Soil Carbon Dynamics in Relation to Soil Surface Management and Cropping System

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Abstract

A high soil organic matter content is synonymous with high-quality agricultural soils, as it affects many soil processes such as microbial activity, nutrient storage and release, water retention and soil aggregate formation. Due pressure on agricultural intensification with improved and science-based technology imposed a challenge to increase agricultural production without accentuating risks of greenhouse gas (GHG) emissions, hence affecting the terrestrial carbon balance, which has been a research focus for more than a half-century. Agricultural practices including soil surface management, crop rotation, residue and tillage management, fertilization, and monoculture affect soil quality, soil organic matter (SOM), and carbon transformation. Consequently, soil surface management practices and cropping system have a major effect on the distribution of C and N and the rates of organic matter decomposition and N mineralization.

Keywords

Carbon dynamics · Cropping system · Soil organic carbon · Surface management

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10.1 Introduction

The world cropland area is estimated at about 1338 million ha (mha) (FAO 1996), which provides more than 97% of the world's food. While the world population is increasing, its land resources are finite and unequally distributed. During the 1970s, the increase in food production in most developing countries was achieved by bringing new land under agricultural production. Presently, however, reserves of potentially arable prime agricultural land are rapidly dwindling. Potentially arable land is located within fragile or ecologically sensitive ecoregions, for example, tropical rainforest, acid savannahs, steep lands, and the West African Sahel.

Agricultural intensification is also an important factor influencing the soil C dynamics and greenhouse gas (GHG) emissions. Because of the disturbance and exposure of the soil surface due to tillage and soil management practices, cropland soils are prone to numerous degradative processes. Degradation of cropland soils is a serious issue (Oldeman 1994), with drastic adverse impacts on global food security and environment quality. Two important environmental impacts of soil degradation are declining water quality (Lal and Stewart 1994) and feedback to the greenhouse effect (Lal 1995). A report of the Intergovernmental Panel on Climate Change estimated that 20% of the greenhouse effect is related to agricultural activities. Therefore, agricultural intensification with improved and science-based technology is inevitable, especially for countries that presently practice predominantly resource-based or subsistence agriculture. Therefore, producers, scientists, and planners have a challenge to increase agricultural production without accentuating risks of GHG emissions. In this regard, the management of soil resources, in general, and soil organic carbon (SOC), in particular, is extremely important. World soil resources may be the key factors in the creation of an effective carbon sink and mitigation of the greenhouse effect.

Long-term experiments are very valuable for evaluating the influence of soil management practices on SOC stocks, and they allow the estimation of average rates of SOM decomposition and stabilization in different soils under distinct climatic conditions (Bayer et al. 2006). Based on these estimates, future scenarios of soil management and their role in building up SOM and mitigating increased atmospheric CO_2 can be forecasted (Bayer et al. 2000, 2006; Lal 2004). In a long-term experiment, Bayer et al. (2006) estimated the SOM decomposition rate under no-till conditions as being about half (0.019 year^{-1}) that found under conventional tillage (0.040 year^{-1}), but the humification coefficient was not affected by the tillage system (14.8% under no-till and 14.6% under conventional tillage). Based on these results, they estimated a minimal requirement of 8.8 mg ha^{-1} of annual C input by the crops under conventional tillage to maintain the original SOC stock in the soil. This C input requirement is more than twice the 3.1 and 3.56 mg ha^{-1} year^{-1} estimated by Kong et al. (2005) and Majumder et al. (2008) under conventional tillage systems on a Mediterranean soil from the USA and a subtropical soil from India, respectively. This difference in C input to maintain SOC levels highlights the favourable climatic conditions for microbial SOM decomposition under humid and hot subtropical climate in southern Brazil. Only half of that quantity was required in a no-till system (3.9 mg C ha^{-1} $year^{-1}$), however, thereby indicating the importance of the no-till system on the SOM stabilization and the improvement of soil quality in this subtropical region (Vieira et al. 2009).

10.2 SOM Dynamics in Tropical and Temperate Soils

Primary plant production and soil microbial activity are the two main biological processes governing inputs and outputs of SOM. The balance between them determines SOM turnover and is controlled by both biotic and abiotic factors. Climate, parent material, biota, topography, and time are the major controlling factors on the production and decomposition (by microorganisms) of SOM (Jenny 1941). Climate, parent material, and biota (e.g., vegetation) are the main factors that vary the most between tropical and temperate regions. It is generally assumed that organic compounds (Ayanaba and Jenkinson 1990) and SOM (Trumbore 1993) have a faster turnover in tropical than temperate soils due to enhanced decomposition under higher moisture and temperature regimes of the tropics. For example, Trumbore (1993) found a mean residence time (MRT) of C of 470 years in the surface layer (0–22/23 cm), estimated with radiocarbon, versus 990 years for a tropical and temperate soil. Another way to estimate C turnover and MRT relies in the difference in ^{13}C natural abundance between plants (and the SOM-C derived from them) with different photosynthetic pathways (Calvin cycle [C_3 plants] vs. Hatch–Slack cycle [C_4 plants]). A change in vegetation type results in a change to the ^{13}C natural abundance signature of the soil C, which enables one to calculate the proportion of C derived from the original vegetation. The turnover of C derived from the original vegetation is then calculated by using a first-order decay model. The higher turnover rate of tropical soils is primarily due to faster turnover rates of the slow C pool in tropical soils. Feller and Beare (1997) compared the incorporation rates of C derived from new vegetation in particle size classes (sand, silt, and clay) in temperate and tropical surface soils.

10.3 Agricultural Management Practices and Soil Carbon Dynamics

SOC is chosen as the most important indicator of soil quality and agricultural sustainability. Agricultural management including soil surface management, crop rotation, residue and tillage management, fertilization, and monoculture affect soil quality, SOM, and carbon transformation. The results confirm that SOM is not only a source of carbon but also a sink for C sequestration. Cultivation and tillage can reduce soil SOC content and lead to soil deterioration. Tillage practices have a major effect on the distribution of C and N, and organic matter decomposition rates and N mineralization. Proper adoption of crop rotation can increase or maintain the quantity and quality of SOM and improve soil chemical and physical properties. Appropriate application of fertilizers combined with farmyard manure could increase soil nutrients, as well as SOC content. Manure or crop residue alone may not be sufficient to maintain SOC levels. The type of crop influences SOC and soil function in continuous monoculture systems (Liu et al. 2005). SOC can be best preserved by rotation with reduced tillage frequency and also with additions of chemical fertilizers and manure. Knowledge and assessment of changes (positive or negative) in SOC status with time are still needed to evaluate the impact of various management practices.

The SOC content is a function of soil management, and change in management can alter SOC content. The rate of change (sequestration or release per unit time), however, depends on the net SOC content under the new management system. The net SOC content in soil depends on several interacting mechanisms, most of which are set in motion by addition of biomass to the soil. The use of a CT system affects C sequestration in soil through its effect on C dynamics, aggregation and soil structure, and interaction with cropping system. Carbon sequestration in soil depends on two factors:

(i) Turnover time and
(ii) Physical or chemical protection against microorganisms and soil erosion (Carter 1995).

10.3.1 Effect of Aggregation on Soil C Dynamics

A principal mechanism of that has a direct effect on C dynamics in soil is through the formation of stable microaggregates. The higher the SOC is, the more and stable are the aggregates. Microaggregates are developed around decomposing particulate organic matter because of the formation of humic polymers and organo-mineral complexes (Beare et al. 1994a, b). These microaggregates consist of clay particles, clay domains, hydrous oxides of Al and Fe, and organo-mineral complexes. Therefore, a strong correlation exists between aggregation and SOC (Table 10.1; Douglas and Goss 1982; Chaney and Swift 1986; Haynes et al. 1991). However, the degree of correlation depends on climate, soil type, texture, clay mineralogy, and cropping history. In pasture soils with high SOC, a substantial portion of SOC is not involved in aggregation, and the correlation is often low. In soils with low SOC, mechanisms of aggregation are different, and the correlation coefficient of SOC with aggregation is also low. Soils with higher clay content usually require more SOC content for maintaining a desired level of aggregation and aggregate stability than those with low clay content (Douglas and Goss 1982). Differences in clay content also cause differences in soil moisture regime. Aggregate stability often increases with decreasing soil moisture content (Perfect et al. 1990). Similar to the degree of aggregation, aggregate stability is also related to SOC content. Water-stable aggregates usually contain more SOC than those that are unstable (Elliott 1986). Source of crop residue is also a factor in aggregate stability. Skidmore et al. (1986) observed that application of sorghum (*Sorghum bicolor*) residue produced more stable aggregates than that of wheat (*Triticum aestivum*) residue.

Table 10.1 Relationship between aggregation and soil organic carbon (×) content

Regression equation	Correlation coefficient	Reference
% WSA (16% clay) = 2.0.× – 11.5	r = 0.86	Douglas and Goss (1982)
% WSA (39% clay) = 1.33× – 14.0	r = 0.73	
%WSA (49% clay) = 1.54.× – 58.0	r = 0.95	
MWD (mm) = 0.24.× + 0.31	$R^2 = 0.86$	Haynes et al. (1991)
%WSA > 2 mm =21.5× – 20.3	$R^2 = 0.93$	Tisdall and Oades (1980)
%WSA > 0.25 mm = 158.9× – 9.5	$R^2 = 0.87$	Tyagi et al. (1982)
%WSA > 20 pm = 74.3 + 6.3 pnX	$R^2 = 0.58$	Dalal and Bridge (1995)
Dispersible clay (%) = 2.39–0.42 x	$R^2 = 0.53$	

x organic carbon (%), *WSA* water-stable aggregation, *MWD* mean weight diameter

10.3.2 Effect of Surface Management on Soil C Dynamics

Tillage is the most important surface management practice that 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. (1994b) indicated that tillage improved 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 activities. Tillage also exposes organic C in both the inter- and intra-aggregate zones and that immobilized in microbial cellular tissues to rapid oxidation (Roscoe and Burman 2003). This is due to the improved availability of O_2 and the exposure of more surfaces for decomposition, thereby stimulating increased microbial activity (Beare et al. 1994b; Jastrow et al. 1996). Conventional tillage significantly reduces biological diversity in surface soil.

No-till (NT) management can increase SOM, both through constant addition of plant residues on the soil surface and through a decrease in its decomposition rate (de Souza Nunes et al. 2011). Positive results in SOM accumulation under NT systems are related to a decrease in soil C emissions to the atmosphere (Bayer et al. 2006), a decrease in soil C lost via surface runoff, and an increase in soil C as a result of crop rotations (Conceição et al. 2013). An important effect to be emphasized is the possibility of recovering lost SOC fractions by adopting high biomass-C inputs (>7 mg ha^{-1}) in cropping systems under NT management (Tivet et al. 2013), but the impact of NT management on SOC is soil and site specific (Christopher et al. 2009; Mishra et al. 2010).

Increased C storage has been usually 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 farmlands, reversing the decline caused by intensive tillage practices used for decades (Campbell et al. 2001). 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 levels along with residue retention increased the proportion of macroaggregates by 21–42%. 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 that the intensity of tillage should be decreased to reduce C loss. Tillage operations control the soil environment strongly by altering the soil geometry. These effects influence many physical, chemical, and biological characteristics of the soil and thereby the conditions for crop growth. Alvarez and

Alvarez (2000) stated that conservation tillage, particularly no-tillage, induced changes in the distribution of organic pools in the soil profile. SOC gains under no-till were about 250 kg ha^{-1} year^{-1} greater than tilled systems regardless of cropping frequency in Canadian prairies under 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^{-1}), particulate organic matter C (by 4.98 mg ha^{-1}), potentially mineralizable N (by 32.4 kg ha^{-1}), and microbial biomass C (by 586 mg ha^{-1}), as well as greater aggregate stability (by 33.4%) and faster infiltration rates (by 55.6 cm h^{-1}) relative to the conventional tillage (Liebig et al. 2004).

After 11 years of different tillage operations in Chinese Mollisols, Liu et al. (2005) reported that integrated tillage, where tillage operation varied with each crop in the rotation (i.e. mouldboard plough for wheat, deep chisel for corn, and rotary plough for soybean), had the highest levels of SOC and N in the upper soil layer in the Chinese Mollisol. Mouldboard ploughing 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 ploughing 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 ploughing but opposite to results with no-tillage practice or conservation tillage (Arshad et al. 1990; Dalal et al. 1991). In general, integrated tillage appeared more effective in maintaining SOC and, maybe, soil productivity. Yang et al. (2003a) indicated that the conversion from conventional tillage to conservation tillage, particularly no-till, at an annual rate of 2% could reverse the loss of SOC in Chinese Mollisols within 20 years. However, this positive effect of conservation tillage on SOC in the 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, distribution of C and N, and organic matter decomposition rate 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 SOC and soil quality under conservation tillage in different agroecological zones is essential. There is also a need to obtain more data on long-term effects of different tillage systems on C and N mineralization and immobilization in field situations.

10.3.3 Effect of Crop Rotation on Soil C Dynamics

Crop rotation could have a major impact on soil health due to emerging soil ecological interactions and processes that occur with time. These include enhancing soil structural stability and nutrient use efficiency, increasing crop water use efficiency and SOM levels, providing better weed control, and disrupting insect and disease life cycles (Carter et al. 2002, 2003). Crop rotations also increase yields and enhance N availability when nitrogen-fixing legumes are included (Galantini et al. 2000, Miglierina et al. 2000). They are more effective at reducing long-term yield variability than monoculture systems, and they 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) observed that losses of SOC during a 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 SOM levels. Blair and Crocker (2000) studied the effect of different rotations, including legumes and fallows on soil structural stability, unsaturated hydraulic conductivity, and the concentration of different C fractions in a long-term rotation trial, and found that the inclusion of legume crops in the rotation resulted in an increase in labile carbon concentrations compared with continuous wheat or a long fallow period.

While comparing maize–rice and rice–rice cropping systems, Witt et al. (2000) found that the replacement of dry season rice by maize resulted in reduction of 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, 11–12% more C sequestration and 5–12% more N accumulation was observed 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 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 more SOC concentration than continuous corn. Huggins et al. (1998) found that in the treatments containing both crops, the aboveground C returned to the soil from corn was on average 40% higher than the 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 found 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.

From a 9-year crop rotation experiment in the Chinese Mollisol, Liu et al. (2003) found that 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 the commonly used wheat–soybean rotation (wheat straw removed), particularly in the 0–17 cm horizon. For the overall SOC concentration (means 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. 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 a decrease in soil bulk density.

The total SOC storage (total of all three horizons) increase was 10.7% for wheat–soybean rotation with manure addition and 14.4% for wheat–soybean rotation with wheat straw addition. The total amount of SOC increase (11,700 kg ha^{-1}) in wheat–soybean rotation with addition of wheat straw would correspond to sequestration of approximately 43 tonnes of CO_2 ha^{-1} from atmosphere. Fang et al. (2005) 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.

10.3.4 Effect of INM on Soil C Dynamics

Integrated use of fertilization sources is one of the most important practices in crop production for its influence on soil nutrient availability. Ishaq et al. (2002) showed that fertilizer application significantly improved soil P and K concentrations, and the concentrations of N, P, K, and SOC were higher in the plough layer than in the subsoil. Nitrogen is the nutrient most limiting to crop production throughout the world and is usually applied to soil in a large quantity. Since the N applied to soil is subject to losses by volatilization, immobilization, denitrification, and leaching, it is necessary to compensate this by adjusting the fertilizer management. Fertilizer use efficiency will 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 reduced N losses by volatilization and leaching. Reducing tillage intensity modified both the crops' N demand 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 application and recycling of crop residues with NPK supplementation are efficient ways of fertilizing maize and wheat. With high levels of NPK fertilizer use, significantly higher yields were obtained especially in rotations, where the proportion of maize or wheat was 50% or higher (Berzsenyi et al. 2000).

After 16 years of three fertilization treatments in crop rotation, Liu et al. (2005) reported 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 depth 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 ($<0.58\%\ \text{year}^{-1}$) when a well-designed crop rotation was used. The results were comparable 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 with application of chemical fertilizer and manure combination. This indicates that corn residue and exudates 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 content, particularly at 0–15 and 16–30 cm soil layers. Francioso et al. (2000) also reported that after 22 years, SOC and N differed significantly for all treatments where the amendments with cattle manure markedly increased the SOC and N contents, while cow slurries and crop residues decreased SOC and N contents. The maximum reduction in SOC and N contents was found in the unamended plots after 22 years. Reeves (1997) also suggested that SOM can be preserved only by 'ley' rotations with reduced tillage frequency. 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.

10.4 Conclusion

World soils, large reservoir of reactive carbon, moderate the global C cycle, atmospheric chemistry, radioactive forcing, and ecosystem services; as such, soil C sequestration is very important in limiting global warming to 2 °C. Therefore, soil carbon management will be an increasingly important strategy during the coming decades because of its numerous co-benefits as a natural fix to climate change. Among uncertainties are emissions from soils and permafrost, the CO_2 fertilization effect, weathering of silicate, the fate of eroded carbon, efficiency of natural sinks, permanence of carbon sequestered in soil, and measurements of changes in soil C over short periods. In addition to being a cost-effective option of reducing the net anthropogenic emission of CO_2, restoring the soil carbon pool is also essential to achieving global food security, improving renewable freshwater supply and quality, and enhancing biodiversity. Food insecurity, affecting approximately 1 billion people globally, can be realized through enhancing soil quality by restoring the soil carbon pool to above the critical level of 1.2–1.5% in the root zone. Adoption of proven technologies such as soil surface management and best agricultural management practices can sequester carbon at the rate of 50–500 kg ha^{-1} $year^{-1}$ in grazing lands, 500–1000 kg ha^{-1} $year^{-1}$ in forestlands and 5–10 kg ha^{-1} $year^{-1}$ of pedogenic carbonates in arid lands. Soil C is stabilized through deep placement, interaction with clays, and formation of stable aggregates. Adoption of recommended practices can be promoted by payments for ecosystems services. Researchable priorities include understanding trends of principal drivers, quantifying feedbacks related to climate change, and impacts on ecosystem services.

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