Carbon Sequestration Potentials in Agricultural Soils
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Introduction

Soils play significant roles in global carbon cycle. It was estimated that soils have contributed as much as 55 to 878 billion tons (GT) of carbon to the total atmospheric CO$_2$ (Kimble et al. 2002). The total soil carbon consists of the soil organic carbon and inorganic carbon, estimated to be approximately over 2250 GT in the top 1 meter depth (Batjes, 1996). The soil organic carbon consists of “a mixture of plant and animal residues at various stages of decomposition, of substances synthesized microbiologically and or chemically from the breakdown products, and of the bodies of live microorganisms and small animals” (Schnitzer, 1996). The soil inorganic carbon includes element carbon and carbonates.

Although carbon emissions from agricultural activities contribute the enrichment of atmospheric CO$_2$, carbon sequestration in agricultural soils, through the use of proper management practices, can mitigate this trend. While the soil inorganic carbon contributes approximately 25% of the overall soil carbon inventory, agricultural activities have more profound influence on changes of soil organic carbon both in the short and the long term. Increasing soil organic carbon content enhances soil quality, reduces soil erosion and degradation, improves surface water quality, and increases soil productivity. Thus, carbon sequestration in soils, i.e., increasing soil organic carbon in agricultural soils through proper management, provides a multitude of environmental benefits. The goals to sequester soil organic carbon is to create a win-win situation to improve soil productivity, reduce unnecessary inputs, and promote sustainability.

The objectives of this paper is to discuss the basic aspects of organic carbon dynamics, to evaluate practical tools for assessing soil organic carbon changes, and to discuss some of the best agricultural practices to enhance carbon sequestration in soils.

Organic Carbon Dynamics in Soils

Central to the carbon cycling processes in soils is the dynamics of soil microbial population, the complex physical, chemical compositions of the soil organic carbon and the associated nutrients, as well as the various degrees of physical and chemical protection afforded to the soil organic carbon and associated nutrient elements in the soil. Soil conditions, particularly temperature, moisture, texture and structure, tillage and cropping management, all have important impacts on carbon dynamics.

One important feature of the process of soil organic carbon turnover is the diverse time scales at which it takes place. As plant materials are added to the soil, as much as 2/3 of the carbon may be lost to the atmosphere as CO$_2$ in a single season as a result of decomposition. Subsequent decomposition, however, is slowed resulting in accumulation of stable organic carbon in soils. The gross turnover time of soil organic carbon, expressed as the ratio between total amount of organic carbon in the soil at steady state and the annual rate of addition, can be more than 20 years in temperate regions (Stout et al. 1981). Organic carbon stabilized in the soil may remain for a great length of time, resulting in a large fraction of very old, stable organic carbon in the soil. Measurements with $^{14}$C dating technique often reveal an average age of soil organic carbon to be more than 1000 years (Patwardhan et al., 1997, Stout et al. 1981, Van Veen and Paul, 1981, Jenkiness et al. 1992, 1994, Smith et al. 1997). In order to be considered as an effective option to counter global greenhouse effects, management practices aimed at carbon sequestration in soils must lead to long term increases in soil organic carbon. In light of the great time span at which soil organic carbon processes
take place, results from most “long term” experiments lasting a few decades, yields empirical evidence in a “short” period. The potential long-term changes in soil organic carbon resulting from changing management can at the present be evaluated only with the aid of the models of soil organic carbon dynamics.

Turnover of nitrogen in soils is closely related to carbon. Both carbon and nitrogen turnover in the soil are driven by microbial biomass. Carbon to nitrogen ratios (C:N ratio) of various forms of organic matter in the soil reveal important features of soil processes. The C:N ratio of humus, the most stable form of organic carbon in the soil, is often close to 10. The C:N ratio of soil microbial biomass averages approximately at 7. The C:N ratio of plant material entering the soil, on the other hand, may vary from 10 for green legumes to more than 50 for straws. Considering the diversity of soil, climate conditions and the plant material entering soils, it is truly remarkable that the C:N ratio of the soil organic matter as a whole is quite stable and differs little from that of humus, i.e. approximately 10 to 12 (McGill et al. 1981, Juma and McGill 1986).

The basic processes of soil organic carbon dynamics can be described, as shown in Figure 1, by the conceptual framework of the K-model developed by Feng and Li (2002). Soil microbial population drives the soil organic carbon and nutrient cycles. Plant residue added to the soil, including manure and other organic materials, is characterized by a metabolic fraction of relatively fast decomposition and a more resistant structural fraction. The metabolic fraction represents the cytoplasmic contents of plant cells, including carbohydrates, protein, etc. The structural fraction consists mainly of the cell wall materials. The metabolic fraction has a higher N content than the structural fraction. The relative quantity of the two fractions are determined by the C:N ratio of the plant residue.

As the plant residues or other organic materials are attacked by the soil microbial population, a portion is assimilated by soil microorganisms, becoming part of the microbial biomass. The second fraction is released into the atmosphere as CO$_2$. The remainder is partially transformed and may be attacked later by the microbial population. Upon death of soil microbial biomass, the soil microbial residue, along with its nutrient contents, is recycled by the succeeding generations of soil microorganisms. Residues of the dead soil microorganisms also consist of two fractions, a metabolic fraction and a structural fraction. The relative proportions of the two fractions are calculated from the overall C:N ratio of soil microbial biomass and the C:N ratios of the individual fractions. Carbon and nutrient elements in the microbial biomass are continuously recycled in the soil. Microbial growth in the soil requires specific C:N:P ratios and thus growth of microbial population is determined by balances in carbon, nitrogen and phosphorous dynamics. As the plant and soil microbial residues undergo decomposition in the soil, the remainder, which has neither been taken up by the soil microorganisms nor released into the atmosphere as CO$_2$, changes in its composition, getting gradually enriched in N and P, eventually approaching that of the humus.

The plant residues decompose relatively quickly in soils. Little recognizable original plant residue carbon remains in the soils after a few years. The continued cycling of microbial residues in a soil is thus the most important process affecting long-term changes in soil organic carbon.
Practical Tools to Evaluate Changes in Soil Organic Carbon

Interest in maintaining and enhancing soil organic carbon stocks continuously increases, partly as a result of increasing concerns for climate change.Reporting of carbon sequestration for individual producers and farmers require reliable tools to evaluate changes in soil organic carbon. Two options are available to this purpose, direct experimental measurement and monitoring, and predictions with soil organic carbon models. To be of practical value to the producers and farmers, these changes need to be evaluated over relatively short periods, from a few years to a decade. Change of soil organic carbon, however, is slow and occurs over much longer time periods, as discussed previously. Direct measurement and monitoring of soil organic carbon changes over short periods must deal with uncertainties of sampling and measurement errors, and more importantly, uncertainties resulting from non-uniformity of field soils. Prediction based on models validated against available experimental evidence is another option. For this purpose, the model must be easy to use, based on sound theoretical description of soil organic carbon processes, and contains only parameters that are physically meaningful and experimentally measurable. The models must also be able to reproduce both the quick decomposition of plant residues within a single season and the exceedingly great age of organic carbon in soils in order to be considered valid for predictions in both the short term changes in soil organic carbon, i.e., a few years to decades, and for predictions in much longer term stabilization of soil organic carbon.


Figure 1: Illustration of soil organic carbon dynamics (Feng and Li, 2002).

\[ \text{INPUT} \quad \text{RECYCLE} \]
kinetic compartments each characterized by a distinct decomposition rate constant. Because of the need to cope with the great diversity of time scales at which soil organic carbon and nutrient processes take place, soil organic matter is often divided into compartments with very different rate constants. Typically, for soil organic matter, three compartments are used with time constants, i.e. $1/k$, where $k$ is the rate constant, of approximately years, decades, and $>100$ years, corresponding to the broad time scales at which soil organic carbon turnover takes place. Plant material entering the soil is also divided into compartments with different rate constants to account for both the initial, fast decomposition and subsequent slow decomposition (Jenkinson and Rayner 1977, McGill et al. 1981, Van Veen and Paul 1981, Parton et al. 1983, Van Veen et al. 1984, Parton et al. 1987, Jenkinson 1990, Smith et al. 1997). An example is RothC model (Jenkinson 1990) where soil organic carbon is divided into decomposable and resistant plant materials (representing the annual input into the soil), and biomass, physically protected, and chemically protected soil organic matter compartments. The CENTURY model is also based on similar fashion. The rate constants used to describe these compartments range from $4.2$/year for decomposable plant material to $3.5 \times 10^{-4}$/year for resistant soil organic matter. Particularly the CENTURY model has been used widely in climate change related studies to simulate possible changes in soil carbon status under various climate and soil management scenarios. McGill et al. (1996) reviewed existing soil organic matter models and their limitations. Smith et al. (1997) conducted an extensive comparison of various compartment models available at the time at predicting changes in long-term soil organic carbon dynamics.

These models are complex and contain a large number of parameters for both the rate constants and the proportions of plant and organic carbon allocated into each of the compartments. For example, with 5 compartments (two to represent decomposable and resistant fractions of the plant litter or manure added into the soil and three to represent biomass, labile, and resistant fractions of soil organic carbon), we need at least 5 rate constants to represent the decomposition of each compartment. In addition, parameters are also needed to describe transfer and transformation of organic carbon among the compartments during decomposition. Moreover, there is a need to specify changes in these rate constants and transfer coefficients with different soil types and environmental conditions. The model by Smith (1979) includes more than 100 parameters that must be evaluated. The fact that these parameters are often unavailable makes it necessary to estimate their values. As a result, considerable knowledge and training is required for the successful application of these models.

One of the problems in this approach is the lack of connection between the "kinetic compartments" and physically recognizable fraction of the soil organic carbon. Because of the chemical complexities and various degrees of physical protection in soil structural units, representation of the kinetics of any physical fraction of the total soil organic carbon with a single or a few of rate constants may not be adequate. More importantly, since there is no correspondence between the conceptual compartments and any measurable fractions of soil organic matter, the formulation of the compartments is somewhat arbitrary. It can be shown mathematically that the formulation of the compartments for any soil is not unique. Models with completely different rate constants and compartment sizes can produce identical mathematical predictions.

The second class of models reported in the literature is represented by the Q model (Bosatta and Agren 1985, Agren and Bosatta 1996). In this model, soil organic carbon is assumed to possess an attribute called "quality", which determines the rate of its decomposition. The decomposition process is slowed by a continuous change in "quality". Unlike the compartment models, in which organic carbon is divided into separate "pools" or compartments with distinct properties, the Q model assumes soil organic carbon as possessing a continuous distribution of "quality". The difficulty of this model is that the concept of "quality", although appealing, is purely conceptual and cannot be related to specific physical and chemical properties or characteristics of soil organic carbon that can be measured experimentally. As a result, we have concluded that this model also does not meet our requirements.

The K-Model developed by Feng and Li (2002) takes a different approach. The development of the K model starts with the recognition that the carbon dynamics in soils can be represented by three basic processes: the initial attack of the plant residue by soil microbial population, the growth and death of the soil microbial biomass, and the decomposition of the dead soil microbial biomass residue. For
each of the processes, the focus is on, instead of what has been decomposed, what has not decomposed. For example, for the plant residue added to the soil, the model considers the fraction remaining in the soil that has never been incorporated into the microbial biomass. This fraction decreases continuously with decreasing rate. Similarly, death occurs after microbial biomass is formed. The fraction that remains alive is also described by a continuously decreasing function. Upon death of the microbial biomass, the fraction of the residue that remains in the soil and has never been recycled into the subsequent generations of the soil microorganisms is also described by a continuously decreasing function. Soil organic carbon dynamics is thus described by three continuously decreasing functions. The total organic carbon in soil at any given time is the summation of the remaining residues of all past additions of plant materials, the remaining residues of all soil microbial biomass died in the past, and all past generations of the soil microbial biomass remaining alive.

Mathematically, the K-Model requires that the three continuously decreasing functions to be “completely monotone”. Consider microbial biomass as an example. After formation of a population of soil microbial biomass, the fraction that remains alive decreases continuously with time. The rate of death also decreases continuously with time. The rate at with the death rate changes also decreases with time…. In the mathematical terminology, this is a “completely monotone” function. Incidentally, the exponential decay function is a completely monotone function. The decomposition of plant and microbial residues described by the compartment models are also completely monotone functions.

The development of the K-Model utilizes the mathematical fact that completely monotone functions can be described by a rate constant distribution. The K-Model uses continuous rate constant distribution functions to represent the three basic processes, the decomposition of plant and microbial residues, and the death of soil microbial biomass. Considerations on the general features of the organic carbon decomposition processes in soils eliminated most common distributions functions. A distribution function based on the Bessel-K function has all of the desirable properties and is used as the basis for the description of the three basic processes of soil organic carbon dynamics (Feng and Li, 2002).

The K-model has been successful in predicting soil carbon and nitrogen dynamics over broad time spans, ranging from a few days to hundreds of years and to the fact that the mean age of soil organic carbon is >1000 years. An example of the validation results, against experimental observations at Breton Classical Plots (>75 years) is shown in Figure 2. The model is capable of predicting a broad spectrum of soil properties, including microbial biomass, rate of respiration, nitrogen and phosphorus mineralization. From the agricultural management point of view, the prediction of cumulative nutrient mineralization from past inputs of organic materials and plant residues is of particular interest. Ability to predict quantitative nutrient mineralization allows one to adjust the inputs of fertilizer and organic materials, including biosolids and manure, accordingly to balance nutrient requirement for crops and nutrient supply from the mineralization of soil organic matter, plant residues, and organic materials. This capability of the model allows the farmers and producers to adjust rates of organic materials application for maximum benefits in increased crop yield and carbon sequestration, while avoiding adverse environmental risks.

**Agricultural Management Practices for Soil Carbon Sequestration**

Research on soil organic carbon dynamics has advanced many decades. Many promising practices for soil carbon sequestration have been identified (Kimble et al, 2002). A wide range of the best agricultural practices exists for sequestering organic carbon in agricultural soils. Appropriate practices differ for different soil, crop, and climate conditions. A site-specific approach should be used to select the most appropriate practice to meet local needs by considering all inputs and benefit associated with each input. A life-cycle analysis that consider inputs and associated environmental and economic benefits need to be applied. For example, no-till or minimum-till has been identified as one of the best practice to sequester soil organic carbon. However, it requires more use of herbicides, which has both environmental and economic implications. In the following discussion we will focus on a few common promising practices that have more broad implications.
Organic Material Inputs

Organic material inputs are necessary to increase soil organic carbon stocks. Figure 3 illustrates the soil organic carbon increased with animal manure application in Rothamstead, U.K., over 125 years. The data are reported by Jenkinson and Rayner (1977) and the model predictions are given by the K-Model. With annual plant carbon input of 1.2 t/ha, the soil organic carbon remained constant over the years. With constant manure application, the soil organic carbon increased continuously. The steady state has not been reached after 125 years and is not expected to be reached for hundreds of years. However, the annual increase of soil organic carbon under constant manure additions decreased with time. Once the manure application was stopped after 20 years, the soil organic carbon started to decline but remained at a level higher than the control. These results suggests that manure inputs increases soil organic carbon. Continued input is required in order to maintain the higher soil organic carbon level. Once the addition stops, much of the carbon “sequestered” in the soil may be lost due to decomposition. Some residual benefits from manure addition, however, may last for long periods, as improved soil conditions increase productivity and plant residue input into the soil.

Figure 4 compares the manure addition with inorganic fertilizer application. Inorganic fertilizer addition only increased soil organic carbon slightly over 150 years, as a result of higher crop yield and therefore higher crop residue input. Compared with manure addition, the change of the soil organic carbon was negligible. Again this illustrate the significant roles of manure application on soil organic carbon accumulation, therefore soil carbon sequestration.
Figure 3: Predicted (Feng and Li, 2002) and experimentally measured soil organic carbon in Rothamsted continuous barley plots (Data from Jenkinson and Rayner, 1977). Treatments are: annual addition of manure at 3 t carbon/ha (●); annual addition of manure at 3 t carbon/ha for the first 20 years and nothing after (♦); control (▲). Solid lines are predictions by K-Model. Plant carbon inputs are assumed to be 1.2 t/ha for control and 1.9 t/ha for manured soils.

Figure 4: Predicted (Feng and Li, 2002) and experimentally measured soil organic carbon in Rothamsted continuous wheat plots (Data from Jenkinson, 1990). Treatments are: annual addition of manure at 3 t carbon/ha (●); annual addition of fertilizer at 144 kg N, 35 kg P, 90 kg K and 12 kg Mg/ha (■); control (♦). Solid lines are predictions by K-Model.
The quality of organic carbon inputs is important for soil carbon sequestration. According to Feng and Li (2002), the conversion efficiencies of manure are almost twice that of plant residues. In other words, for constant rates of addition, net soil organic carbon accumulation from manure is nearly twice of that from plant residue additions. It is a fact that soil microbial residues are more resistant to decomposition than plant residues. It is postulated that the slower decomposition of manure in soils results from the fact that manure consists of largely partially decomposed products. Similarly, products of aerobic composting and anaerobic digestion are also expected to have higher efficiencies for increasing soil organic carbon content than plant materials.

There is an important implication from these results. Soil organic carbon levels have generally decreased upon cultivation. This is partly because of the increased decomposition of soil organic carbon resulting from tillage and partly because of the decreased inputs as a result of the removal of above ground plant biomass. If the above ground biomass is used in animal production and manure is returned to the soil, what is the implication for long-term soil organic carbon sequestration? Approximately one half of the carbon in the animal feed is present in the manure. Since manure is nearly twice as efficient in storing organic carbon in soils, one thus naturally concludes that in an animal production system, if manure is returned to the soil, it will be as effective in maintaining soil organic carbon level as in a natural system in which most of the plant biomass is returned to the soil.

**Enhancing Biological N Fixation Through the Use of Legume Crops**

Increasing crop yields increases plant residue input into the soils and thus has the potential of increasing soil organic carbon level. However, it is clear from existing long term experiments, and from model predictions that inorganic fertilizer application results in little increase in soil organic carbon storage (Figure 4). The long-term studies at Breton Classical Plots also confirm this conclusion. For the 5-year Wheat-Oats-Barley-Hay-Hay rotation, after 75 years, there is little difference in soil organic carbon content between the control treatment and the inorganic fertilizer treatment (Feng and Li, 2002). While the benefits in soil organic carbon storage are minimal, the environmental costs associated with production and application of inorganic fertilizers can be significant. The nutrient use efficiency of plants grown with chemical-N fertilizer is approximately 60% or lower. The principal loss results from leaching of nitrates and gaseous loss through denitrification. During nitrogen fertilizer production, for every kg of NH$_3$ produced, there is a 10 kg of CO$_2$-C emission. Legume crops can fix up to 100 kg of N/ha annually, based on results from Breton Classical Plots. Thus, for each legume crop grown, there is approximately 1 ton of CO$_2$-C emission that is avoided. For a 5-year rotation with two hay crops per rotation cycle, total CO$_2$-C emission that is avoided in a 75-year period is 30 tons. Over the same period, soil carbon storage increase with manure application of 2 tons of carbon per year is approximately 30 tons/ha, with a total manure carbon input of 150 tons/ha. Thus, there is clearly a carbon emission benefit in using legume crops. In addition to reduced carbon emission, there is also an environmental benefit in using legume crops resulting from increased plant residue input and increased soil organic carbon content. More importantly, the carbon emission savings from using legume plants is permanent while soil carbon content increase resulting from increased inputs must be maintained continuously.

**Avoid Use of Fallow**

Fallow significantly increases the rate of soil organic carbon decomposition. Results from Rothamsted (Jenkinson and Rayner 1977, Jenkinson 1990) indicated that during fallow the rate of soil organic carbon decomposition is approximately 2 to 2.5 times faster than in a crop year (Feng and Li 2001). The decomposition rates during fallow at Breton Classical Plots is approximately 2 times faster than during a crop year. Thus, to maintain soil organic carbon level, if the fallow frequency is once every two years, the TOTAL organic carbon input must be 1.5 times higher than in a system with no fallow. As a result, the fallow treatment often results in significantly more soil organic carbon loss than continuously cropped treatment. For example, in the Breton Classical Plots, for the two-year wheat-fallow series, both the control and the inorganic fertilizer treatments lost significant amount of carbon over the years, while the same treatments for the 5-year continuous cropped rotation maintained or increased soil organic carbon content. In Rothamsted, for the continuous manure treatment, inclusion of fallow between 1920 and 1965 (once every 5 years) reversed the increasing trend of soil organic carbon content. It is only with the elimination of fallow the increasing trend continued (Figure 4).
These results emphasize again that the environmental benefits resulting from increased soil organic carbon content must be maintained continuously.

Minimum Tillage

Increased soil organic carbon decomposition from tillage is one of the major factors responsible for the decrease in soil organic carbon content upon cultivation. As a result, avoiding tillage has generally been reported to increase soil organic carbon content. Franzluebbers and Steiner (2002) made 111 comparisons between no-tillage (NT) and conventional tillage (CT) on soil organic carbon from 39 locations with wide ranges of soil and climatic conditions in US and Canada. These results indicate that without regard to other variables such as soil type, climate, crop, etc, the net annual change in soil organic carbon with NT compared with CT was normally distributed with a mean value of 300 kg/ha, with 50% of the values between 50 and 660 kg/ha. However, these results must be interpreted with caution. The data were obtained from experiments with various durations generally between 4 years to 15 years. Because the rate of increase in soil organic carbon content will decrease with time (Figure 3), it is not reasonable to expect these values to be valid for long-term soil carbon storage. Although the annual soil organic carbon storage, or sequestration, of 50 to 600 kg/ha may be expected in the first few years upon conversion to NT from CT, it is not realistic to expect, for example, net carbon sequestration for a 20 year period to be simply 1000 to 12000 kg/ha. Without long-term experimental observations, any extrapolation must be done with the help of models. For example, the K-Model (Feng and Li 2002) predicts that the net average annual benefit for the second 10 year period is approximately 43% of that for the first 10 year period. For the third 10 year period, the net annual benefit is approximately 33% of that of the first 10 year period.

Conclusions

Soil organic carbon dynamics are fundamental soil biological processes, which govern soil nutrient cycling. Increasing soil organic carbon content will enhance soil quality and improve plant growth. Soil carbon sequestration can be a win-win strategy for producers and farmers if the appropriate practices are selected.

The models, which are based on rigorous description of the fundamental processes of soil carbon and nutrient dynamics, are available for producers to assess soil carbon sequestration potential at given soil conditions and agricultural practices. These models will allow users to identify the best suitable practices for maximizing carbon storage and crop production while mitigating environmental impacts.

Sequestration of carbon in soils can be achieved by either reduced decomposition or increased carbon input. Increasing crop residue input through the application of inorganic fertilizers has little impact on soil organic carbon content, in addition to the environmental costs of fertilizer production and application. Incorporation of legumes for N fixation in the crop rotation is a strategy that can lead to long-term, permanent savings in greenhouse gas emissions. Addition of manure and composts in soils can result in significant carbon accumulation in soils. Reducing tillage can result in increase in soil organic carbon.

The effects of changing management, either by addition of manure, or by adoption of reduced or minimum tillage, on soil organic carbon content is most significant in the short period immediately after the change. However, the incremental benefit reduces with time. In addition, the change in soil organic carbon content is reversible: changes in soil management at a later time can result in the organic carbon “sequestered” in the soil to be released into the atmosphere. The environmental benefit of increased soil carbon sequestration must, therefore, be maintained with real long-term commitments.

References


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