# Effects of agricultural management on soil organic matter and carbon transformation – a review

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## ABSTRACT

Soil organic carbon (SOC) is the most often reported attribute and is chosen as the most important indicator of soil quality and agricultural sustainability. In this review, we summarized how cultivation, crop rotation, residue and tillage management, fertilization and monoculture affect soil quality, soil organic matter (SOM) and carbon transformation. The results confirm that SOM is not only a source of carbon but also a sink for carbon sequestration. Cultivation and tillage can reduce soil SOC content and lead to soil deterioration. Tillage practices have a major effect on distribution of C and N, and the rates of organic matter decomposition and N mineralization. Proper adoption of crop rotation can increase or maintain the quantity and quality of soil organic matter, and improve soil chemical and physical properties. Adequate application of fertilizers combined with farmyard manure could increase soil nutrients, and SOC content. Manure or crop residue alone may not be adequate to maintain SOC levels. Crop types influence SOC and soil function in continuous monoculture systems. SOC can be best preserved by rotation with reduced tillage frequency and with additions of chemical fertilizers and manure. Knowledge and assessment of changes (positive or negative) in SOC status with time is still needed to evaluate the impact of different management practices.

**Keywords:** soil organic carbon; crop rotation; soil tillage; fertilization; monoculture; agricultural management

Soil is a vital natural resource that is nonrenewable on the human time scale (Jenny 1980) and is a living, dynamic, natural body that plays many key roles in terrestrial ecosystems. It is the essence of life and health for the well-being of humankind and animals and the major source of most of our food production. The maintenance of soil health is essential for sustained productivity of food, the decomposition of wastes, storage of heat, sequestration of carbon, and the exchange of gases. However, only a limited area of the soil can actually be used for growing food, and when improperly managed it can be eroded, polluted or even destroyed (Brady and Weil 2000).

It is estimated that the soil in 11% of the vegetative area and 38% of the cultivated area in the world have been degraded since 1945 (Hammond 1992, Gardiner and Miller 2004). This is an area of the size of China and India together. Approximately 24 billion tons of topsoil is lost annually, which is equivalent to about 9.6 million hectares of land (Bakker 1990). Therefore, soil degradation and/or changes in soil quality that result from wind and water erosion, salinization, losses of organic matter and nutrients, or soil compaction are of great concern in every agricultural region in the world.

In the last two decades, public interest in soil quality has been increasing throughout the world as humankind recognizes the fragility of earth's soil, water and air resources, and the need of their protection to sustain civilization. The concept of soil quality was first suggested in 1977 at a conference (Doran and Parkin 1994) which focused on the risks and benefits associated with intensive agriculture, but the concept per se was not discussed until 1980s when it was defined based on the soil function, and the methods to evaluate it were published.

Soil quality was defined in many different ways. Power and Meyers (1989) defined soil quality as the ability of soil to support crop growth, including factors such as tilth, aggregation, organic matter content, soil depth, water holding capacity, infiltration rate, pH changes and nutrient capacity. Larson and Pierce (1991) defined soil quality as the capacity of the soil to function within ecosystem boundaries and to interact positively with the environment external to that ecosystem. After the U.S. National Academy of Science published "Soil and Water Quality: An Agenda for Agriculture" in 1993, the concept evolved with a holistic focus emphasizing that sustainable soil management required more than soil erosion control. Mausbach and Tugel (1995) similar to Larson and Pierce (1991) stated that "soil quality reflects the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation". Sojka and Upchurch (1999) further proposed that soil quality must be defined in terms of distinct management and environmental considerations specific to one soil, under explicit circumstances for a given use. The considerations included social, economic, biological and other value judgments. Singer and Ewing (2000) stated that "useful evaluation of soil quality requires agreement about why soil quality is important, how it is defined, how it should be measured, and how to respond to measurements with management, restoration, or conservation practices". Thus, these issues are not easily addressed because determining soil quality requires one or more value judgments and because there is still much unknown about soil.

Worldwide research and technology transfer efforts have increased awareness that soil resources have both inherent characteristics determined by their formation factors and dynamic characteristics determined by human decisions and management practices. In this sense, understanding soil quality means assessing and managing soil so that it functions optimally now and is not degraded for future use (Brady and Weil 2002). Much like air and water, the quality of soil has a profound effect on the health and productivity of a given ecosystem and the environments related to it. However, unlike air and water for which we have quality standards, the definition of soil quality is complicated because in part humans and animals do not directly consume it (Doran and Parkin 1994, Liu and Herbert 2002). Soil quality cannot be measured directly, so there is a need to evaluate indicators. Soil indicators are measurable properties of soil or plants that provide clues about how well the soil can function. A variety of physical, chemical, and biological characteristics can be used as indicators. However, descriptive indicators and quantitative means to monitor soil quality are, at best, difficult to define. Arshad and Coen (1992) gave possible descriptive indicators to characterize soil quality, which included evidence of erosion, soil structure, friability, crusting of the soil surface and ponding of water. All of these are physical attributes of the soil, to a certain extent they can be controlled by Best Management Practices (BMPs), and they are somewhat qualitative in nature. Quantitative measures to monitor soils such as soil pH and extractable N-P-K are more developed but are still being explored as to how these measures affect yield, nutrient levels and the biological health of the soil. Soil quality indicators interact with one another, and thus the value of one is affected by one or more of the other selected parameters. Soil quality also varies due to many external factors such as land use, soil and crop management, environmental interactions, societal goals as well as variation in natural conditions (Campbell et al. 2001a, Follett 2001, Arshad and Martin 2002, Dao et al. 2002, Liu et al. 2003, Liebig et al. 2004).

Soil organic matter (SOM) is the central indicator of soil quality and health, which is strongly affected by agricultural management (Lal et al. 1995, Farquharson et al. 2003). SOM is a major terrestrial pool for C, N, P, and S, and the cycling and availability of these elements are constantly being changed by microbial immobilization and mineralization (Hillel 1991, Feichtinger et al. 2004). The importance of increased SOM or soil organic carbon (SOC) is its effect on improving soil physical properties, conserving water, and increasing available nutrients. These improvements should ultimately lead to greater biomass and crop yield (Bauer and Black 1994, Berzsenyi et al. 2000, Onemli 2004). There is considerable concern that if SOM or SOC concentrations in soils are allowed to decrease too much, the productive capacity of agriculture will be then compromised by deterioration in soil physical properties and by impairment of soil nutrient cycling mechanisms (Bauer and Black 1994, Loveland and Webb 2003). The interactions and negative impacts of agricul-

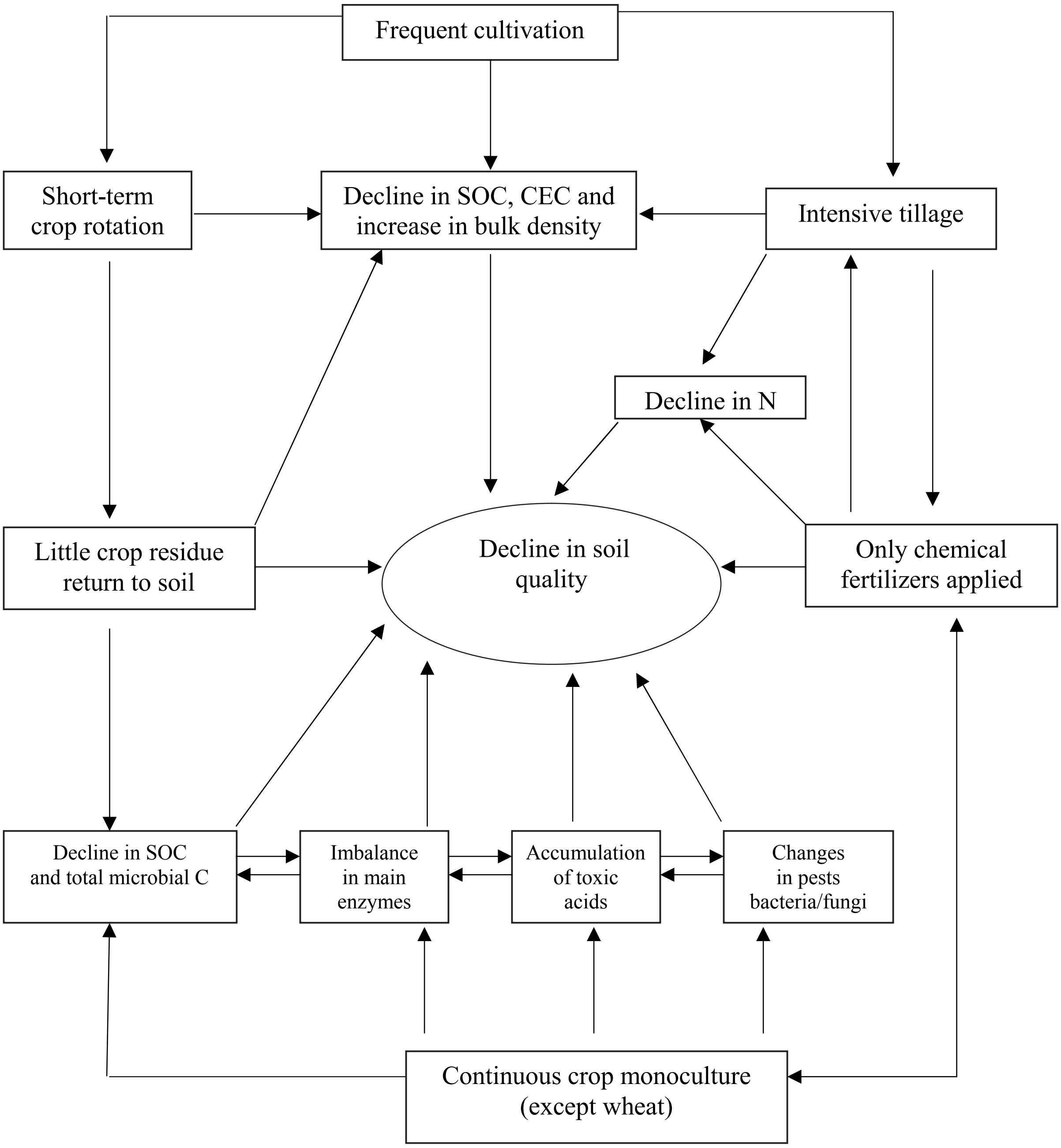

Figure 1. Diagram of interactions and negative impacts of agricultural management on soil quality

tural management on soil quality are illustrated in Figure 1.

Long-term experiments are often required to predict soil management impacts on soil carbon storage and provide leading indicators of sustainability, which can serve as an early warning system to detect impairments that threaten future productivity (Clapp et al. 2000).

In this review, we summarized how cultivation, crop rotation, residue and tillage management, fertilization, and monoculture affect soil quality, SOM and carbon transformation.

### Soil organic carbon and sequestration

SOM is a complex mixture which contributes positively to soil fertility, soil tilth, crop production, and overall soil sustainability. It minimizes negative environmental impacts, and thus improves soil quality (Lal et al. 1997, Reeves 1997, Freixo et al. 2002, Farquharson et al. 2003). Loveland and Webb (2003) suggested that a major threshold is 2% SOC (ca. 3.4% SOM) in temperate regions, below which potentially serious decline in soil quality will occur.

There are two means to increase the organic matter content of soils; one is to increase the organic matter gains or additions to the soil, and the other is to decrease organic matter losses (Magdoff and van Es 2000). Soils contain carbon in their organic and inorganic (carbonates) forms. While little can be done to increase the carbonate content of soils, it is possible to increase the soil organic matter content (Kern and Johnson 1993, Campbell 1998, Chan et al. 2003). Storage of SOC is a balance between C additions from non-harvested portions of crops and organic amendments, and C losses, primarily through organic matter decomposition and release of respired $CO_2$ to the atmosphere. Organic matter returned to the soil, directly from crop residues or indirectly as manure, consists of many different organic compounds. Some of these are digested quickly by soil microorganisms. The result of this is a rapid formation of microbial compounds and body structures, important in holding particles together to provide soil structure and to limit soil erosion, and the release of carbon dioxide back to the atmosphere through microbial respiration (Dao 1998, Kladivko 2001).

Average global C sequestration rates, when changing land use from agriculture to forest or grassland, were estimated to be 33.8 and 33.2 g $C/m^2$ per year, respectively (Post and Kwon 2000). In an analysis of 17 experiments, Kern and Johnson (1993) concluded that the greatest change of C occurred in the top 8 cm of soil, a lesser amount in the 8- to 15-cm depth, and no significant amount below 15 cm. They also concluded that, unlike no-till (NT) in which SOC had increased, no significant change in SOC was detected in response to reduced tillage (RT). From these studies, they estimated the duration of C sequestration to be between 10 and 20 years. Paustian et al. (1998) compared tillage systems, ranging in duration from 5 to 20 years, and estimated that NT resulted in an average soil C increase of 285 $g/m^2$, compared to conventional tillage (CT). Using an average experiment duration of 13 years it implies an approximate C sequestration rate of 22 $g/m^2/yr$. West and Post (2002) analyzed the C sequestration rates using a global database of 67 long-term agricultural experiments and indicated that on average, a change from CT to NT can sequester 57 ± 14 g $C/m^2/yr$, and by enhancing crop rotation complexity it can sequester an average of 20 ± 12 g $C/m^2/yr$. Carbon sequestration rates can be expected to peak in 5–10 years with SOC reaching a new equilibrium in 15–20 years. Following initiation of an enhancement in rotation complexity, SOC may reach a new equilibrium in approximately 40–60 years. The analysis of long-term experiments in Canada indicated that SOC can be sequestrated for 25–30 years at a rate of 50–75 g $C/m^2/yr$, depending on soil type, in well fertilized Chernozemic and Luvisolic soils cropped continuously to cereals and hay (Dumanski et al. 1998).

For total SOC calculation and global carbon cycle, carbon content is often expressed on an area-basis (depth-based) for comparisons (Ding et al. 2002). Liu et al. (2003) showed a significant decline of total SOC that occurred in the first 5 years of cultivation where the average SOC loss per year was about 2300 kg/ha for the 0–17 cm horizon. The average annual SOC loss between 5- and 14-year cultivation was 950 kg/ha and between 14- and 50-year cultivation it was 290 kg/ha. These data clearly showed a rapid reduction of SOC for the initial soil disturbance by cultivation and a relatively gradual loss later. Compared with organic matter in the uncultivated soil, Liu et al. (2003) also indicated that the total SOC loss (the sum of three horizons) was 17%, 28%, and 55% in the 5-, 14- and 50-year cultivation periods, respectively. The latter would correspond to the release of approximately 380 ton $CO_2$/ha to the atmosphere. These results were consistent with the estimation of changes in SOC during cultivation by Davidson and Ackerman (1993). This means that a new equilibrium will be reached when SOC declines to a threshold.

Thus, soil organic matter is not only an important source of carbon for soil processes but also a sink for carbon sequestration. Cultivation can reduce SOC content and lead to soil deterioration, and finally reduce soil productivity. By changing land use and tillage systems or by the adoption of sustainable crop rotations and the inclusion of perennial vegetation, carbon sequestration rates can be increased to a range of 20–75 $g/m^2/yr$, and SOC may reach a new equilibrium within several decades.

## Soil tillage

Tillage is used to mix and aerate the soil, and to incorporate cover crops, crop residue, manure, fertilizers and pesticides into the rooting zone (Acquaah 2002). Soil tillage management can affect factors controlling soil respiration, including substrate availability, soil temperature, water content, pH, oxidation-reduction potential, kind and number of microorganisms, and the soil ecology (Robinson et al. 1994, Kladivko 2001).

Beare et al. (1994) indicated that tillage enhanced short-term $CO_2$ evolution and microbial biomass turnover, and accelerated organic C oxidation to $CO_2$ not only by improving soil aeration, but also by increasing contact between soil and crop residues, and by exposing aggregate-protected organic matter to microbial attack. Tillage also exposes organic carbon in both the inter- and intra-aggregate zones and that immobilized in microbial cellular tissues to rapid oxidation (Roscoe and Burman 2003). This is because of the improved availability of $O_2$ and the exposure of more decomposition surfaces, thereby stimulating increased microbial activity (Beare et al. 1994, Jastrow et al. 1996).

Conventional tillage significantly reduces biological diversity in surface soil. Doran and Smith (1987) summarized data from the U.S.A., Canada, and England and stated that the surface level of SOC, microbial biomass, and potentially mineralizable N was all significantly higher in the no-till than in the plow-till method of seedbed preparation.

Increased C storage has been frequently observed in soils under conservation tillage, particularly with NT (Unger 1991, Zibilske et al. 2002). A widespread adoption of conservation tillage could result in net increases in C sequestration in agricultural lands, reversing the decline caused by intensive tillage practices used for decades (Kern and Johnson 1993, Campbell et al. 2001b). Kushwaha et al. (2001) found that the values of SOC and total N were the highest in the minimum tillage and residue retained treatment and the lowest in conventional tillage and residue removed treatment. Tillage reduction from conventional to minimum and zero conditions along with residue retention increased the proportion of macro-aggregates over 21–42% over control in soil (Kushwaha et al. 2001). Active microbial biomass and C mineralization were higher under NT than under conventional tillage in the top 5 cm of the soil profile (Alvarez and Alvarez 2000). Dao (1998) indicated that cultivation, high temperature, and a semiarid climate accelerated organic carbon loss and weakened soil structure in the Southern Plains, and tillage and residue incorporation enhanced C mineralization and atmospheric fluxes, suggesting tillage intensity should be decreased to reduce C loss.

Tillage operations strongly control the soil environment by altering the soil geometry. These effects influence many physical, chemical and biological properties of the soil and thereby the conditions for crop growth. Alvarez and Alvarez (2000) stated that conservation tillage, especially no-tillage, induced changes in the distribution of organic pools in the soil profile. SOC gains under no-till were about 250 kg/ha/yr greater than for tilled systems regardless of cropping frequency in Canadian prairies with climate in semiarid conditions (Campbell et al. 2005). Within the surface 7.5 cm, the no-till system possessed significantly more SOC (by 7.28 Mg/ha), particulate organic matter C (by 4.98 Mg/ha), potentially mineralizable N (by 32.4 kg/ha), and microbial biomass C (by 586 kg/ha), as well as greater aggregate stability (by 33.4%) and faster infiltration rates (by 55.6 cm/h) relative to the conventional tillage (Liebig et al. 2004). Balota et al. (2003) showed that no-tillage increased microbial biomass C, N, and P, and higher levels of more labile C existed in no-tillage systems than in conventional systems. However, conversion to zero tillage may not always result in an increase in soil C or N without adequate fertility (Campbell et al. 2001a).

Much of the decomposition, as a result of soil tillage, takes place immediately after the soil is plowed and is directly related to the volume of soil disturbed and the roughness of the surface after plowing (Dao et al. 2002). The moldboard plow causes the largest amount of carbon losses, while a deep tillage tool that does not invert soil causes little decomposition of organic matter. Any reduction of soil disturbance can be expected to reduce soil carbon losses. Conversely, the techniques of minimum tillage and no-till mean slower rates of organic matter decay (Acquaah 2002). In a University of Guelph experiment comparing different tillage practices for corn, the topsoil (0–15 cm depth) of plots devoted to no-till corn production had an average of 19.8 t/ha more organic matter after 18 years of research than did the plots where corn was grown using traditional tillage methods (fall moldboard plowing plus secondary tillage in spring time) (Vyn and Raimbault 1993). In this experiment, no difference was found among tillage treatments in soil organic matter levels at lower soil depths. More SOC was found in the top 10 cm and less in the 10–20 cm soil depth of the chisel plow than in the moldboard plow soils. However, chisel plow did not increase the SOC content (0–20 cm) above that of moldboard plow indicating this form of reduced tillage did not increase C sequestration in any of the rotations (Yang and Kay 2001).

After 11 years of different tillage operations in Chinese Mollisols, Liu et al. (2005) reported that integrated tillage, where tillage system varied with each crop in the rotation (i.e. moldboard plow for wheat, deep chisel for corn and rotatory plow for soybean), had the highest levels of SOC and N in the upper soil layer in the Chinese Mollisol. Moldboard plowing had the lowest level of SOC and N content in the profile, with the largest reduction being in the top two layers. The SOC and N contents at 16–30 cm in the rotary plowing and conventional tillage were higher than in the depth between 0 and 15 cm, indicating that more root residues were incorporated into this layer. This result was consistent with mixing of organic matter by plowing but opposite to results with no-tillage practice or conservation tillage (Arshad et al. 1990, Dalal et al. 1991, Ding et al. 2002). Overall, integrated tillage appeared effective in maintaining SOC and, maybe, soil productivity. Yang et al. (2003a) indicated that the conversion from conventional tillage to conservation tillage at an annual rate of 2%, particularly no till, could reverse the loss of SOC in Chinese Mollisols within 20 years. However, this positive effect of conservation tillage on SOC in black soil area of China was only effective in severely eroded soil or in the farmland with slope, and it was not effective in flat and low-damp farmland.

It is thus evident that tillage practices have a major effect on soil properties, the distribution of C and N, and the rate of organic matter decomposition and N mineralization. The adoption of conservation tillage for reversing the decline of SOC in agricultural lands is possible in the black soil area of China, as it has been in many other countries. Continuous monitoring of long-term changes in the soil organic carbon and soil quality under conservation tillage in different agro-ecological zones is essential. There is also a need to obtain more data on long-term effects of different tillage systems on carbon and nitrogen mineralization and immobilization in field situations.

## Crop rotation

Crop rotation can have a major impact on soil health, due to emerging soil ecological interactions and processes that occur with time. These include improving soil structural stability and nutrient use efficiency, increasing crop water use efficiency and soil organic matter levels, providing better weed control, and disrupting insect and disease life cycles (Carter et al. 2002, Carter et al. 2003). Crop rotations can also increase yields, and enhance nitrogen availability when nitrogen-fixing legumes are included (Galantini et al. 2000, Miglierina et al. 2000). Crop rotation systems are more effective at reducing long-term yield variability than monoculture systems, and can increase total soil C and N concentrations over time, which may further improve soil productivity (Varvel 2000, Kelley et al. 2003).

Carter et al. (2003) indicated that losses of SOC during 11-year period ranged from marginal (4%) for rotations with Italian ryegrass, to significant (16%) under barley rotation, which illustrates the importance of C inputs in maintaining soil organic matter levels. Blair and Crocker (2000) examined the effect of different rotations, including legumes and fallows on soil structural stability, unsaturated hydraulic conductivity, and the concentration of different carbon fractions in a long-term rotation trial, and found that the inclusion of legume crops in the rotation resulted in an increase in liable carbon concentrations compared with continuous wheat or a long fallow period.

In comparison of maize-rice and rice-rice cropping systems, Witt et al. (2000) found that the replacement of dry season rice by maize caused a reduction in soil C and N due to a 33–41% increase in the estimated amount of mineralized C and N during the dry season. As a result, there was 11–12% more C sequestration and 5–12% more N accumulation in soils continuously cropped with rice than in the maize-rice rotation with the greater amounts sequestered in N-fertilized treatments. Their results documented the capacity of continuous, irrigated rice systems to sequester C and N during relatively short time periods.

Yang and Kay (2001) found that continuous alfalfa had the greatest average SOC concentration (0–40 cm), and rotations had higher SOC concentration than continuous corn. Huggins et al. (1998) reported that in the treatments containing both crops aboveground C returned to the soil from corn was in average 40% higher than C returned from soybean. Although more aboveground C was returned with corn, SOC did not differ with crop sequence or depth. Smith et al. (2000) developed a dynamic soil quality model to evaluate optimum cropping systems in the northern Great Plains, and indicated that a crop production system with continuous spring wheat and direct planting was the most profitable system and had lower soil erosion and higher soil quality attributes.

During a 9-year crop rotation experiment in the Chinese Mollisol, Liu et al. (2003) found that cropping systems significantly altered SOC concentration. The SOC in the treatments of the wheat-sweet clover and wheat-soybean with addition of pig manure or wheat straw was significantly higher than that of the commonly used wheat-soybean rotation (wheat straw removed), particularly in the 0–17 cm horizon. For the overall SOC concentration (means of SOC of all three horizons), soil with addition of wheat straw was 22% greater than that of wheat-soybean alone, and similar differences occurred for overall SOC in the wheat-sweet clover rotation and wheat-soybean rotation with addition of pig manure. However, all three treatments increased SOC content in the 18–32 cm soil depth relative to the wheat-soybean rotation.

Liu et al. (2003) also showed that the wheat-sweet clover rotation not only increased the SOC content in all soil depths, but also had the greatest amount of SOC and had a decrease in soil bulk density. The wheat-soybean rotation with addition of wheat straw had a total of SOC (62 300 kg/ha), or an increase of 7.5% as compared with SOC in the typical wheat-soybean rotation in the region. The total SOC storage (sum of all three horizons) increase was 10.7% for wheat-soybean rotation with addition of manure, and 14.4% for wheat-soybean rotation with addition of wheat straw. The total amount of SOC increase (11 700 kg/ha) in wheat-soybean rotation with addition of wheat straw would correspond to sequestration of approximately 43 ton $CO_2$/ha from atmosphere. Fang et al. (2005) indicated that 2.24–5.0 Tg C was released into atmosphere annually ever since the cultivation of black soil in China, and maximum soil carbon sequestration potential could be as much as 1.55 Tg if appropriate measures were taken especially in crop rotations.

These results indicated that improved crop rotation strategies can increase the organic carbon reserve and improve soil structure and quality of the black soils, thereby sequestrating $CO_2$ from the atmosphere and thus mitigating against the greenhouse effect. Further, the adoption of appropriate crop rotations to increase the quantity and quality of soil organic matter and hence soil chemical and physical will help to ensure the long-term sustainability of agriculture in the world.

### Monoculture

The impacts of continuous monoculture systems on SOC, soil function and sustainability differed among crops (Russell and Jones 1996, Ryszkowski et al. 1998). Acosta-Martinez et al. (2004) concluded that continuous monoculture systems had a negative impact on soil function and sustainability. They found that organic C was higher in perennial pasture compared with continuous cotton at the depth of 0–5 cm, and soil microbial biomass, C, N and soil enzymes were also lower in the continuous cotton. In a Brown Chernozem, continuous wheat increased soil organic N in the 0–15 cm soil layer by 7–17 kg N/ha/yr more than fallow/wheat, and was accompanied by an increase in the proportion of mineralizable soil organic N (Liang et al. 2004). Potter et al. (1997) showed that total SOC content in the surface 20 cm increased by 5.6 t C/ha in the continuous wheat no-till treatment compared with the stubble mulch treatment. Campbell et al. (2005) reported that replacing wheat with lentil had little effect on SOC gains, and replacing wheat with lower-yielding flax reduced SOC gains, while replacing wheat with erosion-preventing fall rye increased SOC gains. A large increase in SOC level for a rotation compared to a monoculture maize system was found by Gregorich et al. (2001). Gil and Fick (2001) indicated that soil inorganic N of alfalfa monoculture was three- to fivefold higher than the alfalfa, red clover, and gamagrass-alfalfa mixture, but 30–50% lower than in gamagrass monoculture. Havlin et al. (1990) assessed SOC dynamics in: (1) continuous sorghum (*Sorghum bicolor* L.), continuous soybean (*Glycine max* L.), and sorghum-soybean rotations combined with tillage and N fertilization; and (2) continuous corn with corn-soybean rotation. The high residue-producing continuous sorghum in the first and the continuous corn in the second rotation combined with reduced tillage and surface residue maintenance resulted in more SOC sequestration than grain-legume rotations. Similar results were obtained by Omay et al. (1997) who reported more SOC under continuous corn than under corn-soybean rotation. The results by Yang et al. (2003b) in Chinese Mollisols also supported this conclusion. Drury et al. (1998) compared continuous corn with continuous Kentucky bluegrass (*Poa pratensis* L.) and 4-year corn-oat (*Avena sativa* L.)-alfalfa-alfalfa (*Medicago sativa* L.) rotation. The SOC level was in the order bluegrass > 4-year rotation > continuous corn.

Gajda and Martyniuk (2005) showed that the activities of the dehydrogenase and phosphatase and microbial biomass C and N contents in the monoculture soil were significantly lower than those in the soil from the organic and conventional-short rotation systems. Ryszkowski et al. (1998) reported that continuous cultivation of rye led to fauna impoverishment, and increased the number of crop pests and fungi with bacteria, and that actinomycetes became less abundant. Besides, the average concentration of phenolic acids in the soil of continuous rye was 400% higher than under rye in a diversified rotation. However, Gregorich et al. (2001) reported that chemical composition of organic matter was little affected by the nature of crop residues.

Liu et al. (2005) reported that for the Chinese Mollisols, continuous cropping of wheat, corn and soybean, compared to a rotation, reduced soil C and N contents at all depths in the profile with the exception of N content in continuous wheat. These results were similar to those of Mikhailova et al. (2000). Continuous wheat had the least impact on soil C and N contents. The total microbial C of topsoil layer was 533 mg/kg in continuous wheat, 429 mg/kg in the crop rotation, but only 350 mg/kg for continuous corn and 398 mg/kg for continuous soybean. Thus, continuous corn and soybean not only reduced SOC and N but also led to a decline of soil biological activity. Collins et al. (1992) reported a greater amount of soil organic matter and soil microbial biomass in continuous wheat than in a wheat-fallow rotation after 58 years. Liu et al. (2005) indicated that 11-year continuous corn, soybean, and wheat resulted in a 10%, 11% and 5.3% decline in SOC, respectively, compared with a rotation of all crops; continuous cropping also resulted in a 6.5% decline in N for corn and soybean but there was no decline for wheat. These results suggest that if continuous corn, soybean, or wheat were to be adopted on Chinese Mollisols, an average annual decline rate of soil carbon in the 0–90 cm soil profile would be 0.91%, 0.97% and 0.48%, respectively. The decline in soil N would be 0.53% for continuous soybean or corn. Another research showed that a decline in SOC significantly reduced the N supply and resulted in the deterioration of soil physical properties (Stevenson 1994).

Liu (2004) reported that for Chinese Mollisols continuous soybean had a greater decline in SOC and N contents at the 51–70 cm and 71–90 cm depths than the other treatments. This effect may be due to the tap root system of soybean as well as harmful impacts of continuous cropping on soybean root nodules and nitrogen fixation (Liu and Herbert 2002). Liu (2004) also found declines in soil pH and of phosphatase, urease, invertase and dehydrogenase activities, but an increase in sucrase activity in continuous soybean soil. Moreover, the number of bacteria in continuous soybean was significantly lower than in normal soybean rotations, whereas fungi were more numerous, resulting in a decline in the bacteria/fungi ratio. This imbalance in the microbe populations in soybean monoculture may contribute to the decline in soil fertility. A higher bacteria/fungi ratio is consistent with higher soil fertility, whereas a lower ratio favoring fungi is consistent with a low fertility soil. Liu and Herbert (2002) proposed that some acid compounds were deposited in the continuous soybean soil, contributing to the deterioration of soil biological activity. Hence, the increase and influence of fungi in the continuous soybean soil rhizosphere demonstrates that continuous soybean is not sustainable unless countermeasures are taken to deal with the fungi increase.

Crop type therefore influences SOC and soil function in continuous monoculture systems. The negative prominent impacts of monoculture are fauna impoverishment, increased number of crop pests, declined activities of dehydrogenase and phosphatase, and higher phenolic acids in the soil. Although continuous wheat increased microbial biomass and alfalfa haycrop increased inorganic N significantly, continuous monoculture is not sustainable for many crops unless countermeasures are taken to deal with.

## Fertilization

Fertilization is one of the most important practices in crop production for its influence on soil nutrients availability. Ishaq et al. (2002) showed that a fertilizer application significantly increased soil P and K concentrations, and the concentrations of N, P, K and SOC were greater in the plough layer than in the subsoil. Nitrogen is the nutrient most limiting to crop production in all areas of the world and is generally applied to soil in a large quantity. Since the application of N to the soil is subject to losses by volatilization, immobilization, denitrification and leaching, it may be necessary to compensate this by adjusting the fertilizer management. Fertilizer use efficiency may also change with changes in tillage management. Malhi et al. (2001) indicated that placing the fertilizer in a band reduced contact with soil microorganisms, and reducing immobilization of both ammonium ($NH_4^+$) and nitrate ($NO_3^-$). Banding also slowed down the conversion of urea to $NH_3$ and $NH_4^+$ to $NO_3^-$, which can reduce N losses by volatilization and leaching. Reducing tillage intensity modified both the demand of crops for N due to changes in yield potential, and supply of N due to changes in N cycling and losses. The N fertilization effects on SOC were most evident when stover was returned to no-till plots (Clapp et al. 2000). Farmyard manure and the recycling of crop residues with NPK supplementation are efficient ways of fertilizing maize and wheat. Significantly higher yields were obtained at high levels of NPK fertilization, especially in rotations where the proportion of maize or wheat was 50% or higher (Berzsenyi et al. 2000). Hao et al. (2002) showed that the effects of manure application, tillage, crop rotation, fertilizer rate, and soil and water conservation farming on SOC pool were cumulative.

No tillage continuous corn with NPK, lime, and cattle manure was an effective cropland management system for SOC sequestration. Campbell et al. (2000) found that SOC was increased most by annual cropping with application of adequate fertilizer N and P in semiarid southwestern Saskatchewan. They also found that soil organic C and total N, microbial biomass, light fraction organic C and N, mineralizable N and wet aggregate stability, generally had positive responses to fertilization (Campbell et al. 2001b). Reddy et al. (2003) showed that continuous application of NPK plus farmyard manure led to a marked increase in organic C and total N as compared to an adjacent areas of left fallow in an Eutrochrept soil. The introduction of crop residue mulch and higher rates of fertilizers were recommended for sustaining soil quality (Sarno et al. 2004). However, the effects of fertilization on soil C were small, and differences were observed only in the monoculture maize system (Gregorich et al. 2001).

After 16 years of different fertilization treatments in the crop rotation, Liu et al. (2005) found that the profile average SOC content (0–90 cm) was only 0.9%, 4.1%, and 8.6% higher for manure, chemical fertilizers, and manure plus fertilizers, respectively, than that with no fertilizer application or control in the Chinese Mollisols. However, SOC at the 0–15 cm soil layer was 6.2%, 7.7%, and 9.3% higher with manure, chemical fertilizers, and manure plus fertilizers, respectively, than with no fertilizer application. These results indicated that the annual rate of decline rate of SOC in the 0–15 cm layer without fertilizer was not very high (< 0.58%/yr) when a well-designed crop rotation was used. The results were similar to data from long-term experiments in Denmark and England that revealed a slow change in SOC levels under temperate conditions in response to changes in different land uses (Christensen and Johnson 1997). Yang et al. (2003b) further indicated that the SOC content could be maintained at a relatively stable level under sufficient chemical fertilizer application without return of manure and crop residue conditions, and SOC content was increased at the combination of chemical fertilizer and manure application. This indicates that corn residue and exudates themselves could keep SOC equilibrium under current production level and management practices.

Liu et al. (2005) also reported for the Chinese Mollisols that manure alone did not increase the N content in the soil profile compared to that of no fertilizer application in the crop rotation. However, chemical fertilizers and manure plus fertilizers significantly increased N contents, especially at the 0–15 cm and 16–30 cm soil layers. Francioso et al. (2000) also reported that SOC and N differed significantly after 22 years for all treatments where the amendments with cattle manure markedly increased the SOC and N contents, while cow slurries and crop residues reduced SOC and N contents. The greatest reduction for SOC and N contents was in the unamended plots after 22 years. Reeves (1997) suggested that soil organic matter can be preserved only by ley rotations with reduced tillage frequency.

Generally, an adequate application of fertilizers combined with farmyard manure could increase soil nutrients, and SOC content in the Chinese Mollisols. Manure or crop residue alone could not maintain SOC levels, and SOC can only be preserved by rotation with reduced tillage frequency and additions of chemical fertilizers and manure.

## Summary

The dynamic processes that influence soil quality are complex, and they operate through time at different locations and situations. Soil organic matter is both a source of carbon release and a sink for carbon sequestration. Cultivation and tillage can reduce and change the distribution of SOC while an appropriate crop rotation can increase or maintain the quantity and quality of soil organic matter, and improve soil chemical and physical properties. The return of crop residues and the application of manure and fertilizers can all contribute to an increase in soil nutrients and SOC content, but would need to be combined into a management system for more improvement. The negative prominent impacts of monoculture are influenced by crop type with fauna impoverishment, an increased number of crop pests, a decline in activities of dehydrogenase and phosphatase, and increased levels of phenolic acids in the soil. SOC can only be preserved by using crop rotations with reduced tillage frequency and additions of chemical fertilizers, crop residues and/or manure. Continuous monitoring of long-term changes in the SOC and soil quality under conservation tillage in different agro-ecological zones is essential. There is also a need to obtain more data on long-term effects of different tillage systems on carbon and nitrogen mineralization and immobilization in various field situations. The issue involved in understanding soil quality and the design of crop and soil systems for agricultural sustainability should be more holistic, and it needs further investigation.

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