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# Management options for reducing $CO_2$ emissions from agricultural soils

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**Abstract.** Crop-based agriculture occupies 1.7 billion hectares, globally, with a soil C stock of about 170 Pg. Of the past anthropogenic $CO_2$ additions to the atmosphere, about 50 Pg C came from the loss of soil organic matter (SOM) in cultivated soils. Improved management practices, however, can rebuild C stocks in agricultural soils and help mitigate $CO_2$ emissions.

Increasing soil C stocks requires increasing C inputs and/or reducing soil heterotrophic respiration. Management options that contribute to reduced soil respiration include reduced tillage practices (especially no-till) and increased cropping intensity. Physical disturbance associated with intensive soil tillage increases the turnover of soil aggregates and accelerates the decomposition of aggregate-associated SOM. No-till increases aggregate stability and promotes the formation of recalcitrant SOM fractions within stabilized micro- and macro-aggregate structures. Experiments using $^{13}C$ natural abundance show up to a two-fold increase in mean residence time of SOM under no-till vs intensive tillage. Greater cropping intensity, i.e., by reducing the frequency of bare fallow in crop rotations and increasing the use of perennial vegetation, can increase water and nutrient use efficiency by plants, thereby increasing C inputs to soil and reducing organic matter decomposition rates.

Management and policies to sequester C in soils need to consider that: soils have a finite capacity to store C, gains in soil C can be reversed if proper management is not maintained, and fossil fuel inputs for different management practices need to be factored into a total agricultural $CO_2$ balance.

## Introduction

The earth's soils contain approximately 1500 Pg of C, making them the largest surface terrestrial C pool, about 2–3 times greater than the amount of C stored in the earth's vegetation (Post et al. 1990; Eswaran et al. 1993). Crop-based agriculture (i.e., excluding grazing land) occupies around 1.7 billion hectares globally, with a soil C stock of about 170 Pg, slightly more than 10%

of the total soil C inventory (Paustian et al. 1997a). Reconstructions of global landuse change suggest that terrestrial ecosystems have contributed as much as half of the increases in $CO_2$ emissions from human activity in the past two centuries (Post et al. 1990; Houghton & Skole 1990). Of the past anthropogenic $CO_2$ additions to the atmosphere, about 50 Pg has been contributed by cultivated soils (Paustian et al. 1997a), through the mineralization of soil organic carbon (SOC).

In agricultural soils, reducing net $CO_2$ emissions is synonymous with increasing soil C storage, a process usually referred to as C sequestration. Because a large part of the biomass produced in agricultural systems (i.e., the portion not used as food, fodder or fuel) cycles through the soil decomposer community, the magnitude of gross $CO_2$ fluxes between agricultural soils and the atmosphere is large – several Pg per year. However, the net difference between the photosynthetically-fixed $CO_2$ that enters the soil as plant residues and the $CO_2$ that is emitted from decomposition is much smaller. This difference determines the net C balance of the ecosystem, i.e., whether it is a source or sink for $CO_2$.

For a given climatic regime and management system, SOC in most permanent agricultural systems tends toward an equilibrium level. Exceptions include systems such as shifting cultivation, which are characterized by fluctuations in SOC levels between cropped and vegetated-fallow phases. In most temperate industrialized countries, the period of major agricultural expansion ended in the early 20th century. Thus, most temperate agricultural soils have been cultivated for 50–100 years or more. The large losses of C which typically follow initial cultivation (Davidson & Ackerman 1993; Haas et al. 1957) have largely abated and most soils are thought to be near equilibrium, or perhaps increasing slightly in C content, due to long-term trends of increasing crop productivity (Cole et al. 1993; Janzen et al. 1998). In contrast, rates of new landuse conversions to agriculture remain high in much of the tropics, causing significant net losses of SOC. In both regions, however, improved management can reduce net $CO_2$ emissions from soils and stabilize and/or increase the storage of SOC.

The mechanisms by which the C content of agricultural soils can be increased are widely recognized. Soil C levels are governed by the balance between inputs of C through plant residues and losses of C, primarily through decomposition. Thus, management to increase C can be directed towards increasing residue inputs and/or reducing decomposition rates (i.e., heterotrophic soil respiration).

Increasing residue inputs to soil entails increasing net primary productivity (NPP), while maintaining or increasing the share of NPP which is returned to the soil. Most agronomic practices are designed to increase NPP, although the emphasis is on increasing the harvestable products and not crop residues. The relationship between C inputs and SOC levels is relatively straightforward; steady-state C contents for many agricultural soils have been shown to be linearly related to C input levels (Rasmussen & Collins 1991; Paustian et al. 1995), which conforms to current theory of SOM dynamics (Paustian et al. 1997b). This may not hold for soils with very high C levels, which may exhibit a C 'saturation' behavior (Hassink 1996). However, it is likely that many agricultural soils, which have been significantly reduced from their original C levels through cultivation, will show C gains in proportion to increases in C inputs. Addressing the other side of the C balance equation (reducing C mineralization rates), is more complex and cannot readily be reduced to a single factor or relationship. We will focus on management practices that contribute to reducing the relative rate of decomposition of soil C and plant residues, and thus decrease net soil respiration.

## Management controls on SOC mineralization

The mineralization of SOC is influenced by the physical and chemical environment of the soil (e.g., moisture, temperature, aeration, pH, nutrient availability), the physical and chemical characteristics of the organic matter itself (i.e., its susceptibility to microbial decay), and the physical accessibility of the organic matter to microbes and extracellular enzymes. All of these factors are likely to be influenced by agricultural management practices, in differing combinations and to different degrees. We will discuss two classes of management adaptations which can contribute to reduced $CO_2$ emissions from agricultural soils: (i) reducing or eliminating soil tillage and (ii) increasing cropping intensification and plant production efficiency.

### *Reduced tillage*

Soil tillage involves the physical disturbance of the upper soil layers for a variety of purposes, including seedbed preparation, weed control, and incorporation and mixing of crop residues, fertilizers or other amendments. Tillage methods vary widely depending on climate and soil type, crop management objectives, availability of technology, tradition and the personal preference of farmers. The depth, intensity and frequency of soil disturbance are the main factors needed to evaluate tillage effects on organic matter. Tillage using the moldboard plow (which inverts the soil), followed by secondary tillage to break up and homogenize the soil layer, remains the conventional practice in many areas. This represents the most intensive type of tillage. Such practices were once nearly ubiquitous, but over the past several decades they have been partially replaced by less intensive tillage methods. The tillage practice with least soil disturbance is no-till (also referred to as zero-till or direct drilling), in which seeds are sown into a narrow slot cut into the soil. Weed growth is suppressed by herbicides and crop residues are left on the surface. Thus the soil is not mixed and there is minimal physical disturbance of the soil profile. In evaluating the effects of tillage disturbance on C sequestration and soil respiration, we will focus on comparisons of intensive tillage regimes (e.g., moldboard plowing) versus no-till.

The relationship between tillage, soil structure and soil organic matter (SOM) dynamics is integral to the C sequestration capacity of agricultural soils. While the cause and effect relationship between soil structure and SOM is not fully clear, it is widely accepted that soil aggregates physically protect certain SOM fractions, thus increasing their residence time in soil (Adu & Oades 1978; Beare et al. 1994; Golchin et al. 1994a, b; Jastrow 1996). Management-induced enhancements in soil structure and SOC levels can act as a positive feedback by improving soil fertility and thus increasing plant C inputs, which can further enhance soil biological activity and reinforce the processes of aggregation.

Soil tillage can have profound direct and indirect effects on soil structural properties, including aggregation. Conventional tillage (CT) including plowing is generally detrimental to soil structure. Tillage continually exposes new soil to wet-dry and freeze-thaw cycles at the surface (Rovira & Greacen 1957; Beare et al. 1994), thereby increasing the susceptibility of aggregates to disruption. Consequently, converting from conventional tillage to no-till (NT) often increases the numbers and stability of soil aggregates (Figure 1).

Six et al. (1999) indicated that, in addition to the amount of aggregation, the rate of turnover of soil aggregates influences C stabilization. They evaluated the amount and the $^{13}C$ natural abundance of total C and particulate organic C associated with soil aggregates of differing stability in long-term CT and NT treatments in western Nebraska. The experiments were established in a mixed $C_3/C_4$ native grassland, with cultivated treatments converted to winter wheat (*Triticum aestivum* L.). The change to pure $C_3$ (wheat) plants, which have a greater photosynthetic discrimination against $^{13}C$ than do $C_4$ plants, made it possible to distinguish SOC derived from native prairie vegetation compared to that from more recent wheat residues. Thus, it was possible to determine the relative ages of organic matter fractions associated with different aggregate size fractions from the two cultivated systems and the native grassland.

These and other data provide the basis for a conceptual model of aggregate turnover and $CO_2$ release from organic matter decomposition (Figure 2). According to the model, fresh plant residues provide the coarse particulate

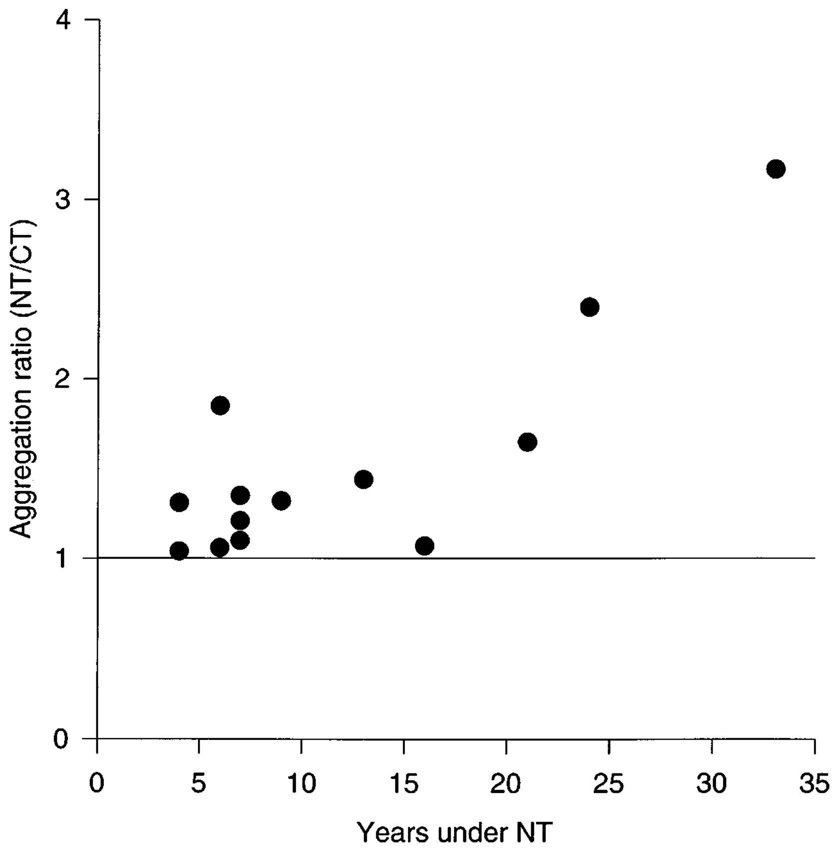


*Figure 1.* Relative aggregate stability in soil under no-till (NT) versus conventional tillage (CT), expressed as a ratio of the mean weight diameter of water-stable aggregates. Data from Angers et al. 1993; Cambardella & Elliott 1993; Beare et al. 1994; Franzlubbers & Arshad 1996).

organic matter (POM) that acts as nucleation sites for the growth of fungi and other soil microbes (Puget et al. 1995; Angers & Giroux 1996; Jastrow 1996) and the production of extracellular polysaccharides, resulting in the binding of residue and soil particles into macroaggregates. In the newly formed macroaggregates, respiration rates are relatively high. Following the incorporation of fresh residue, microorganisms utilize the more easily decomposable carbohydrates, yielding more recalcitrant intra-aggregate particulate (iPOM) with a higher proportion of alkyl carbon (Golchin et al. 1994a, 1995). This iPOM is further decomposed and fragmented into smaller particles, but decomposition occurs at a slower rate within macroaggregates as compared to non-aggregate associated POM. Some of this finely-fragmented iPOM

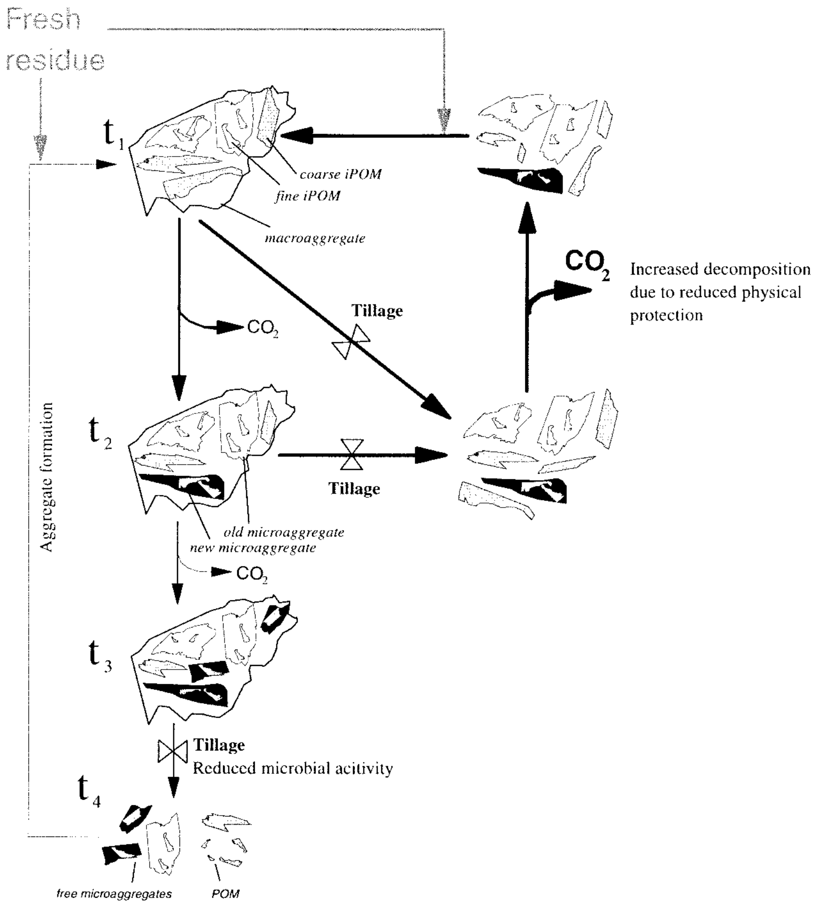


*Figure 2.* This conceptual model depicts organic C accumulation and organic C mineralization in conjunction with the formation and turnover of soil aggregates, including the effects of tillage-induced disturbance. At $\mathbf{t}_1$, fresh residue is incorporated into macroaggregates and forms coarse intra-aggregate particulate organic matter (iPOM). Subsequently (from $\mathbf{t}_1$ to $\mathbf{t}_2$), the iPOM is further decomposed and fragmented into fine iPOM within the aggregates, which forms the core of a new microaggregate and is physically protected from decomposition. At $\mathbf{t}_3$, carbon is depleted and microbial activity and production of binding agents decrease. This cessation results in a destabilization and potential disaggregation of the macroaggregates. Upon disaggregation, microaggregates, the mineral fraction, and POM are released. These fractions may be reincorporated into new macroaggregates when fresh residue is added. In CT some macroaggregates go through the same sequence. However, the majority of them are disrupted from cultivation or slaking in the field at $\mathbf{t}_2$ and go through a shorter cycle resulting in faster turnover. This faster turnover results in fewer macroaggregates reaching $\mathbf{t}_3$ and less fine iPOM is formed in CT compared to NT. When iPOM is released from the aggregates, it becomes exposed to microbial decay which leads to a loss of iPOM and an increased $CO_2$ flux in CT compared to NT. This loss precludes re-incorporation of the iPOM into macroaggregates and thereby accounts for the differences in composition of macroaggregates in NT and CT. (Modified from Six et al. 1999)

becomes encrusted with clay particles and microbial byproducts, leading to increased physical protection of the iPOM within more stabilized micro-aggregates ($< 250\ \mu$m dia.) (Oades 1984; Elliott & Coleman 1988; Beare et al. 1994; Golchin et al. 1995; Jastrow 1996). The loss of $CO_2$ during this phase is less than in the process of aggregate formation (Figure 2). As the macroaggregate 'matures', the binding agents generated by the decomposition of the fresh residues are eventually lost, resulting in the release of highly recalcitrant residual POM and stabilized microaggregates ($< 250\ \mu$m dia.). These materials may subsequently be incorporated into new aggregates.

Data from the Nebraska study suggested that the rate of formation of new macroaggregates ($> 250\ \mu$m dia) was similar in the two tillage systems (Six et al. 1998) and that new aggregate formation was mainly driven by the amount of fresh residues added to the soil (which was similar in both cropping systems). However, the frequent soil disturbance in the CT treatment caused greater aggregate disruption, resulting in fewer of the stable and older macroaggregates, and increased mineralization rates of previously protected organic matter (Figure 2). The longevity of macroaggregates was much greater in the no-till soil, as evidenced by the greater amounts of older fine iPOM found within macroaggregates and the greater proportion of total soil in stable macroaggregates (Six et al. 1998).

The reduced rate of decomposition under no-till was reflected in estimates of mean residence time (MRT) of the prairie-derived organic matter determined from $^{13}C$ natural abundance; MRT was 73 yr in NT versus 44 yr under CT (Six et al. 1998). Data on $^{13}C$ abundance from two other tillage comparisons were similar, with approximately a two-fold greater MRT for organic matter under no-till than under conventional till (Table 1).

In summary, the faster turnover of aggregates in intensively tilled systems (compared with no-till) causes increased decomposition of SOM and greater soil respiration by accelerating the turnover cycle of soil aggregates and exposing more relatively young and labile organic matter to decomposition. This accelerated turnover also inhibits the formation and stabilization of more recalcitrant organic matter fractions within microaggregates that have a longer residence time in soil (Six et al. 1999).

### *Cropping intensification and increased production efficiency*

Environmental conditions favorable for plant growth – warm, moist soil with abundant nutrients – are also favorable for heterotrophic microorganisms. Thus, it is not feasible or desirable to design agricultural management systems which present a highly unfavorable environment for decomposers. However, by managing crop production to obtain the most efficient use of limiting

*Table 1.* Comparison of mean residence time (MRT)[1] of the soil C (present prior to the initiation of the experiment) under no-till and conventional (plow-based) tillage, derived from measurements of $^{13}C$ natural abundance.

| Site | MRT in NT (years) | MRT in CT (years) | NT/CT | Reference |
|---|---|---|---|---|
| Sidney, Nebraska | 73 | 44 | 1.7 | Six et al. 1998 |
| Boigneville (France) | 38 | 18 | 2.1 | Balesdent et al. 1990 |
| Delhi (Canada) | 26 | 14 | 1.9 | Ryan et al. 1995 |

[1] Mean residence times were calculated using a first-order decomposition model, $k = \ln(A_0/A_t)/t$, where $A_0$ is the SOC present at the beginning of the experiment and $A_t$ is the amount of the original SOC remaining after time $t$. The MRT is the inverse ($1/k$) of the decomposition rate constant. In each of the experiments, a shift in vegetation (between $C_3$ and $C_4$ species) occurred at the start of the experiment. Thus, SOC present at the start of the experiment could be differentiated from that derived from subsequent crop residues, based on the $^{13}C$ signatures.

resources, such as water and nutrients, soil respiration can be reduced and the input side of the C balance equation favored.

In semiarid ecosystems, water limits both production and decomposition during much of the year. In this section, we present a concept describing how allocation of water loss through evaporation (E) and transpiration (T) in semi-arid agroecosystems influences the balance between production (P) and decomposition (D) and thus the size and dynamics of soil organic matter.

We divide the soil into three zones for conceptual purposes: (1) the surface ET zone (ca. the top 10 cm depending upon soil texture) is where both E and T occur, (2) the T zone located below the ET zone but within the rooting zone, and (3) the zone below the rooting depth that is neither affected by E nor T. Within the ET zone, water lost from E will decrease both P and D. However, water lost from T in this zone increases P while decreasing D. The net result is a greater P/D, hence a tendency towards SOM accumulation. Water moving into the T zone has little effect on D in these systems because most decomposable material is located at the soil surface (ET zone). There is some mineralization of deep SOM, but there is less and it is of poorer quality (Cole et al. 1977). However, water moving into the T zone increases P as water is extracted from lower depths by roots.

In many semiarid regions dominated by wheat and other small grains, summer fallow is used to increase soil water storage prior to planting and thereby reduce the risk of crop failure from drought. Often, crops are only grown every other year. During the fallow year, the soil is kept free of vegetation, with cultivation and/or herbicides, to cut transpiration losses. The warm, moist conditions in the ET zone during fallow promote high microbial activity and $CO_2$ emissions – C mineralization is further enhanced if there is recurrent cultivation for weed control (Paustian et al. 1997b). Consequently, many wheat-fallow systems sustain large losses of soil C that may continue over many decades (e.g., Rasmussen & Smiley 1997; Peterson et al. 1998).

Recently developed management systems that improve water conservation, through the use of no-till, greatly reduce or eliminate the use of summer fallow (Peterson et al. 1998). Under no-till, litter accumulates at the soil surface. The surface residues provide a barrier between the soil and the atmosphere which reduces soil evaporation. Surface residues (Bond & Willis 1969) and standing stubble (Smika 1983) decrease wind speed at the soil surface, resulting in less turbulent exchange of water and heat. Also, dry plant residues have higher albedo and thermal radiative properties (emissivity) than soil, causing lower heat load and lower temperature at the soil surface. This evaporative barrier increases the water availability for plants in the ET zone, making it possible to reduce the frequency of summer fallow in the crop rotation, thereby increasing total crop production and residue C inputs. Thus, C sequestration with these intensified cropping regimes is due to the increase of production relative to decomposition, induced by the increased transpiration/evaporation ratio.

We used the Grassland Ecosystem Model to explore this mechanistic explanation. The model was originally developed for perennial grasses (Hunt et al. 1991), but has been adapted for winter wheat by adding management routines for planting, harvesting, and grain yield, and by changing root depth distribution as a function of crop development. Many of the plant parameters are identical to those for crested wheatgrass (*Agropyron cristatum*, a $C_3$ grass for which the model was originally developed) which is morphologically similar to wheat. Four no-till cropping systems, with increasing cropping intensities, ranging from alternate wheat-summer fallow (WF) to continuous wheat (WW) (i.e. one crop each year), were simulated for a 12 year period at a site in eastern Colorado.

Crop residue production (shown as above-ground primary production excluding grain yield), on an annual basis, increased with increasing cropping intensity (Figure 3). While production in an individual wheat year was highest following summer-fallow (due to the additional stored water), total production and residue C inputs increased with cropping intensity. Decomposition (shown as $CO_2$-C emissions from surface residues) also increased as a function of cropping frequency and crop residue inputs. However, production exceeded decomposition where fallow frequency was reduced, resulting in the buildup of surface litter. With less frequent fallows, soil evaporation decreased due to greater transpiration and greater surface litter levels.

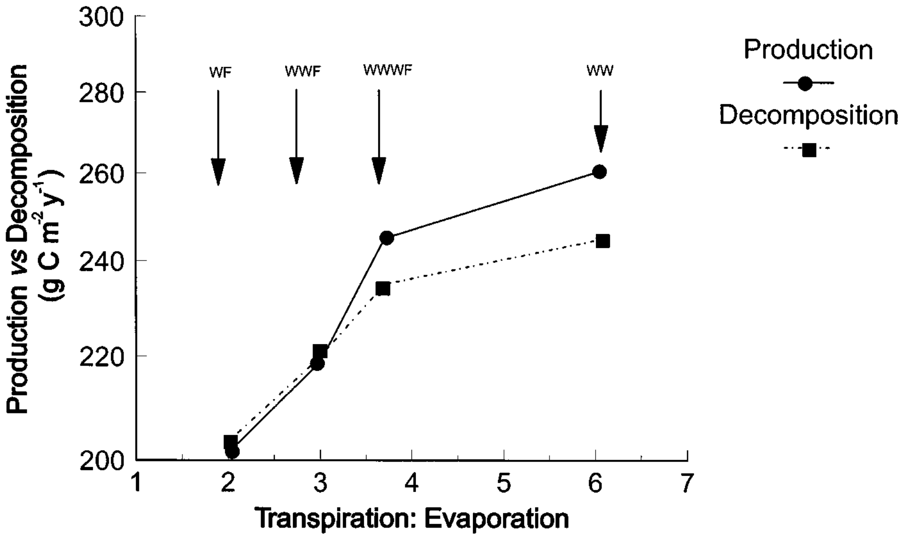


*Figure 3.* There is a strong relationship between transpiration/evaporation and the production versus decomposition of crop residues, based on model output from the Grassland Ecosystem Model (Hunt et al. 1991), for 12-year runs of a series of crop rotations in eastern Colorado. Production represents average annual above-ground NPP, excluding grain production, while decomposition is the average annual $CO_2$-C flux from surface crop residues. Differences between production and decomposition rates represent the net annual change in surface residue levels. Total evapotranspiration losses (510 mm per year) were the same for all cropping systems. W = Wheat, F = Fallow.

Increasing cropping frequency resulted in drier soils, which decreased the specific rate (i.e., g $CO_2$-C per g C) of residue decomposition (data not shown), further reinforcing the accumulation of surface residues.

In support of this modeling result, numerous field experiments, in which different cropping intensities have been compared (ranging from alternate wheat-fallow to continuous cropping), show increases in soil C in direct proportion to decreased fallow frequency (Campbell & Zentner 1997; Bremer et al. 1994; Peterson et al. 1998). In a long-term experiment in eastern Washington, varying levels of C inputs (as crop residues plus organic matter additions as straw, green manure or animal manure) were applied to both wheat-fallow and continuous wheat systems over a 31 year period (Horner et al. 1960). The relationship between C input rates and changes in soil C, expressed as average annual loss rate (negative values denote a net increase) over the course of the experiment, was linear in both cases (Figure 4). However, for the same C input, net C losses were ca. 20–25 g $m^{-2}$ higher under the wheat-fallow system compared with continuous wheat. If most of the C loss was as $CO_2$ (i.e., assuming erosional losses were minimal), then

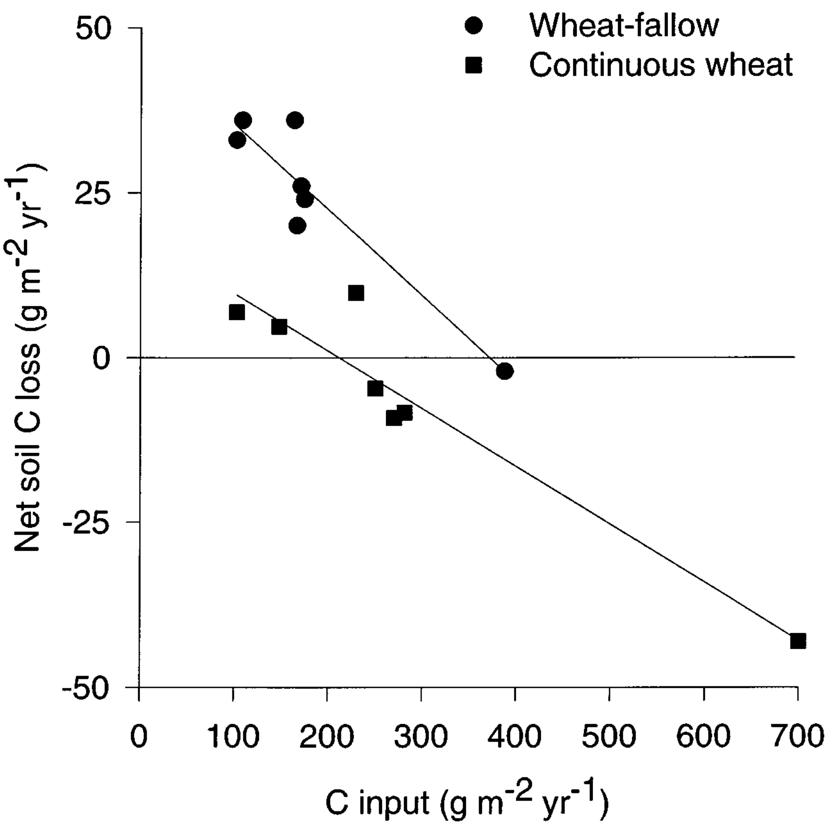


*Figure 4.* Annual net change in soil C as a function of annual C inputs, for long-term experiments under wheat-summer fallow versus continuous wheat rotations near Pullman, Washington. Within rotations, treatments consisted of different levels of organic C additions, including *in situ* crop residues plus exogenous inputs of straw, green manure and farmyard manure. From Horner et al. (1960).

the data suggest that the greater C retention under continuous wheat was due to a reduction in the specific rate of decomposition.

Cropping intensity can also be promoted by increasing the use of perennial species in crop rotations. Perennial grasses, in particular, have a high relative allocation of C belowground. Higher C inputs and an absence of tillage disturbance are the principal reasons that perennial grasses sequester C (Paustian et al. 1997b). However, perennial species can also have higher evapotranspiration rates over an extended growing season (compared to annuals), which can lead to drier soils and reduced decomposition rates. In detailed C budgets compiled over two seasons, Paustian et al. (1990) found that C inputs were higher in a second year grass ley than in fertilized and

*Table 2.* Partitioning of annual heterotrophic respiration for three cropping systems in central Sweden (from Paustian et al. 1990).

| | Barley unfertilized | Barley fertilized w/120 kg N ha$^{-1}$ (g C m$^{-2}$ y$^{-1}$) | Grass ley |
|---|---|---|---|
| C input | 147 | 184 | 265 |
| Respiration from litter | 87 | 92 | 174 |
| Respiration from SOM | 80 | 76 | 72 |
| Net $CO_2$ emission | 20 | −16 | −20 |

unfertilized barley monocultures (Table 2). Total heterotroph respiration, both from fresh litter and SOM, increased in the same order (unfertilized barley < fertilized barley < grass ley). However, most of the $CO_2$ emitted was from the current year's litter and the C budgets suggested that $CO_2$ emissions from existing soil organic matter was lowest in the grass ley and that total C was increasing in the system (i.e., net $CO_2$ emissions were negative). Decomposition experiments using standardized litter material in each treatment (Andrén 1987) and soil moisture measurements (Jansson et al. 1990) support the concept of a reduced decomposition potential under the grass ley because of lower soil moisture levels.

Another factor influencing the SOM accumulation within more intensive cropping systems is the interaction between nutrients, roots, water and SOM. Available nutrients are very dynamic in the surface soil layer; they may be depleted by net microbial immobilization at times of high litter input, but abundant at times of net mineralization. Roots affect microbial activity through their influence on inorganic nutrient availability and water, while microorganisms influence root proliferation through their effects on nutrient availability. In the short term, increased litter inputs stimulate competition between microbes and plants for nutrients thus reducing the efficiency with which added nutrients are utilized by plants. Over longer periods of time, as litter and organic matter pool sizes increase, improved plant water availability and a greater nutrient recycling capacity, with less nutrient leakage, reinforce processes favoring C sequestration.

Other factors influencing soil respiration, such as pH and plant litter composition, are affected by agricultural management practices. Reducing soil temperature through the use of surface mulches and no-till practices is important for maintaining SOM stocks especially in tropical soils (Lal 1989). Litter quality affects rates of decomposition (Heal et al. 1997), but it is generally not a primary criterion for choosing which crops to grow and most food crop residues are relatively easily decomposed. Research is ongoing in tropical agroecosystems to determine how to manage the quality of litter inputs to improve nutrient use efficiency and promote SOM improvement (Swift et al. 1994).

In summary, net $CO_2$ emissions from soil can be reduced through practices that increase C inputs to soils and reduce the decomposition potential in soil. Among the most effective ways to achieve these objectives are to decrease soil disturbance by eliminating or reducing tillage and through intensified cropping, which maximizes the utilization of water and nutrients and increases the production relative to decomposition, thereby shifting the C balance equation in favor of soil C accumulation.

## Conclusions

The international community, through the Framework Convention on Climate Change, has agreed on the need to reduce greenhouse gas emissions, including $CO_2$. With the Kyoto accords, further steps towards mandatory reductions have been set forth, although they have yet to be ratified by several countries, including the U.S. Consequently, attention is being focused on the assessment of various greenhouse gas mitigation strategies and the development and implementation of the most beneficial and cost effective options. Current knowledge strongly suggests that agricultural soils have the capacity to act as a significant sink for $CO_2$ over the next several decades, if appropriate changes in management practices are implemented. Arguments in favor of including agricultural soil C sequestration as a mitigation option are that additional benefits, such as improved soil and water quality, reduced erosion, better soil fertility and crop production, will accrue from increasing soil organic matter. Such additional benefits, and the fact that C sequestering practices are already being implemented, imply that increased rates of adoption (and hence increased C sequestration) may be achievable at a relatively low cost.

Caveats, however, include a recognition that soils have a finite capacity to store C. Following a change in management the sink capacity of the soil declines over time with the highest rates of C storage occurring during the first few decades. In addition, the effects of management improvements are reversible; if soils revert to their former management (e.g., perennial grassland returned to annual cropping, reversion of no-till to intensive cultivation), soil respiration will increase and previously sequestered C will be released as $CO_2$. Thus management improvements will need to be maintained in order for C sequestering strategies to be effective (whether in soils or in other forms such as forest biomass). It should also be recognized that modern agriculture is highly dependent on fossil fuel subsidies for operating machinery, heating and cooling, and for the production of fertilizer and pesticides. For example, the manufacture and transportation of 1 unit of N as mineral fertilizer corresponds to 1–1.5 units of C emissions from fossil fuels (Janzen et al. 1998, Paustian et al. 1998). Thus, efforts to improve agricultural management for the purposes of sequestering C in soils must also consider these emission sources (as well as potential effects on other greenhouse gases such as $N_2O$ and $CH_4$). Finally, scientists and policy experts will need to devise reliable and cost-effective means of quantifying these changes in net C fluxes, including quantification of the uncertainties in estimates, in order for C sequestering strategies to be accepted as components of greenhouse gas reductions in international agreements.

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