of non-harvested organic matter returned to soil. Thus, C inputs to soil are influenced by nearly every facet of agricultural management. In cropland and pasture these management factors include the crop type (i.e., production potential), frequency of fallow, fertilization, and residue management. In addition, the use of organic amendments such as manure and sewage sludge constitute a direct management control on C supply to soil.

Residue amounts do not necessarily vary in direct proportion to crop yields. For instance, yield increases from N application, may not necessarily result in greater soil C input. Production responses to management are likely to be different for the harvested vs. non-harvested portions of the plant, and until recently relatively little information has been available for relating total crop productivity (including root production) to management. Therefore, it is difficult to extrapolate knowledge of how management affects crop yield to the management effects on C inputs and soil organic matter dynamics.

Nevertheless, several long-term field experiments in which C inputs have been directly controlled (through crop removal and subsequent readdition of known amounts of organic matter) shed considerable light on the response of soil to C inputs. Such experiments generally impose the same cropping treatments across C addition treatments such that differences in root C inputs and abiotic conditions as they affect decomposition rates are minimized. These experiments have generally found a close linear relationship between C addition rates and soil C amounts (Figure 2). The relationship between annual C addition rates and the average annual change in soil C varies depending on climatic and edaphic factors affecting decomposition rates at a particular site, as well as on the duration of the experiment, e.g., mean annual rates of change are higher for the short-term experiments at Lind, WA (17 years) and Culbertson, MT (7 years) (Figure 2). Note also that while the slopes for the wheat-fallow and the continuous wheat treatments at Pullman are roughly similar, the intercept for the wheat-fallow system is lower, suggesting a more favorable decomposition regime associated with the higher soil moisture in the fallowed system.

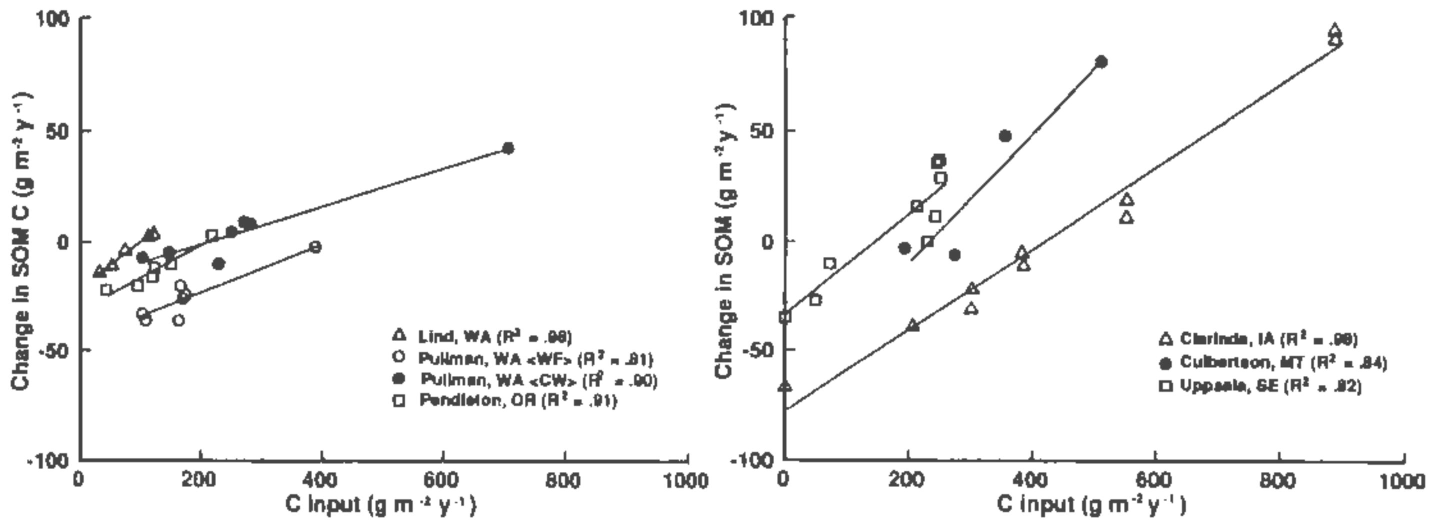

Figure 2. Relationship between annual C input rates and net changes in soil C, averaged over the duration of the experiment. Data are from Black (1973), Horner et al. (1960), Larson et al. (1972), Paustian et al. (1992) and Rasmussen et al. (1980).

The linear relationship between C inputs and soil C storage agrees with what would be predicted theoretically if the decomposition of the total soil C is assumed to follow first-order kinetics, i.e.,

$$dC_t/dt = I - kC_t,$$

where the soil C (C_t^*) at steady-state, ($dC_t/dt = 0$), is directly proportional to C inputs (I), i.e.,

$$I = kC_t^*.$$

The same relationship holds if multiple soil C pools having different characteristic turnover times (e.g., Parton et al., 1987; Jenkinson et al., 1987) are included, provided they follow first-order decomposition, i.e.,

$$dC_t/dt = d(C_1 + C_2 + \ldots + C_n)/dt = I - k_1C_1 - k_2C_2 - \ldots - k_nC_n.$$

Since at steady-state each individual pool would make up a constant fraction of total C (i.e., $C_i = f_iC_t^*$), then,

$$\begin{aligned} I &= k_1(f_1C_t^*) + k_2(f_2C_t^*) + \ldots + k_n(f_nC_t^*) \\ &= (k_1f_1 + k_2f_2 + \ldots + k_nf_n)\, C_t^* \\ &= k_tC_t^*. \end{aligned}$$

In summary, both empirical and theoretical evidence suggests that C storage in soils can be increased in direct proportion to increases in C inputs, provided there is no change in specific decomposition (more specifically, C mineralization) rates. Management controls on decomposition rates are discussed in the following section.

B. Controls on Decomposition Rate

The decomposition rates of soil C and crop residues are controlled by a variety of factors including soil abiotic conditions, residue composition, and soil disturbance, all of which can be affected, directly and indirectly, by management. However, designing management systems to reduce decomposition rates may not always be commensurate with production goals, particularly with respect to modifying the abiotic environment. In most temperate soils (excluding wetlands) decomposition rates could be reduced by decreasing temperature, decreasing soil water, and decreasing soil oxygen, all of which would be likely to reduce crop growth. One exception would be the reduction in soil moisture occurring in conjunction with reduced fallow frequency. In semiarid regions a major consequence of conversion from wheat-fallow to more continuous cropping are drier soils and reduced potential decomposition rates.

Other strategies could include manipulating chemical and/or physical factors of crop residues to restrict decomposition activity in soil. It is well recognized that different chemical compounds in plant materials vary widely in their decomposition rate. In particular, the lignin content of plant tissue has often been found to correlate well with litter decomposition rates (Aber and Melillo, 1982). The complex structure of lignin and the high energetic costs of lignin degradation restrict the number and activity of organisms adapted to decompose lignin and lignin-associated products.

The influence of residue quality on soil organic matter formation has been examined in a few long-term field experiments. Figure 3 shows results from two experiments where similar amounts of different residues were added to small field plots. The same cropping regime was imposed across treatments (within an experiment) with similar amounts of N inputs between treatments. In the Swedish experiment, the highest soil C values were found in manure and sawdust-amended plots, having lignin contents estimated to be ~30%, and the lowest where grass litter (~6% lignin) was added (Paustian et al., 1992). Wheat straw (15% lignin) yielded intermediate soil C increases. Similar results were found by Sowden and Atkinson (1968) in Canada, with the highest gains of soil C in peat and manure-amended soil and the lowest with alfalfa additions. However, Larson et al. (1972) found no significant effect of residue type on soil C accumulation in an 11 year experiment.

Physical protection of soil organic matter is widely believed to play an important role in restricting the access to substrates by microorganisms and extracellular enzymes, thereby reducing decomposition rates.

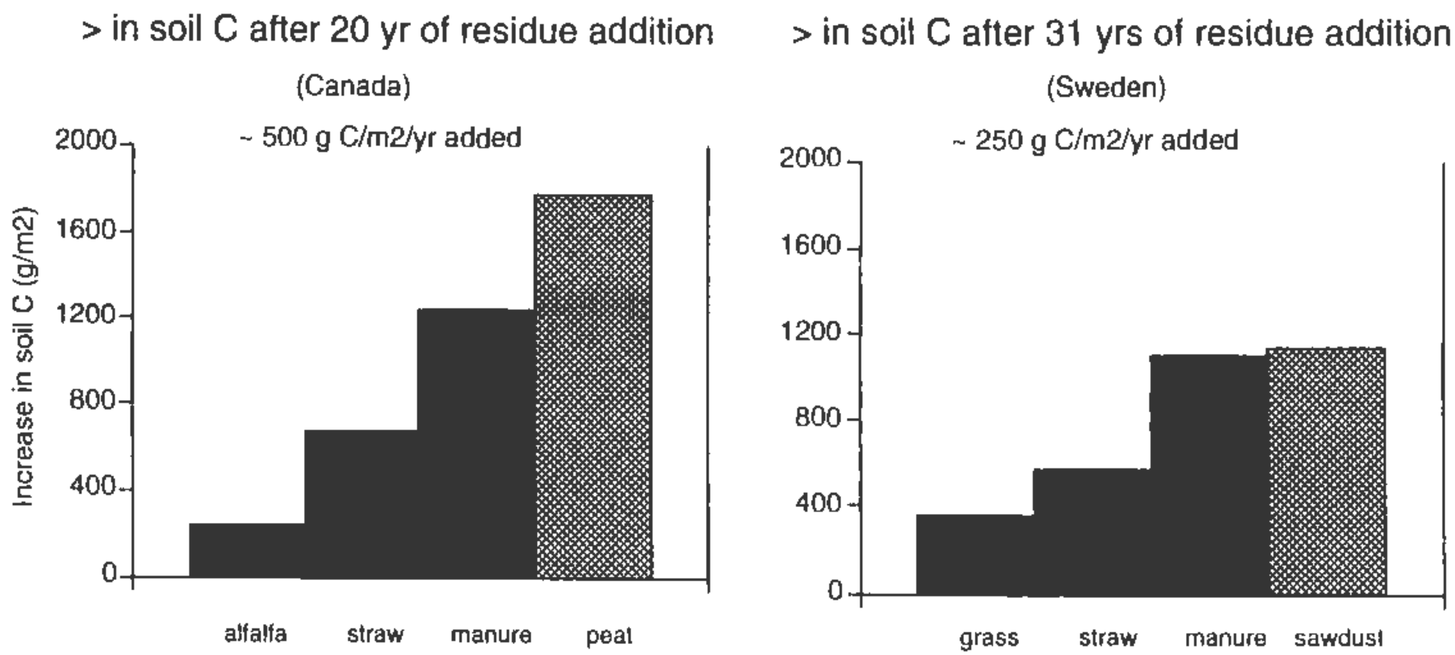

Figure 3. Net increments in soil C with different residue types added in equal amounts to a sandy soil in Canada (data from Sowden and Atkinson, 1968) and a sandy clay loam in Sweden (data from Paustian et al., 1992).

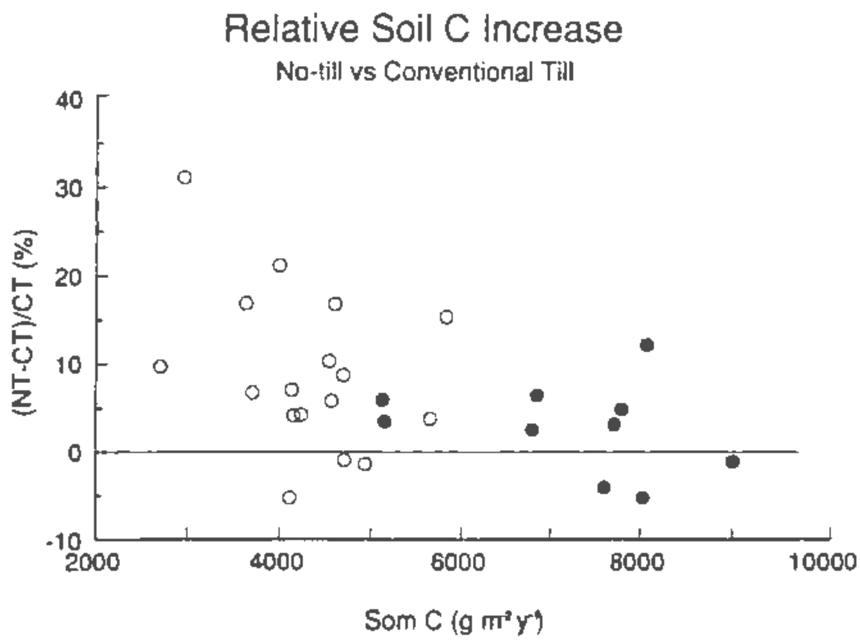

Figure 4. Differences in C in surface soils between no-tilled and moldboard plowed treatments in paired field plots. Values are for total C to depths at or below the depth of plowing, adjusted for differences in bulk density. Data are from Balesdent (1990), Blevins et al. (1983), Dalal (1989), Dick (1983), Dick et al. (1986a, 1986b), Doran (1987), Havlin et al. (1990), Groffman (1985) and Powlson and Jenkinson (1981).

In simple terms this physical protection has been conceptualized as an "encapsulation" of organic matter by clay particles and soil aggregates (Tisdall and Oades, 1982; Elliott, 1986). Tillage and other mechanical disturbance of soil has been found to decrease aggregate stability which may result in increased susceptibility to decomposition of physically-protected organic matter. While tillage influences a number of other factors affecting decomposition rates, including soil moisture, temperature, and aeration, the degradation of soil structure and loss of physical protection has been postulated as a major cause of soil C losses when undisturbed soils are cultivated (Cambardella and Elliott, 1992). Thus, greater use of reduced and no-till cultivation could help to decrease organic matter decomposition in cropland soils.

Results from a number of field experiments comparing no-till with conventional (moldboard plow) tillage show in most cases higher C storage under no-till (Figure 4). Only data for paired tillage plots were included, in which soil C values were available to or below depth of plowing (to ~20-30 cm depth in most cases). Differences between no-till and conventional till systems were calculated on an absolute (per m^2) basis, corrected for differences in bulk density. The duration of the experiments varied from 5 to 30 years.

For the experiments surveyed, no-till had up to 30% more C in the upper profile, although in most cases increases were below 20% On a relative basis, the difference between no-till and plow tillage decreased with increased soil C content which may indicate a greater impact of changes in tillage for low C and/or degraded soils. Fine textured soils (filled circles) tended to have the highest C amounts, irrespective of tillage, and showed less response to no-till. No-till may affect other factors which can act differentially on decomposition rates, such as reducing soil temperature (< decomposition) and increasing soil water (> decomposition). Also decreased soil erosion under no-till might result in substantial differences in soil C as a function of tillage at sites with a high erosion potential. Therefore, the high variability in the apparent effects of no-till across sites is not surprising. However, the available empirical evidence does support the potential for tillage reductions to help sequester C.

C. Controls on Humus Yield

The main products of aerobic decomposition of organic carbon compounds are CO_2 and microbial biomass and metabolic products, including non-assimilated decomposition products. Soil organic matter is formed from the amalgamation and stabilization of dead microbial material, metabolites and residual decomposition products. Conceptually, one way to increase soil C storage is to decrease the relative proportion of C mineralized directly to CO_2 and increase the formation of more stable C forms in SOM. This stabilization efficiency is sometimes referred to as the "humus yield"

At the microbial level, it is well know that the growth yield (biomass produced/C assimilated) can vary widely depending on growth conditions as well as species differences. As yet there is little knowledge about microbial energetics and growth yield applicable at the whole soil or ecosystem level although it's reasonable to suppose that these factors might be influenced through management practices. For instance, no-till may favor a greater degree of fungal (vs. bacterial) dominance compared with conventionally tilled systems (Hendrix et al., 1986; Beare et al., 1992). Fungi are important agents of soil aggregation (Tisdall and Oades, 1982; Gupta and Germida, 1988), which may lead to increased C stabilization through protection of soil aggregates in fungal-dominated no-till systems (M. Beare, unpubl.). It has been further suggested (Holland and Coleman, 1987) that the product yield (i.e., biomass and metabolite production per unit CO_2 respired) of fungi may be higher, possibly due to accumulation of fungal cell walls (C. Cambardella, unpubl.), than that of bacteria, which would effectively increase the humus yield under no-till. While data is limited at present, a more in-depth understanding of how decomposer communities and their metabolism respoud to environmental and management influences may give insight into appropriate strategies for increasing soil C sequestration.

Other chemical and physical factors can affect soil C stabilization. It is widely accepted that lignin degradation products and proteinaceous compounds (peptides, amino acids) are major constituents of recalcitrant humic substances in soils. Thus formation of stabile organic matter in soil should be enhanced where these hnmic precursors are in abundant supply. Data from the Swedish field experiment cited earlier indicate a potential strong interaction between the lignin content of residues and nitrogen availability (Figure 5). Where either straw or sawdust were added there was a strong additional affect of nitrogen addition on the accumulation of soil organic matter. Some additional C inputs (i.e., more root production) and, potentially, drier soils in the fertilized treatments (due to higher evapotranspiration) could have contributed to these differences in C buildup. However, simulation analyses of these data (Paustian et al., 1992) indicated that these factors could not fully explain the magnitude of the differences, suggesting the importance of a direct stabilization mechanism associated with N availability in the system. Thus, the combination of high lignin residues and N addition may be a management option conducive to increasing soil C storage.

IV. Agricultural Soils as Attenuated Sinks for CH_4

That forest and grassland soil can act as sinks for atmospheric methane, and that these sinks can be effectively switched off by nitrogen addition, is by now well established (Steudler et al., 1989; Mosier et al., 1991). The importance of this sink is globally significant: ca. 30 Tg CH_4 yr^{-1} of a total sink of 500 Tg CH_4 yr^{-1} is thought to be captured by upland soils (IPCC, 1992). About 37 Tg CH_4 yr^{-1} is now accumulating in the atmosphere. Thus, in the absence of such uptake, atmospheric methane concentrations would likely be significantly greater than current concentrations of ca. 2.1 ppmv, leading to more atmospheric heat trapping and to important changes in tropospheric [OH^-] scavenging by CH_4 molecules.

That nitrogen additions to soil can reduce methane uptake potentials (e.g., Steudler et al., 1989; Bronson and Mosier, 1993) suggests a potential for substantial historical changes in the soil CH_4 sink strength due to agricultural activity, and in particular an attenuation of this sink as tillage and fertilizer practices reduce CH_4 uptake in former grassland and forest soils. Available evidence, while limited, suggests that this change is in fact occurring: in one U.S. corn belt experiment (Robertson et al., 1993) uptake in conventionally-tilled soybeans (*Glycine max* L.) was 7-8 times less than uptake in a never-tilled soil under grassland vegetation (Table 1). Uptake under other cropping systems was equally attenuated, although less so in the organic-based no-fertilizer systems.

Such results suggest yet another impact of agriculture on a carbon-cycle greenhouse gas. And again agriculture acts as a net source of the gas, although in this case by attenuating an existing sink rather than

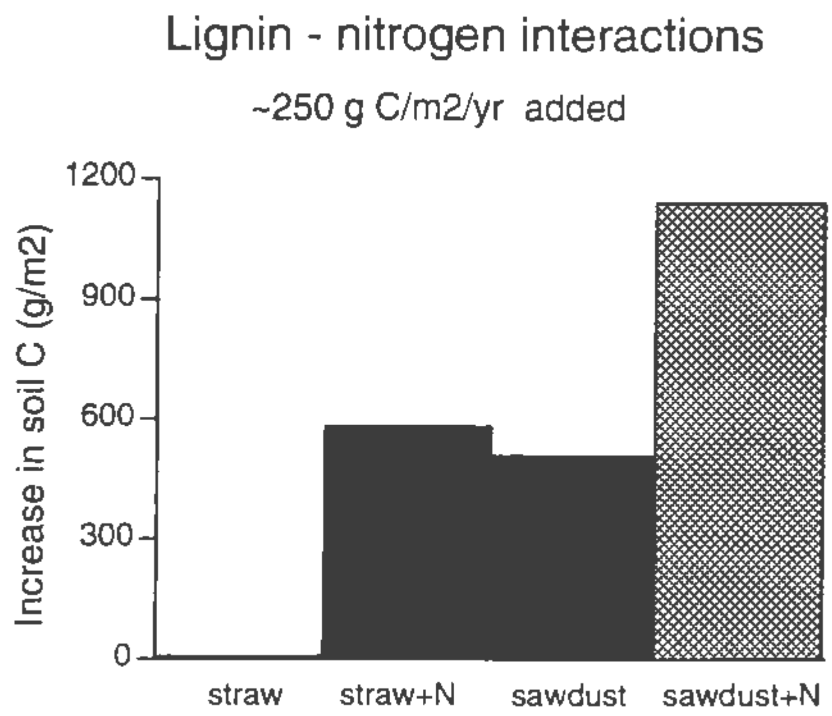

Figure 5. Effect of residue quality and N addition rate on net soil C increase after 31 years. Treatments received the same amounts of residue added to the soil after removal of all aboveground plant material C inputs from roots are included in the input estimate. Fertilizer nitrogen was added to two of the treatments at a rate equivalent to 80 kg N ha^{-1} yr^{-1} as $Ca(NO_3)_2$, the other two treatments received no N fertilizer. Data from Paustian et al. (1992).

Table 1. Daily mean CH_4 uptake in soil under conventional till soybeans (*Glycine max* L.) vs. a never-tilled soil under native vegetation in southern Michigan. Values are means of 15 or 16 dates in 1992 for each of 4 replicate croppiog/native systems

System	Daily Mean Uptake g CH_4-C ha^{-1} d^{-1}	Standard Error
CT Soybeans	0.176	.078 (n=16)
Never-tilled native	1.440	.408 (n=15)

by an absolute increase in source (as for CO_2). Early results suggesting that the effect of nitrogen on CH_4 uptake may be closely related to the organic matter status of soil (Robertson, unpubl.) suggest in turn that future management for soil C sequestration may also lead to the re-establishment of significant CH_4 uptake in these soils.

V. Management and Climate Change Interactions

Forecasting changes in the carbon balance of agricultural soils over the next 50 to 100 years is complicated by the anticipated rapid rate of change of climate conditions and land-use practices. Current projections are for mean global temperature to increase by about 1-4 °C by the middle of the next century with somewhat greater increases predicted for mid- and high-latitude regions (IPCC, 1990). There is greater uncertainty about changes in precipitation patterns but the potential for major regional shifts in weather patterns associated with global warming is apparent. In addition, agricultural land use is changing rapidly in response to a variety of social, economic, and environmental considerations. However, our current understanding of soil C dynamics as embodied in simulation models (e.g., Jenkinson et al., 1987; Parton et al., 1987) and experience from long-term field experiments provide a powerful tool for assessing changes in soil C (see Metherell et al., this volume; Patwardhan et al., this volume).

To evaluate changes in potential soil C storage as a consequence of global warming and changes in agricultural productivity and management, we performed an equilibrium analysis of the CENTURY model (Parton et al. 1987). At equilibrium, the model can be solved analytically and the interactions between different factors affecting soil C levels can be shown explicitly (Paustian, unpubl.). It should be emphasized that this kind of analysis does not address transient changes in soil C but rather provides a measure of the potential soil C level under a given set of conditions.

We analyzed the model for two long-term field sites, the High Plains Agricultural Laboratory near Sidney, Nebraska, and the Long-Term Ecological Research site at Kellogg Biological Station (KBS) in Michigan, which are included in a network of long-term sites being used to evaluate management effects on soil C (Elliott et al., 1994). The cropping treatments at Sidney include wheat-fallow (*Triticum aestivum* L.) rotations under different tillage regimes and at KBS the dominant row crops are corn (*Zea mays* L.) and soybeans with different tillage and with and without winter cover crops.

Equilibrium C levels (0-20 cm) were calculated for five different scenarios (Figure 6). "Present" management was wheat-fallow with moldboard plowing at Sidney and corn-soybean with moldboard plowing at KBS. "Best" management at Sidney represented no-till with a chemical fallow and, at KBS, corn-soybean under no-till with a winter cover crop. Climate change was represented by a 2°C increase in mean annual temperature by 2050, based on the best estimate for temperature increase in the central U.S. (IPCC, 1992). Three scenarios also include an increase in crop residue inputs of 40% (assumed to accompany projected productivity increase) above current levels by 2050. Over the past 40 years, agricultural productivity has increased by an average of 1.8% per year and is projected to increase at an annual rate of 1.4% over the next 20 years (Crosson, 1993). Finally, the potential effect of breeding crop varieties to have higher lignin contents was represented by assuming increases in residue lignin contents to 20% of total dry matter.

The model was executed using rate parameters determined by Parton et al. (1987), except for reduction in the yield efficiency of litter decomposition from 0.45 to 0.35, based on model applications to other agricultural treatments (Paustian et al. 1992). This parameter change has little effect on the relative differences between scenarios and results in slightly lower C levels than if the higher yield efficiency is assumed. Long-term (30 year) averages of temperature and precipitation measurements at the sites were used to calculate the effect of present temperature and soil moisture on decomposition rates. The 2°C temperature increment assumed in the global warming scenarios was distributed over the year such that the increase in winter temperature would be 50% higher and summer temperatures 50% lower than the mean annual increase, reflecting seasonal differences projected by the climate models. Precipitation rates for the warming scenarios were assumed to be unchanged from the 30 year averages. Present C inputs levels were estimated from field measurements of aboveground productivity at Sidney (Power et al., 1986) and KBS (S. Halstead, pers. commun.) and estimates of relative belowground allocation were based on Buyanovsky and Wagner (1986)

Potential (equilibrium) C levels predicted under present management, 3.4 kg C m^{-2} at Sidney and 4.6 kg C m^{-2} at KBS (Figure 6), are roughly in line with current measured C levels (about 3 kg C m^{-2} for 0-20 cm at both sites; Elliott et al., 1994, S. Halsted, pers. commun.) Under the global warming scenario, assuming no changes in management or C input levels, the model predicts a slight decrease in potential C storage at KBS due to increased decomposition rates. At the drier site in Sidney, increased temperature increases evapotranspiration and thus decreases soil moisture, such that the net effect of warming on decomposition rates is negative, resulting in increased C storage potential. The interaction between temperature and C inputs as they affect equilibrium C levels for the two sites are shown in more detail in Figure 7.

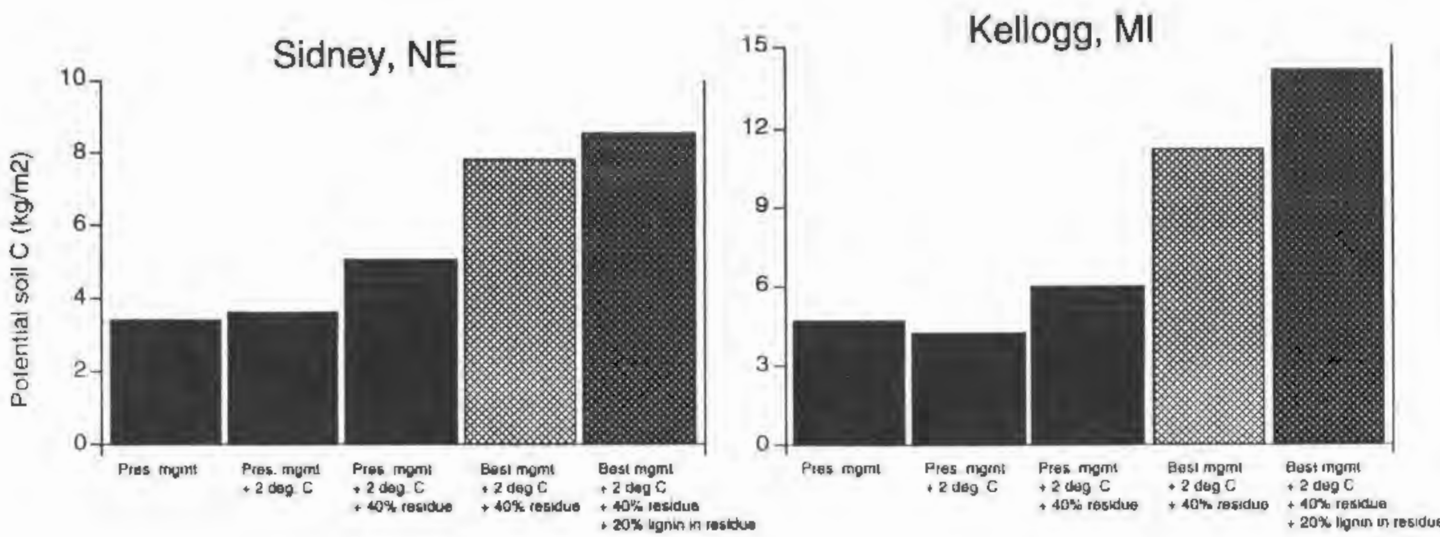

Figure 6. Steady-state solutions of the CENTURY model, showing potential soil C levels in surface soil for 5 management-climate change scenarios, for a semiarid wheat-fallow at Sidney, NE and a corn-soybean based rotation in southwest Michigan (KBS). See text for explanation of model scenarios.

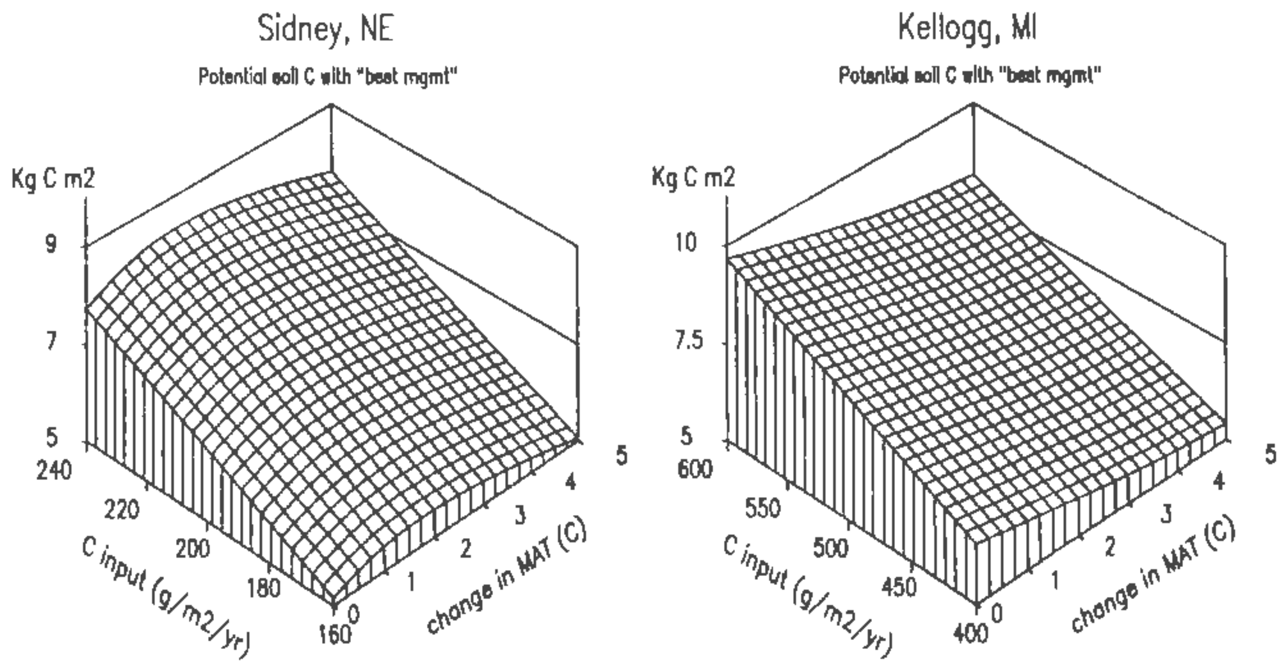

Figure 7. Steady-state values of soil C as a function of C inputs at the NE and MI sites, ranging from current levels up to 50% higher annual C inputs, and change in mean annual temperature, ranging from present climate (0) conditions to a 5 degree rise in average temperature. Other model parameters were the same as used in the "present" management scenario.

In scenario 3, with an increase in C inputs from crop residues of 40%, C storage potential increases and at KBS, C levels under the increased input scenario more than compensate for the increase in decomposition rates due to warming. Using "best" management practices, i.e., no-till at both sites and a winter cover crop (adding an additional 200 g C m^{-2} yr^{-1}) at KBS, substantially increases C storage potential. Finally, the effect of increased residue lignin is higher at KBS due to the greater relative increase for corn and soybean stover (~10 to 20%) than for wheat (15 to 20%).

VI. Summary and Conclusions

Data from long-term field experiments and model analyses clearly illustrate the key role of C inputs, and to a lesser extent reduced tillage intensity, in altering soil C sequestration. The potential for modifying crop residue quality and the stabilization efficiency of C provide additional means for increasing C levels in agricultural soils. Thus, both theory and empirical evidence from long-term field experiments suggest that gains in C storage in proportion to increases in C additions to soil are feasible, particularly in C-depleted agricultural soils. Considering only climate effects on decomposition, model analyses suggest that relatively modest gains in C inputs would be sufficient to compensate for global warming influences. However, climate change, including increased drought risk, and other factors may constrain increases in productivity, particularly in semiarid croplands. The challenge to agricultural management will thus be to design systems capable of maintaining economically viable harvests while increasing the allocation of NPP to the soil and minimizing the soil disturbance.

Acknowledgments

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