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CHANGES IN SOIL QUALITY UNDER DIFFERENT AGRICULTURAL MANAGEMENT IN CHINESE MOLLISOLS

A Dissertation Presented

by

XIAOBING LIU

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DEDICATION

To my motherland, parents, wife and son

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ABSTRACT

CHANGES IN SOIL QUALITY UNDER DIFFERENT AGRICULTURAL MANAGEMENT IN CHINESE MOLLISOLS

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Mollisols (called Black soils) are of major agricultural importance in China. Most of these soils have been used agriculturally for the last 50 years or so. Due to intensive cultivation and improper soil management, loss of organic matter and yield suppression resulting from soil erosion are serious problems in the region. The current research studied the physical and chemical properties of a typical Mollisol in China, characterized the changes of soil organic carbon (SOC) with cultivation, investigated the effects of agricultural management systems on SOC and total organic nitrogen (TON) contents and their vertical distribution, and examined the negative impacts of continuous soybean on crop and soil productivity.

The soil is characterized with a thick (60 cm) mollic epipedon, higher organic carbon (5.8%), CEC (43.7 cmol(+)/kg) and macro-aggregate (> 0.25 mm) stability, and greater macronutrients and water availability in the upper epipedon. Bulk density increases with depth, and total porosity declines with depth. Soil texture is clay loam. Overall characteristics make this soil fertile and productive.

The SOC content declined rapidly at early years of cultivation and gradually afterwards. Compared with organic matter in the uncultivated soil, total SOC loss was 17%, 28%, and 55% in 5-, 14- and 50-year cultivation, respectively. Wheat-soybean rotation with addition wheat straw or pig manure resulted in a substantial increase in SOC content in 9 years.

Compared with a wheat-corn-soybean rotation, continuous cropping reduced SOC and N contents in the profile, particularly SOC content. Moldboard plowing significantly reduced SOC and N contents whereas integrated tillage increased SOC and N relative to conventional tillage. Use of chemical fertilizers (N, P, and K) along with return of crop residues resulted in a substantial increase in SOC and N in top layers of the soil.

Continuous soybean results in unbalanced soil enzymes activities, declines of SOC, total K, Zn, available K and N contents, soil pH and bacteria/fungi ratio.

It is proposed that the best management for maintaining soil productivity in the area would be crop rotation along with the integrated tillage and addition of crop residues and chemical fertilizers.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Introduction

Soil is one of our most precious natural resources. It is a living, dynamic resource that supports plant life, decomposes wastes, stores heat, and exchanges gases. Soil is the home to billions of macroscopic organisms. It is also a material used for construction, medicine, and art. Besides, it provides the geologic, climatic, biological, and human history at the place that they are found (Brady and Weil, 2000). However, only a limited amount of the soil can actually be used for growing food, and when improperly managed, soil can be eroded, polluted or even destroyed.

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; Gliessman, 1998). This is an area of the size of China and India combined. 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 of soil quality that result from wind and water erosion, salinization, loss of organic matter, or soil compaction are of great concern in every agricultural region in the world.

In the last decade, there has been a gradual evolution of the soil quality concept, and public interest in soil quality is increasing throughout the world as humankind recognizes the fragility of earth's soil, water, and air resources and the need to protect them to sustain civilization. The concept of soil quality was first suggested in 1977 at a conference focused on the tradeoffs associated with intensive agriculture, but the concept per se was not discussed until 1980s when it was defined based on soil function and methods to evaluate it were published. Soil function includes such things as a medium for nutrient cycling; water entry, retention, and release; supporting plant growth and development (Brady and Weil, 2002). Karlen et al. (1990) attempted to identify the specific soil properties within identical soil mapping units that were responsible for yield variation in an otherwise uniformly treated corn crop.

The concept of soil quality developed rapidly throughout the 1990s. An early definition of soil quality was offered by Larson and Pierce (1991), "Soil quality (Q) can thus be defined as the state of existence of soil relative to a standard, or in terms of a degree of excellence." 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) defined 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." Furthermore, Sojka and Upchurch (1999) 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 include social, economic, biological, and other value judgments. Singer and Ewing (2000) stated: "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". Because determining soil quality requires one or more value judgments and because there is still much unknown about soil, these issues are not easily addressed.

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.

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 humans and animals do not directly consume it (Doran and Parkin, 1996; Liu et al., 2002).

Soil quality can’t be measured directly, so we need to evaluate indicators. Indicators are measurable properties of soil or plants that provide clues about how well the soil can function. Indicators can be a variety of physical, chemical, and biological characteristics. 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 and to a certain extent can be controlled by Best Management Practices (BMPs) and are somewhat qualitative in nature. Quantitative measures to monitor soils such as soil pH and extractable N-P-K are more developed and are still being explored as to how these measures affect yield, nutrient levels and the biological health of the soil. As many soil quality indicators interact with each other, and thus, the value of one is affected by one or more of the selected parameters, and it 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. Thus, soil quality is difficult to define and measure. However, in order to develop soil quality assessment, a minimum set of data on soil indicators must be identified (Arshad and Martin, 2002). Suitable indicators for crop production in most cases were: organic matter, topsoil-depth, infiltration, aggregation, pH, electrical conductivity, suspected pollutants and soil respiration.

Recent studies have shown that agricultural management strongly affects soil quality and soil organic matter is the central indicator of soil quality and health (Lal et al., 1995). The best means of improving and/or restoring soil quality/health is by proper and regular additions of organic matter primarily through the use of cover crops, crop residues, manure, and reduced tillage practices. The importance of increased soil organic matter (SOM) is its effect in improving soil physical properties, conserving water, and increasing available nutrients. This should ultimately lead to greater biomass and crop yield. Organic matter plays an important role in nutrient availability and soil aggregate stability. Soil productivity decreases when SOM declines (Bauer and Black, 1994). The decline of SOM or soil organic carbon (SOC) in agricultural systems coupled with increased awareness of the importance of the terrestrial ecosystem in global C budgets has stimulated evaluations of land management effects on soil C dynamics and storage (Lal et al., 1995).

Since the maintenance of soil quality is critical to agricultural and environmental sustainability, knowledge and assessment of changes (positive or negative) in its status with time is still needed to evaluate the impact of different management practices.

Long-term experiments are among the best means to predict soil management impacts on soil carbon storage and leading indicators of sustainability, which can serve as an early warning system to detect problems that threaten future productivity (Clapp et al., 2000). A non-decreased trend in yield is necessary to call a system sustainable, and what's more, the stability of yield is also an important characteristic to be considered when judging the value of a cropping system relative to others, which can be used as an integrator of the forgoing soil quality indicators (Berzsenyi et al., 2000; Arshad and Martin, 2002).

There is considerable concern that, if SOM or SOC concentrations in soils are allowed to decrease too much, then the productive capacity of agriculture will be compromised by deterioration in soil physical properties and by impairment of soil nutrient cycling mechanisms (Loveland and Webb, 2003). Changes in agricultural management can increase or decrease SOC. Optimizing agricultural management for accumulation of SOC can result in the sequestration of atmospheric CO_2, thereby partially mitigating the current increase in CO_2 (Sampson and Scholes, 2000). Additions and losses of C are regulated by agricultural practices such as crop rotation (Janzen et al., 1992), residue and tillage management (Havlin et al., 1990), and fertilization (Paustian et al., 1992).

Literature review

Soil organic matter and sequestration

Soil organic matter (SOM) is a complex mixture, which contributes positively to soil fertility, soil tilth, crop production, overall soil sustainability and minimizes negative environmental impacts, and thus improves soil quality (Bauer and Black, 1994; Lal et al., 1997; Reeves, 1997; Freixo et al., 2002). It influences a number of soil properties and nutrient cycling, and is itself influenced in kind and amount by land-use, soil type, climate and vegetation (Bauer and Black, 1994; Loveland and Webb, 2003). The importance of increased SOM is its effect in improving soil physical properties, conserving water, and increasing available nutrients. This should ultimately lead to greater biomass and yield production. Additionally, SOM binds soil particles to form stable aggregates that resist erosion and permit water to infiltrate easily, thereby reducing erosion (Swift, 1991). In adequate quantities, SOM reduces soil crusting and soil bulk density, and helps to maintain a stable soil pH. Overall, SOM improves soil structure and soil tilth, and it provides a favorable medium for crop growth (Rose, 1991). Loveland and Webb (2003) suggested that a major threshold is 2% soil organic carbon (SOC) (ca. 3.4% SOM) in temperate regions, below which potentially serious decline in soil quality will occur. The 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, to limit soil erosion, and the release of carbon dioxide back to the atmosphere through microbial respiration (Dao, 1998; Kladivko, 2001).

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 matter (carbonates). While little can be done to increase the carbonate content of soils, it is possible to increase the organic matter content of soils. Such an increase would lead to a greater storage of carbon in soils. 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. Loss of SOC can be reversed by reducing cultivation, returning to original land cover or other perennial vegetation, or by changing from monoculture to rotation cropping system (Post and Kwon, 2000).

While SOM provides many benefits, it can also have negative environmental and crop production impacts. Increasing SOM content increases the application of many soil-incorporated pesticides (Ross and Lembi, 1985; Gaston et al., 1997). Economics of crop production, environmental quality and human exposure to pesticides are all negatively affected by the increased pesticide loading, and human exposure necessitated by higher SOM. Increased DDT (dichlorodiphenyltrichloroethane) and PCBs (polychlorinated biphenyls) solubility was attributed to complexing with soluble SOM (Chiou et al., 1987). Complexing with dissolved SOM promoted rapid transport of napropamide through soil (Nelson et al., 1998). In soils of high organic matter content and with simultaneously high microbial activity prolonged periods of waterlogging lead to the accumulation of soil-borne toxins such as volatile fatty acids and phenolics in the soil, which are additional stress factors affecting root metabolism and growth, especially at low soil pH (Marschner, 1998). However, compared with its positive benefits, the negative impacts are minor.

Recently, more consideration has been given to the implementation of a C credit trading system. The system may provide economic incentives for C sequestration initiatives (Marland et al., 2001). Changes in agricultural practices for the purpose of increasing SOC must either increase organic matter inputs to the soil, decrease decomposition of soil organic matter (SOM) and oxidation of SOC, or a combination thereof (Follett, 2001; Paustian et al., 2000; Rickman et al., 2002). These practices include, but are not limited to, reducing tillage intensity, decreasing or ceasing the fallow period, using a winter cover crop, changing from monoculture to rotation cropping, or altering soil inputs to increase primary production (e.g., fertilizers, pesticides, and irrigation). Implementing practices that sequester C can reverse the loss of SOC that may have occurred under intensive cultivation thereby increasing SOC to a new equilibrium (Johnson et al., 1995).

Average global C sequestration rates, when changing land use from agriculture to forest or grassland, were estimated to be 33.8 or 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 assumed that 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 year, and estimated that NT resulted in an average soil C increase of 285 g m^{-2}, compared to CT. Using an average experiment duration of 13 year implies an approximate C sequestration rate of 22 g m^{-2} per year. 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 conventional tillage to no-till can sequester 57±14 g C m^{-2} yr^{-1}, and by enhancing rotation complexity can sequester an average 20±12 g c m^{-2} yr^{-1}. Carbon sequestration rates can be expected to peak in 5 to 10 year with SOC reaching a new equilibrium in 15 to 20 year. Following initiation of an enhancement in rotation complexity, SOC may reach a new equilibrium in approximately 40 to 60 year.

In an analysis of 17 European tillage experiments, Smith et al. (1996) found that the average increase of SOC, with a change from CT to NT, was 0.73±0.39% yr^{-1}, and that SOC may reach a new equilibrium in approximately 50 to 100 year. Analysis of some long-term experiments in Canada indicated that SOC can be sequestrated for 25 to 30 year at a rate of 50 to 75 g C m^{-2} yr^{-1}, depending on soil type, in well fertilized Chernozemic and Luvisolic soils cropped continuously to cereals and hay (Dumanki et al., 1998).

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. 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).

Tillage enhances short-term CO_2 evolution and microbial biomass turnover. Tillage accelerates 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 (Beare et al., 1994). Tillage also exposes organic carbon in both the inter- and intra-aggregate zones and that immobilized in microbial cellular tissues to rapid oxidation because of the improved availability of O_2 and exposure of more decomposition surfaces, thereby stimulating increased microbial activities (Beare et al., 1994; Jastrow et al., 1996). Carbonate, HCO_3, and CO_2 are end products of catabolic reactions in soil. These reactions provide energy to drive essential agronomic processes such as N mineralization, nitrification, and detoxification of agricultural chemicals and natural toxins.

Increased C storage has frequently been observed in soils under conservation tillage, particularly with no-tillage (NT) (Unger, 1991). 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). Kushwaha et al. (2001) found that the values of soil organic C 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 no-tillage 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 accelerate organic carbon loss and weaken 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.

Change in frequency and intensity of tillage practices alters soil properties, distribution of nutrients, and soil organic matter in the soil profile. These changes become stable with time and could affect availability of nutrients for plant growth, crop production, and soil productivity. Long-term no-till systems accumulate nutrients in the soil surface, whereas moldboard plow (MP) distributes nutrients relatively uniformly through the tillage depth, and soil mixing promotes uniform distribution of nutrients in MP and chisel plow (Karlen et al., 1991).

Any changes in organic C contents due to tillage can affect soil cation exchange capacity (CEC) of the soil. Accumulation and distribution of organic C in soil is affected by different tillage practices and time after initiation of tillage. However, no significant difference between annualized crop yield and SOC concentrations at 0 to 5 cm was found when a large number of treatments were used (Bowman et al., 1999).

Crop-residue management through conservation tillage is one of the best and most-effective ways to reduce soil erosion. Conservation tillage is defined by USDA as a tillage practice that leaves a minimum 30% of the surface covered by crop residues (Acquaah, 2002). Conservation tillage and residue management may reduce machinery expenses and save soil, labor, fuel and money. Crop residues uniformly distributed over the soil surface will significantly reduce soil losses over entire field. Alvarez and Alvarez (2000) stated that conservation tillage, especially no-tillage, induced changes in the distribution of organic pools in the soil profile. However, Roscoe and Burman (2003) found that plow tillage and no-tillage systems did not alter the total C (100 Mg/ha) and N (7 Mg/ha) stocks in the first 45 cm depth at the end of 30 years of cultivation.

No-till resulted in significantly greater soil organic C in the top 4 cm of soil, where the organic C concentration was 58% greater than in the top 4 cm of the plow-till treatment. In the 4-8 cm depth, organic C was 15% greater than the plow-till control. Higher concentrations of total soil N occurred in the same treatments, however, a significant reduction in N was detected below 12 cm in the ridge-till treatment (Zibilske et al., 2002).

Soil tillage has a major effect on the rate of organic matter decomposition. More tillage means faster rates of organic matter oxidation (breakdown). Soil tillage has been observed to increase the decomposition of organic matter compared to no tillage system. Much of this decomposition 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, which are becoming popular, mean slower rates of organic matter decay. 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 tons ha^{-1} more organic matter after 18 years of research than did 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 depth in the soil. 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).

Tillage operations strongly control the soil environment by altering the soil geometry. In addition, tillage determines the placement of crop residues. These effects influence many physical, chemical and biological properties of the soil and thereby the conditions for crop growth and the risk of nitrogen leaching. Stenberg et al. (1998) showed that both soil structure and soil microbial processes changed when annual tillage practices were altered. On a week-structured clay soil, cultivation to 12 cm instead of moldboard plowing to 20-25 cm improved soil structure and increased the microbial activity in the upper 12 cm. There was also an increase in yields, which promoted better nitrogen utilization. However, an increase in potential nitrogen turnover may lead to a higher risk of nitrogen leaching. When a sandy soil was stubble cultivated or moldboard ploughed soon after harvest in early autumn, soil mineral nitrogen content and nitrate leaching were higher than if it was ploughed in late autumn or in spring. Incorporation or removal of straw did not affect the soil nitrogen content or leaching rates. Carter et al. (2002) found that use of rotational tillage resulted in an intermediate soil physical condition between continuous no-tillage and plowing. 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 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). Thus, there is 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.

Crop Rotation

Regardless of the tillage system, rotating crops is always considered as a best management practice. Crop rotation can have a major impact on soil health, due to emerging soil ecological interactions and processes that occur with time, such as 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 cycles (Carter et al., 2002; Carter et al., 2003). In the absence of tillage, it may become even more important in no-till systems, especially to break insect, disease and weed cycles (Berzsenyi et al., 2000; Barberi and Lo Cascio, 2001). Crop rotations can also increase yields, build soil organic matter and enhance nitrogen availability if nitrogen fixing legumes are included (Liu et al., 1990; 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). Rosell et al. (2000) indicated that the crop rotation led to greater concentrations of P in the fine fraction.

It must be recognized that there is no single right rotation which will optimize water and nutrient use, minimize disease and weed problems, and most importantly, bring in the highest return per acre. The best rotation depends on available moisture and nutrients, diseases and weed levels, equipment availability, commodity prices, ability and desire to accept risk, and so forth. The best rotation can vary from field to field on the same farm and from year to year for the same field. Actually, the knowledge of the combined effects of crop rotation and fertilization on soil physical and chemical properties is the key for a sustainable crop production (Miglierina et al., 2000).

Carter et al. (2003) indicated that losses of soil organic C during 11-year period ranged from marginal (4%) for rotations with Italian ryegrass, to significant (16%) under barley rotation, which illustrated the importance of C inputs to maintain 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 some legume rotation crops resulted in an increase in liable carbon concentrations compared with continuous wheat or a long fallow treatment.

Low water and soil nutrient levels are usually the two most limiting factors to crop production. These factors affect, and are affected by crop rotation. Thus, crop rotation can be used to optimize water and nutrient use, since the sequence of crops in the rotation affects the availability and use of water and, thus, crop yields. In a 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 sequestration due to a 33-41% increase in the estimated amount of mineralized C and N input from biological N fixation during the dry season maize crop. 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.

A major objective for evaluating rotation and tillage systems is to determine the most efficient and economic crop sequencing for each environment. The SOM status correlates well with a number of important physical, chemical, and soil nutrients such as available N, P, S, Ca, Mg, K and micronutrients (Johnson, 1991; Loveland and Webb, 2002). Because of the unfavorable effects of conventional tillage on SOM through erosion and accelerated decomposition, cropping system research has been directed toward longer rotation and less tillage (Peterson et al., 1997).

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 aboveground C returned to the soil from corn was 40% greater in average than C returned from soybean in treatments containing both crops. Although more aboveground C was returned with corn, SOC did not differ with crop sequence or depth ($p<0.05$). 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 is the most profitable system which has lower soil erosion and higher quality attributes.

Thus, the investigation of ways to better increase the quantity and quality of soil organic matter and, hence soil chemical and physical fertility is necessary if long-term agriculture is to be possible.

Fertilization

Fertilization is one of the most important practices in crop production and hence influences soil nutrients availability. 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 sub-soil (Ishaq et al., 2002). 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. Applied N to the soil is subject to losses by volatilization, immobilization, denitrification and leaching and its efficiency of use by plants is governed by soil and climatic factors, fertilizer material, and soil, crop and fertilizer management practices. Reducing tillage intensity modifies both the demand of crops for N due to changes in yield potential, and the supply of N due to changes in N cycling and losses. Consequently, it may be necessary to compensate for this by adjusting the fertilizer rate. Fertilizer use efficiency may also change with changes in tillage management. Malhi et al. (2001) indicated that placing the fertilizer in a band reduces 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 denitrification and leaching. 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 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 accumulative. No tillage continuous corn with NPK and manure, 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).

Objectives

Although much has been done regarding the agricultural management on soil organic matter and its changes, more information is still needed on the changes of soil organic matter in Chinese Mollisols, especially in responses to different management systems. Mollisols in China (also called black soils) are distributed primarily in the northeast region, which is one of the three largest contiguous Mollisol areas in the world. The majority (nearly 70%) of black soils in China are in Heilongjiang Province. The total area of these soils is 6 million ha with about 4.4 million ha being cultivated (He et al., 1992). The black soils are fertile and productive, thus, they are of major agricultural importance in China. For example, black soils account for about 43% of total cultivated land in Heilongjiang Province. The mollic horizon or epipedon (soil organic matter rich) of these soils normally ranges from 30 to 70 cm, but can be up to 100-cm thick, depending on locations. Although some areas of black soils were cultivated 200 years ago, most of these soils have been used agriculturally for the last 50 years or so. Several main crops grown on these soils include wheat, soybean, and corn.

Areas with black soils are relatively humid in Heilongjiang Province. Annual precipitation is about 600 mm with 90% between April and September and about 55% between July and September. The slope of these soils ranges from 1 to 5%, and they have fine-textured parent geological materials (i.e., high clay content). The clay minerals include hydrous mica, goethite, montmorillonite, and kaolinite (He et al., 1992). The water table of black soils is very deep (50 to 200 m). Natural vegetation consists of mainly mixed grass species with nearly 100% ground coverage.

However, due to intensive cultivation, SOC loss and associated yield suppression and soil erosion are serious problems in the region. Accordingly, the objectives of this research are: 1) to study the physical and chemical properties of a typical black soil as baseline data for other studies of these soils in the region; 2) to evaluate and characterize the changes of SOC in the black soil of China with cultivation; 3) to determine if agricultural management systems alter SOC and total organic nitrogen (TON) contents and their vertical distribution and 4) to investigate the negative impacts of continuous soybean, a dominant practice in the region, on crop and soil productivity.

CHAPTER 2

PHYSICAL AND CHEMICAL CHARACTERISTICS OF A TYPICAL CHINESE MOLLISOL

Abstract

Mollisols (called black soils) in China are distributed primarily in the northeast region, which is one of the three largest Mollisol areas in the world. Black soils are of major agricultural importance in China. We report the physical and chemical properties of this soil using a typical black soil profile selected in Heilongjiang Province, China, and standard soil analytical procedures. The soil is characterized with a thick (60 cm) mollic epipedon. The upper layer of the epipedon contains 5.8% organic carbon, and its CEC is 43.7 cmol(+)/kg. The macro-aggregate (> 0.25 mm) stability of the epipedon is high (between 63 and 68% of the soil sample weight), which provides favorable soil structure and conditions for plant growth. Soil texture is clay loam for all horizons except the upper layer of the mollic epipedon, which is sandy clay loam. Bulk density increases with depth, and total porosity declines with depth, due most likely to the profile distribution of organic carbon (decreasing with depth). Total N and P and available water are also larger in the upper epipedon than the lower horizons. Overall characteristics make this soil fertile and productive. The results of this study can be used as baseline data for examining any change in soil properties of the same soils resulting from agricultural management and practices and for comparisons of pedogenic and carbon cycling studies of Mollisols in China or worldwide.

Introduction

Mollisols in China (called black soils) are distributed primarily in the northeast region, which is one of the three largest Mollisol areas in the world. Majority (nearly 70%) of black soils in China is in Heilongjiang Province. The total area of these soils is 6 million ha with about 4.4 million ha being cultivated (Liu et al., 2003). Black soils are fertile and productive, and thus, they are of major agricultural importance in China. For example, black soils account for about 43% of total cultivated land in Heilongjiang Province (Liu et al., 2003). The Mollic horizon or epipedon (soil organic matter rich) of these soils normally ranges from 30 to 70 cm, but can be up to 100-cm thick, depending on locations. Although some areas of black soils were cultivated 200 years ago, most of these soils have been used agriculturally for the last 50 years or so. Several main crops grown on these soils include wheat, soybean, and corn.

Areas with black soils are relatively humid in Heilongjiang Province. Annual precipitation is about 600 mm with 90% between April and September and about 55% between July and September (He et al., 1992). The slope of these soils ranges from 1 to 5%, and they have fine-textured parent geological materials (i.e., high clay content). The clay minerals include hydrous mica, goethite, montmorillonite, and kaolinite (He et al., 1992). Water table of black soils is very deep (50 to 200 m). Natural vegetation consists of mainly mixed grass species with nearly 100% ground coverage. Although these soils are important, both agriculturally and ecologically, a detailed and systematic examination of soil properties is lacking or not reported in international journals. Therefore, the objective of this work was to study the physical and chemical properties of a typical black soil selected in Heilongjiang Province. The results will be served as baseline data for other studies of these soils in the region and of other Mollisols worldwide. Also, the results are expected to be useful for selecting soil and agronomic management strategies to maintain and improve soil productivity, which is strongly affected by soil organic matter content.

Materials and Methods

A typical black soil profile was chosen near the Agro-Ecological Experiment Station (Chinese Academy of Sciences), Hai Lun City, Heilongjinag Province, the People's Republic of China (47°26′N, 126°38′E, altitude of 240 meters). The sampling site is in the north temperate, continental monsoon zone (cold and arid in winter, hot and rainy in summer with average annual temperature of 1.5 °C and annual precipitation of about 550 mm). The sampling area was cultivated before but has been returned to grassland for more than 30 years. A large pit (1.2 m x 2.0 m x 2.0 m) was excavated to sample a soil profile. Due to the thickness of the mollic epipedon (A horizon), soil samples were collected from two depths (0-20 cm and 40-60 cm). Soil samples of AB (60-80 cm, a transition horizon between A and B), B (100-120 cm), and C (140-160 cm) were also taken (one sample from each horizon). Except for soil samples for water-stable aggregate measurements, all samples were air-dried and passed through 2-mm sieves for subsequent analyses.

Particle size distribution was determined by the pipette method after H_2O_2 treatment to remove organic matter (McKeague, 1978). Bulk density was measured using the core method (Carter, 1993). Water-stable aggregate analysis was performed using field-moist soil samples with wet-sieve (Beare and Bruce, 1993). Aggregate percentages were corrected by accounting for the dry weight of primary particles retained on the sieves after complete dispersion by mixing in 0.05 M NaOH solution. The aggregate analysis was performed for only the two surface horizon samples due to the agricultural relevance (i.e., 0-20 cm and 20-

40 cm). Soil pH was determined in distilled water (1:5 W/V), and cation exchange capacity (CEC) was determined by an ammonium acetate method (Carter, 1993) because of the neutral pH of the soil. Exchangeable cations (Ca, Mg, K, Na) were measured by atomic absorption spectrophotometry (AAS).

Total carbon and nitrogen were determined by a dry combustion method (Spark, 1996) after the soil samples were finely ground (<100 mesh). It should be noted that the carbon content would approximate the total organic carbon because inorganic carbon was not detected in these soil samples with a dilute HCl test. Total potassium (K) and phosphorus (P) were determined after microwave-assisted, acid (HCl-HNO_3) digestion (Xing and Veneman, 1998). Contents of Fe, Al, and Si in clay separates were determined using inductively coupled plasma–atomic emission spectrometry after the microwave-assisted acid digestion (Xing and Veneman, 1998; Xing and Dudas, 1994). Then, these contents were calculated and expressed as their respective oxide compounds (i.e., Fe_2O_3, Al_2O_3, SiO_2). Available N, P, and K were extracted and analyzed using the methods by Spark (1996) and Carter (1993). Soil porosity and moisture contents at the field capacity and wilting point of these soils samples were determined following the method by Carter (1993) and Hillel (1998). All measurements were repeated three times (three separate soil samples) and the averages are reported.

Results and Discussion

Physical properties of this Black soil profile are shown in Table 2.1. Bulk density increases with depth where the lowest being in the A1-1 horizon (1.04 g/cm^3). A decrease in total porosity occurs with increasing depth. These trends are due most likely to the organic carbon profile distribution, which declines with depth (See the discussion below). High organic carbon contents can improve soil physical structures (Stevenson, 1994; Ding et al., 2002; Loveland and Webb, 2003) leading to formation of soil aggregates, thus high porosity and low bulk density. Similar results were reported elsewhere (Xing and Dudas, 1992). Furthermore, addition of organic amendments such as plant residues and manure increased organic matter contents and reduced soil bulk density for the same type of soils (Liu et al., 2003).

Particle-size distribution shows lower clay and higher sand concentration in the A horizons than the deeper horizons (Table 2.1). The deeper three horizons have basically the same particle-size distribution. According to the USDA textural triangle (Brady and Weil, 2002), the A1-1 horizon is sandy clay loam, and the other four horizons are clay loam. The lower clay content at the surface horizon may be due to the inability to completely remove organic matter before particle-size distribution analysis, preferential loss of fine particles from wind and water erosion or to the both factors. Clay downward translocation may lead to lower clay concentration in surface horizons (Xing and Dudas, 1992; Xing and Dudas, 1993), but such transport can be ruled out for this soil because there is no evidence for clay accumulation at the lower depths (Table 2.1). Parent geological material discontinuity may be another reason for the textural difference between the horizons; however, such discontinuity cannot be important because the chemical composition of clay separates is essentially identical (Table 2.2). For example, SiO_2 content ranges from 49 to 51%, and the molar ratios of SiO_2 to Al_2O_3 are all about the same (4.2), indicating that clay separates are from the same source. The overall high clay content for this soil is consistent with derivation from a fine-textured parent material, sediment that was deposited during the Pleistocene. This fine-textured sediment is about 10 to 40 meters deep (He et al., 1992).

Favorable soil structure for crop growth depends on the formation of water-stable macroaggregates (> 0.25 mm). The presence of these aggregates also makes soils resistant to erosion and compaction (Angers and Giroux, 1996; Degens, 1997). Moreover, formation of soil aggregates can incorporate organic matter into them, thus protecting the organic matter from microbial degradation and improving soil quality for sustained agricultural production (Franzluebbers and Arshad, 1996; Denef et al., 2001).

The results of water-stable aggregate analysis are presented for the top two soil horizons (Table 2.3). The Al-1 (0-20 cm) horizon (68%) has a slightly higher total percentage than the A1-2 (20-40 cm) (63%), probably due to the organic carbon concentration difference. Organic matter helps soil aggregation, as indicated by a high correlation between organic matter and aggregate stability (Albiach, 2001). Cultivation has reduced soil organic C content and macro-aggregation (Elliott, 1986; Gupta and Germida, 1988). In addition, soils with an incorporation of manure had much higher macro-aggregate stability (72%) than the same Black soil (about 35%) without manure addition (He et al., 1992). The high aggregate stability (over 60%) of this particular soil is a consequence of high organic matter content (Table 2.3), resulting from maintaining the soil as grassland for more than 30 years. The aggregate stability and size distribution closely resemble the ones of uncultivated Black soils (He et al., 1992). Therefore, it is essential to maintain or increase soil organic matter content through using conservation tillage, addition of organic amendments, or both practices. It should be noted that the A1-1 horizon has larger percentages of aggregates of size > 1 mm than the A1-2, but lower percentage of aggregates of size < 1 mm (Table 2.3).

Water (or moisture) characteristics are shown in Table 2.4. The water content in field capacity decreases with increasing depth, similar to the trend for total porosity (Table 2.1).

This distribution is again due to the higher organic C contents in the top horizons (Table 2.5). The wilting point remains relatively constant with depth. As a result, available water for plant growth (the difference between the field capacity and wilting point) is greater in the surface horizons, probably due to macro-aggregate formation.

The surface horizon has a much higher organic matter concentration than the underlying horizons (Table 2.5). The C/N ratios are also higher in the upper horizons. The pH values are about neutral ranging from 6.5 to 7.0. High CEC at the surface is associated with organic matter, which contributes greatly to CEC, particularly at neutral or high pH (Stevenson, 1994). The relatively high CEC of the other horizons can be attributed to high clay content. The dominating exchangeable bases are Ca and Mg. These soils have high base saturation, ranging from 91 to 97% (He et al., 1992). High CEC and organic matter content may be one of the important reasons why Black soils are fertile and productive.

Macronutrients (N, P, K) are presented in Table 2.6. Total N and P concentrations are highest at the surface horizon due to the organic matter, but total K does not vary much with depth. Available N declines with depth due to lessening of the CEC and organic matter. Available P does not change much, but available K appears higher at the deeper horizons. Overall, these nutrient concentrations are higher than those of other soils in the regions (He et al., 1992; Xing and Dudas, 1992) and the general properties of Mollisols are favorable for the growth and development of many plants and thus crop plants production.

Conclusions

This study summarizes the basic physical and chemical properties of a typical black soil profile from Heilongjiang Province, China. The soil is characterized with a deep Mollic epipedon, up to 60-cm thick. The epipedon has much higher organic matter content and cation exchange capacity (CEC) than the underlying horizons. Due to the relatively high organic matter and clay content, the macro-aggregate stability of epipedon is about 70% and provides favorable soil porosity and bulk density for plant growth. In addition, high CEC and neutral pH along with favorable macronutrient status make the black soils fertile and productive. Thus, they are important agricultural soils in China. Effort should be made to use conservation tillage to increase organic matter and aggregate stability of cultivated black soils, therefore, maintaining and improving the quality and productivity of these soils.

Table 2.1 Physical Properties of a Typical Mollisol

Horizon	Depth (cm)	Bulk density (g/cm^3)	Total Porosity (%)	Particle-size distribution (%)			Textural class
				Sand	Silt	Clay	
A1-1	0-20	1.04	59.6	44	26	30	Sandy clay loam
A1-2	40-60	1.24	52.0	37	29	34	Clay loam
AB	60-80	1.29	50.7	27	33	40	Clay loam
B	100-120	1.39	47.9	26	34	39	Clay loam
C	140-160	1.41	47.6	26	35	40	Clay loam

Table 2.2 Chemical Analysis of Clay Separates (< 0.002 mm)

Horizon	Depth (cm)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3
A1-1	0-20	48.7	19.9	9.89	4.16	13.1
A1-2	40-60	49.9	20.3	9.67	4.17	13.8
AB	60-80	50.5	20.5	8.85	4.19	15.4
B	100-120	51.0	20.8	8.77	4.17	15.5
C	140-160	51.5	20.4	8.73	4.29	15.7

SiO_2/Al_2O_3 and SiO_2/Fe_2O_3 are the molar ratios.

Table 2.3 Water-Stable Aggregates (%) of the Mollisol at Cultivated Layers

Horizon	Depth (cm)	Organic C (%)	>5 mm	5-2 mm	2-1 mm	1-0.5 mm	0.5-0.25 mm	Total (%)
A1-1	0-20	5.84	8.8	13.8	14.0	16.2	15.3	68.1
A1-2*	20-40	5.35	4.5	10.4	11.5	17.8	19.1	63.3

*A1-2 in this table is from a depth of 20-40 cm, different from the A1-2 in other tables

Table 2.4 Water Characteristics of a Typical Mollisol Profile

Horizon	Depth (cm)	Field capacity (%)	Wilting point (%)
A1-1	0-20	39.8	20.6
A1-2	40-60	36.9	18.9
AB	60-80	31.3	19.1
B	100-120	28.1	18.9
C	140-160	27.2	18.5

Table 2.5 Chemical Properties of the Mollisol

Horizon	Depth (cm)	pH	C (%)	N (%)	C/N	Exch. cations (cmol(+) /kg)				CEC
						Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	total
A1-1	0-20	6.70	5.84	0.46	12.7	34.88	7.28	0.69	0.81	43.66
A1-2	40-60	7.00	3.23	0.32	10.1	24.85	6.56	0.77	1.54	33.72
AB	60-80	6.70	2.41	0.19	12.6	20.65	6.79	0.75	1.10	29.29
B	100-120	6.50	0.62	0.11	5.6	15.83	4.12	0.54	1.36	21.85
C	140-160	6.60	0.73	0.12	6.1	13.96	4.92	0.52	1.76	21.16

CEC = Cation Exchange Capacity

Table 2.6 Macronutrient Status in the Profile of the Mollisol

Horizon	Depth (cm)	Total N (%)	Available N (mg/kg)	Total P (mg/kg)	Available P (mg/kg)	Total K (g/kg)	Available K (mg/kg)
A1-1	0-20	0.46	549	1.59	23.9	13.8	152
A1-2	40-60	0.32	511	0.69	22.6	13.3	148
AB	60-80	0.19	473	0.62	19.2	13.7	143
B	100-120	0.11	366	0.56	20.9	14.0	187
C	140-160	0.12	386	0.63	29.2	15.7	219

CHAPTER 3

SOIL ORGANIC CARBON DYNAMICS IN CHINESE MOLLISOLS UNDER DIFFERENT ROTATION MANAGEMENT

Abstract

Cultivation can reduce soil organic carbon (SOC) content and lead to soil deterioration, but some agricultural management systems may increase SOC content and soil productivity. This research examined the SOC dynamics during 50-year cultivation and how long-term crop rotation management practices influenced SOC content in a typical black soil (Mollisol) region of P.R. China. The experiments selected four fields with different cultivation periods: uncultivated, five years, fourteen years, and fifty years. In addition, four long-term rotation managements were initiated in 1992: conventional wheat-soybean rotation, wheat-sweet clover rotation, wheat-soybean rotation with addition of pig manure, and wheat-soybean rotation with addition of wheat straw. The SOC content declined rapidly at early years of cultivation and gradually afterwards. Wheat-soybean rotation with addition of wheat straw or pig manure resulted in a substantial increase in SOC content in 9 years. Thus, proper soil management can improve soil quality and health by increasing SOC content, and mitigate the greenhouse effect by sequestrating carbon dioxide from the atmosphere as indicated by the significant increase of organic carbon content in soil.

Introduction

Soil organic matter (SOM) is a very reactive, ubiquitous component in soils. It is closely related to desirable soil physical, chemical and biological properties and soil productivity (Stevenson, 1994; Tate, 1987). When soils are properly managed, SOM contributes to a favorable soil structure and increases water retention and nutrient availability. Because SOM strongly influences many soil characteristics and processes that are important for soil quality and productivity, it is suggested to be the heart to sustaining agricultural productivity (Reeves, 1997). In addition, SOM can be a major source or sink of atmospheric carbon and may be able to mitigate the greenhouse effect through appropriate soil management (Lal, 2001).

Soil organic matter contents and properties are a function of agricultural practices and the amounts and kinds of plant residues returned to the soil (Mann, 1985; Doran et al., 1987; Cheshire et al., 1990; Campbell et al., 1999). For example, crops grown in rotation often produce higher quantities of plant dry matter than those grown in monoculture (Copeland and Crookston, 1992). Wander and Traina (1996) also showed that SOM in crop rotation with cover crops was significantly higher than those in rotations without cover crops. However, Lal et al. (1991) in a similar type of study reported no or minimal change of SOM content, probably due to the lack of homogeneous distribution of soil organic carbon that can cause a large variation in carbon analysis. Moreover, crop sequences varying in the quantity and quality of residue production can result in changes in SOM. Collins et al. (1992) reported that continuous wheat and wheat-pea sequences produced a greater amount of SOM than wheat-fallow after 58 years. Through a long-term study, Reeves (1997) observed consistent benefit of manure, adequate fertilization, and crop types on maintaining agronomic productivity by increasing carbon inputs into the soil. However, lack of SOM can result in poor soil structure, enhanced runoff and erosion, and low productivity. Thus, it is important to maintain or increase SOM content to improve soil and environmental quality.

The black soil (Mollisol), the most fertile and productive soil in China, is distributed mainly in Heilongjiang and Jinlin Provinces of northeastern China with a total area of 6 million ha where about 4.4 million ha of that have been cultivated. Due to intensive cultivation, SOM loss and associated yield suppression and soil erosion are serious problems in the region. However, only limited information is available for SOM dynamics with cultivation and the effect of soil management on SOM content in the black soils of China. Accordingly, the objectives of this research were to: a) evaluate and characterize the changes of SOM contents in the black soil of China with cultivation and b) to determine if SOM contents and its vertical distribution are affected by long-term crop rotation management.

Materials and Methods

The research was conducted on Zhaoguang Farm, Heilongjiang Province, P.R. China. The research site (48°30′N, 127°15′E) has the average annual precipitation of 600 mm with 50% in July and August and a frost-free period of 120 days. The study area was about 9 km^2 with a slope of 3%. The detailed experiments are shown below.

- **Experiment I: Dynamics of Soil Organic Carbon with Cultivation**

Four fields with different cultivation histories were selected after consulting with local farmers and agronomists. They were: uncultivated soil, five-year cultivation, fourteen-year cultivation, and fifty-year cultivation. All cultivated soils were under wheat-soybean rotation that is the normal practice in the region. The soil was a typical black soil and is one of the main agricultural soils in the province. Fifteen soil samples were randomly collected from each field at three depths (0-17 cm; 18-32 cm, and 33-43 cm). All soil samples were air-dried and passed through 2-mm sieves before analysis. The textural class of the black soil is silty clay loam or silty clay with about 40% clay. Soil pH is neutral (7.0±0.1) as determined in distilled water (1:5 V/V). Cultivation periods did not significantly change soil pH. Cation exchange capacity (CEC) was determined by the ammonium acetate method (Carter, 1993) because of the pH of the soils.

- **Experiment II: Effect of Rotation Management on Organic Carbon and Distribution**

Long-term experimental plots were established in 1992 at Zhaoguang Farm, Heilongjiang province, to assess the impact of different rotation management systems on a typical black soil. The soil had been cultivated for 42 years before 1992. Four treatments used in this study were based on local farmers' common and available practices. Crops were grown from 1992 through 2000.

Treatment 1: Wheat-soybean rotation

Fertilizers were applied at 45 kg N ha^{-1} (urea) and 15 kg P ha^{-1} (ordinary superphosphate) in wheat, and 15 kg N ha^{-1} and 12 kg P ha^{-1} in soybean. After harvest, wheat and soybean residues (straw) were removed, a normal practice by the local farmers. Then soil was plowed: plow depth using a disc harrow was 18 cm for the wheat field and 25 cm for the soybean field.

Treatment 2: Wheat-sweet clover rotation

The same rate of chemical fertilizers was used as in Treatment 1 for wheat, but no fertilizer was applied to sweet clover. After harvest, wheat straw was removed, and soil was plowed as above; but the biomass of sweet clover was plowed into the soil.

Treatment 3: Wheat-soybean rotation with addition of pig manure (approximately 15,000 kg organic carbon ha^{-1} year^{-1}). Other treatments were the same as used in treatment 1 for either wheat or soybean.

Treatment 4: Wheat-soybean rotation with addition of wheat straw (approximately 15,000 kg organic carbon ha^{-1} year^{-1}). Other treatments were the same as used in treatment 1 for either wheat or soybean.

All the treatments were arrayed in a randomized complete block design with four replications. Plot size was 30 m by 23 m. Soil samples were collected from three depths (0-17 cm, 18-32 cm, and 33-43 cm) in each plot in October 2000. Crop residues were removed from the surface before the samples were taken. All samples (15 per plot at each depth) were mixed to form one composite soil sample for each depth of every plot. The composite samples were air-dried and sieved (2-mm) before soil organic carbon was analyzed. Total soil organic C was measured by a dry combustion method (Nelson and Sommers, 1982). Soil bulk density was determined by a soil core method (Carter, 1993). The organic carbon content was calculated using the organic carbon concentration and soil bulk density (Ding et al., 2002). The means of each measurement were reported instead of individual values. Experimental data were analyzed by ANOVA (analysis of variance), and for mean comparisons, Duncan's Multiple Range Tests were performed (SAS Institute, 1996).

Results and Discussion

- **Experiment I. Dynamics of Soil Organic Carbon during Cultivation**

Soil organic carbon (SOC) content in the surface layer (0-17 cm) of the uncultivated soil was 54.4 g kg^{-1}, typical for a black soil in the area (Liu et al., 2002). The SOC contents of surface and subsurface horizons declined significantly with the increase in cultivation years (Table 3.1). This observation is consistent with the results of Magdoff and van Es (2000). They concluded that after cultivation of tall-grass prairies soils for 50 years, a substantial amount of SOM was lost. The SOC content of uncultivated soil at the 0-17 cm depth was nearly twice that of soil with 50-year cultivation, 3.5 times at 18-32 cm depth, and 4.5 times at 33-43 cm depth. At the depth of 0-17 cm or 18-32 cm (Table 3.1, Figure 3.1), we did not observe any significant SOC difference between 5- and 14-year cultivations, indicating a rapid reduction of SOC at initial cultivation at those two depths. For all four soils of different cultivation periods, the same profile distribution of SOC (i.e., declining with depth) was observed. The high SOC content of surface horizons is one of the main reasons that top soils are more productive compared with subsurface horizons exposed by erosion. Low SOC can reduce soil productivity through poor soil structure, reduced CEC, soil erosion, low retention of water and nutrients, and reduced microbial activity among many SOC-related soil properties.

Cation exchange capacity (CEC) of surface soil (0-17 cm) was 45.8 meq/100 g for uncultivated soil, 42.6 meq/100g for the soil of 5-year cultivation, 38.1 meq/100 g for 14-year cultivation, and 31.5 meq/100 g for 50-cultivattion (Figure 3.2). The reduction of CEC with cultivation years is most likely due to the SOC loss because SOM contributes greatly to CEC (Stevenson, 1994) and soil texture was not significantly affected by the periods of cultivation.

Bulk density increased with long-term cultivation (Table 3.2). Significant difference was found between soils from the 50-year cultivation and other three soils, and no significant differences were observed among the uncultivated, 5-year cultivated, and 14-year cultivated soils (Figure 3.3). These results indicate that long-term cultivation may result in soil compaction, probably related to loss of SOC. Profile (vertical) distribution of bulk density was similar for all four soils, and increased with depth probably due to lack of soil organic matter (Table 3.2, Figure 3.3). A similar trend was reported earlier for a white clay soil in Heilongjiang province, China (Xing and Dudas, 1992).

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). A significant decline of total SOC occurred in the first 5 years of cultivation; the average SOC loss per year was about 2300 kg ha^{-1} for the 0-17 cm horizon (Table 3.3). The average annual SOC loss for the period between 5- and 14-year cultivation was 950 kg ha^{-1} and for the period between 14- and 50-year cultivation was 290 kg ha^{-1}. These data clearly show the rapid reduction of SOC for the initial soil disturbance by cultivation and relatively gradual loss later. A similar trend was observed for the other two soil depths (Figure 3.4).

Compared with organic matter in the uncultivated soil, total SOC loss (the sum of three horizons) was 17%, 28%, and 55% in 5-, 14- and 50-year cultivation, respectively (Table 3.3). The latter would correspond to the release of approximately 380 ton CO_2 ha^{-1} to the atmosphere. In addition, these SOC losses could be sufficient to cause changes in soil-available water content according to Hudson (1994). He found a significant positive correlation between soil organic matter and available water content. An increase of soil organic matter from 0.5% to 3.0% more than doubled available water content.

- **Experiment II. Effects of Rotation Management on SOC and Distribution**

Cropping treatments significantly altered SOC concentration during the 9-year experiment from 1992 to 2000 (Table 3.4). The SOC in the treatments of wheat–sweet clover and wheat–soybean with addition of pig manure or wheat straw was significantly higher than that of wheat-soybean rotation, particularly in the 0-17 cm horizon (Figure 3.5). For the overall SOC concentration (i.e., the means of SOC of all three horizons), soil with addition of wheat straw had 22% more SOC than that of wheat–soybean alone, and no difference occurred between the wheat-sweet clover rotation and wheat-soybean rotation with addition of pig manure (Table 3.4). Moreover, all three treatments increased SOC content in the 18-32 cm soil depth relative to the wheat-soybean rotation. The lack of SOC content change at the depth of 33-43 cm indicates minimal incorporation of crop residues or pig manures into this layer except for wheat-sweet clover rotation (Table 3.4), which is a result probably due to the deep rooting system of sweet clover.

The wheat-sweet clover rotation not only increased the SOC content in all soil depths (Table 3.4), but also decreased soil bulk density except for the 33-43 cm depth (Table 3.5). No significant difference in soil bulk density was observed for other treatments (Figure 3.6), although relatively lower values in the surface horizon were found for the two treatments of wheat-soybean with addition of pig manure or wheat straw. Thus, wheat-sweet clover rotation may be able to increase SOC and improve soil structure.

The SOC storage is displayed in Table 3.6. Significant differences of SOC were observed after 9-year rotation management in the 0-17 cm soil depth (Figure 3.7). The wheat-soybean rotation with addition of wheat straw yielded the highest total of SOC (62300 kg ha^{-1}). Compared with organic matter in the wheat–soybean rotation, commonly used in the region, total SOC storage (the sum of all three horizons) increased by 7.5% for wheat-sweet clover rotation, 10.7% for wheat-soybean rotation with addition of manure, and 14.4% for wheat–soybean rotation with addition of wheat straw. The amount of total SOC increase (11700 kg/ha) in wheat–soybean rotation with addition of wheat straw (Table 3.6) would correspond to sequestration of approximately 43 ton CO_2 ha^{-1} from atmosphere. These results indicate that proper crop rotation management can increase the organic carbon reserve in the black soils and sequestrate CO_2 from atmosphere, thus, mitigate the greenhouse effect. Meanwhile, soil quality can be improved.

Conclusions

The changes in SOC contents and soil bulk density observed in the study suggest that different agricultural and crop rotation management can strongly influence soil properties and subsequently its productivity. Based on average annual loss, SOC declined sharply at early years of cultivation and then slowly afterwards. More than 50% of SOC was lost after 50-years of cultivation, and losses can potentially reduce soil productivity, increase soil erosion, and contribute to the greenhouse effect. However, the long-term management with return of wheat straw and addition of pig manure in the wheat-soybean rotation resulted in substantial increases in SOC after nine years. Similarly, wheat-sweet clover rotation also increased SOC content relative to the wheat-soybean rotation. These long-term soil management practices will improve soil quality and productivity and reduce soil erosion through increase of SOC content. Further, these practices will help sequestrate CO_2 from atmosphere and mitigate the greenhouse effect.

Figure 3.1 Soil Organic Carbon Concentration and Distribution during 50 Years of Cultivation
L=linear

Figure 3.2 Changes in CEC during 50 Years of Cultivation

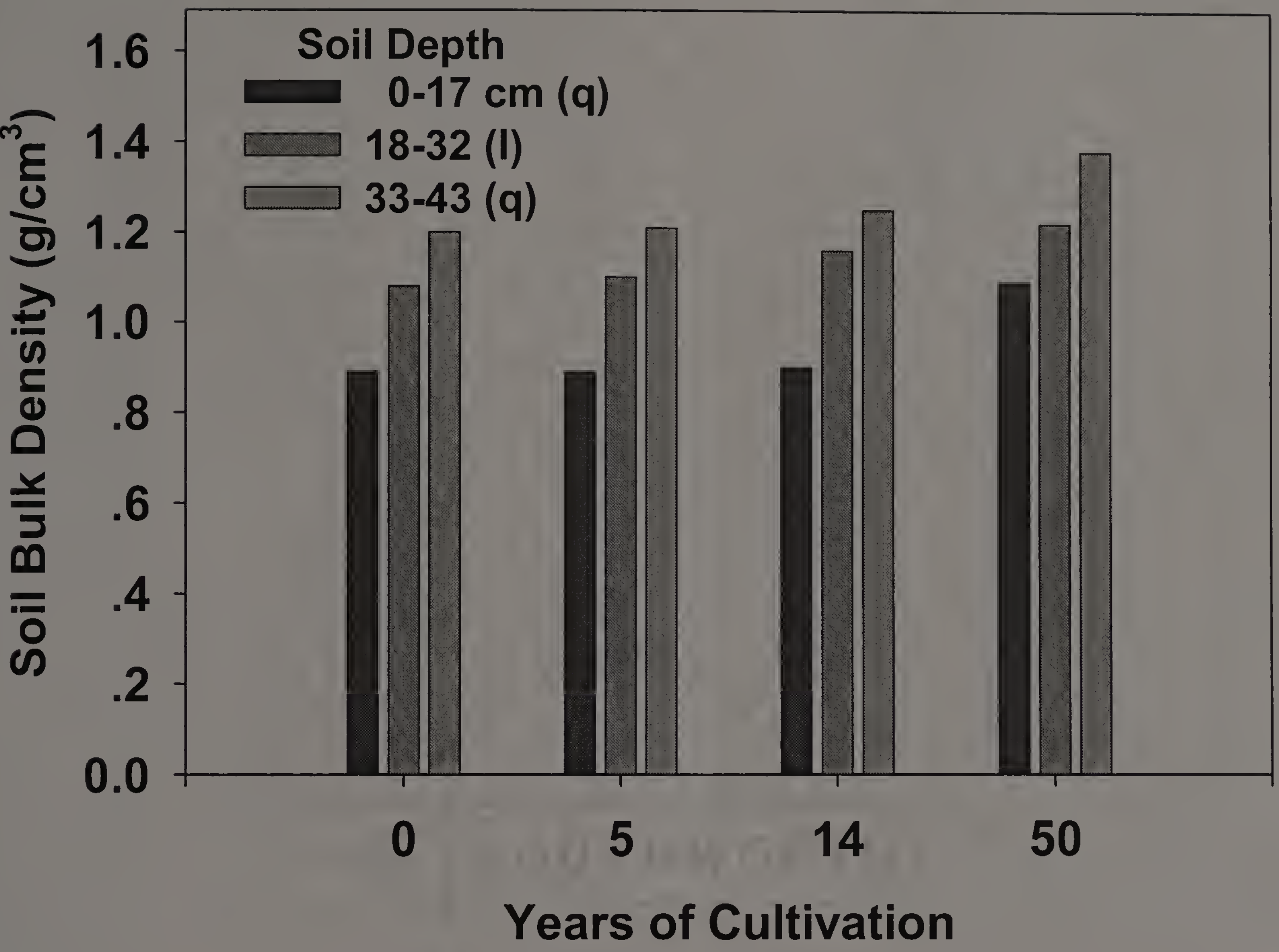

Figure 3.3 Changes in Soil Bulk Density during 50 Years of Cultivation
L=linear Q=quadratic

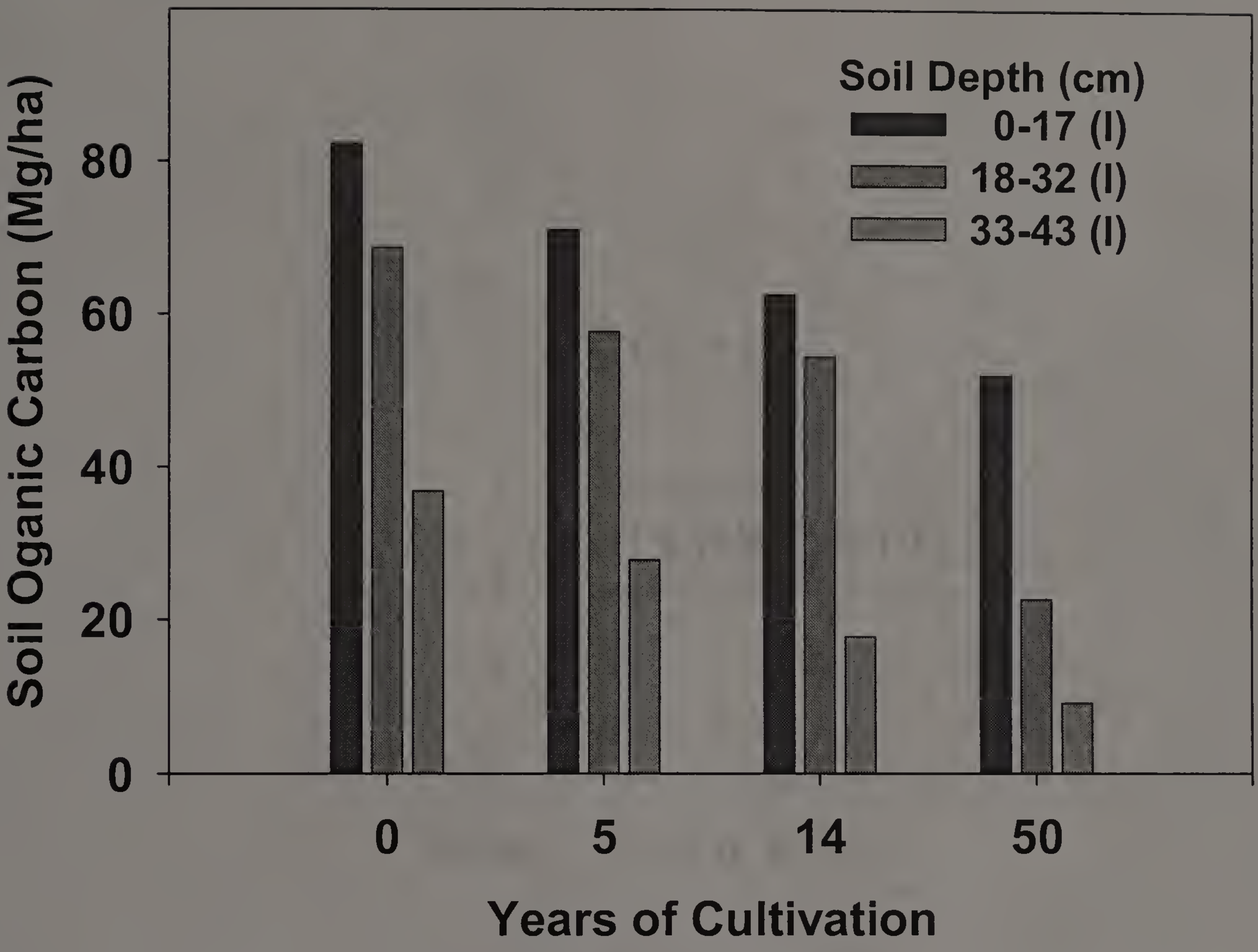

Figure 3.4 Changes in Soil Organic Carbon Quantity during 50 Years of Cultivation
L=linear

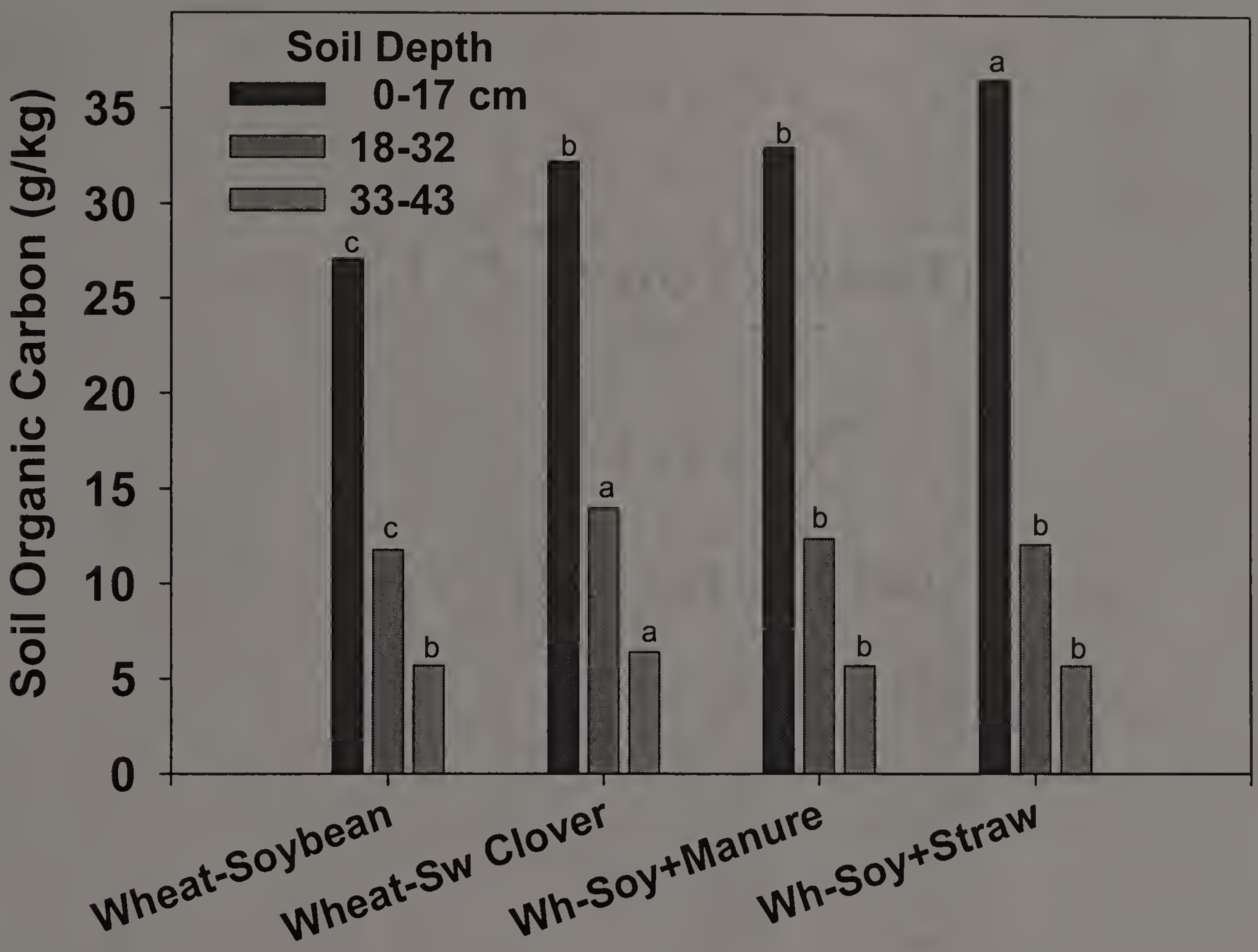

Figure 3.5 Effects of Rotation Management Systems on Soil Organic Carbon Concentration
Sw: Sweet Clover; Wh-Soy:Wheat-soybean
Means followed by the same letter in the same soil depth
are not significantly different ($P \leq 0.05$).

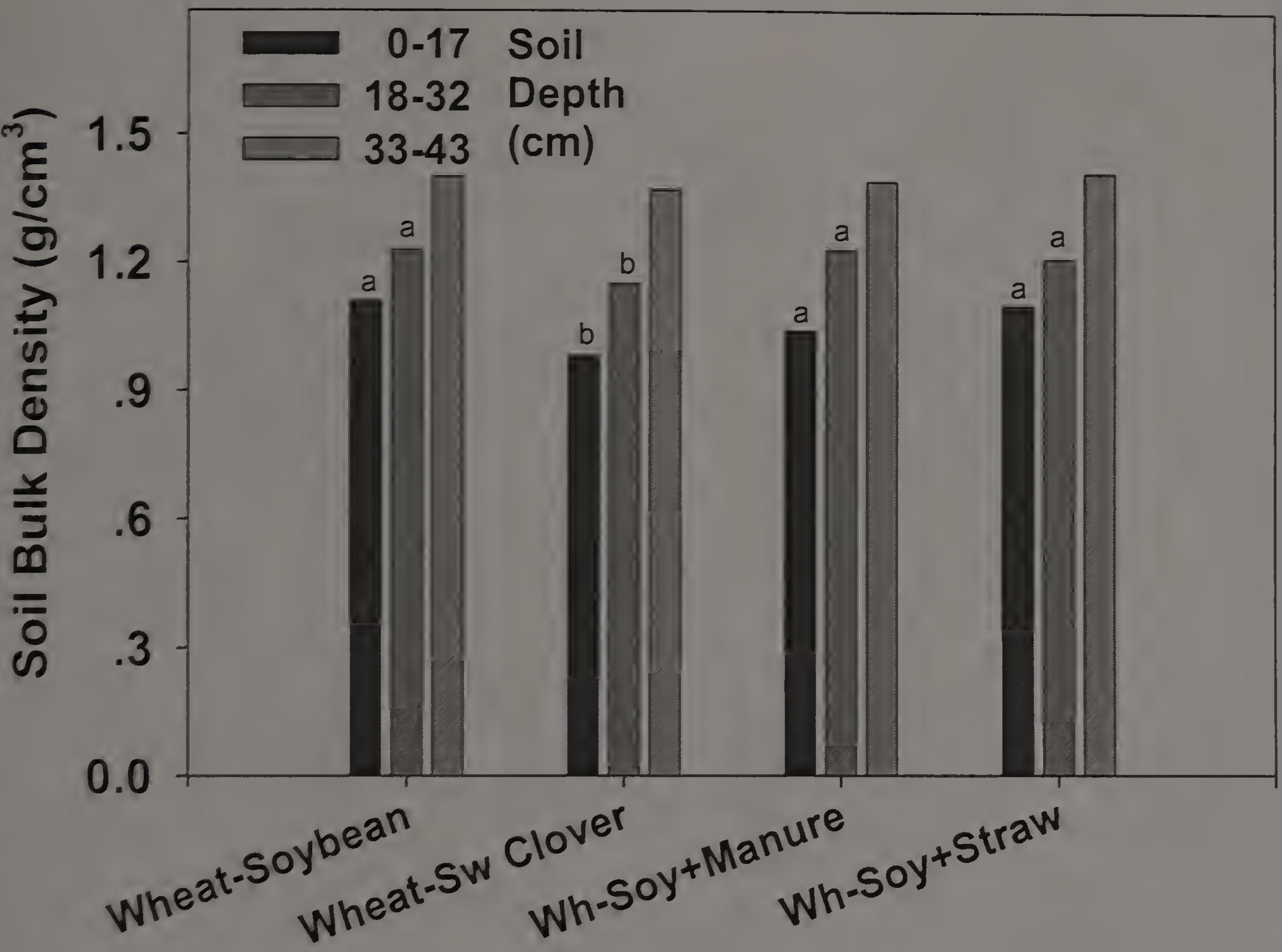

Figure 3.6 Effects of Rotation Management Systems on Soil Bulk Density
Sw: Sweet Clover; Wh-Soy: Wheat-soybean
Means followed by the same letter in the same soil depth are not significantly different ($P \leq 0.05$).

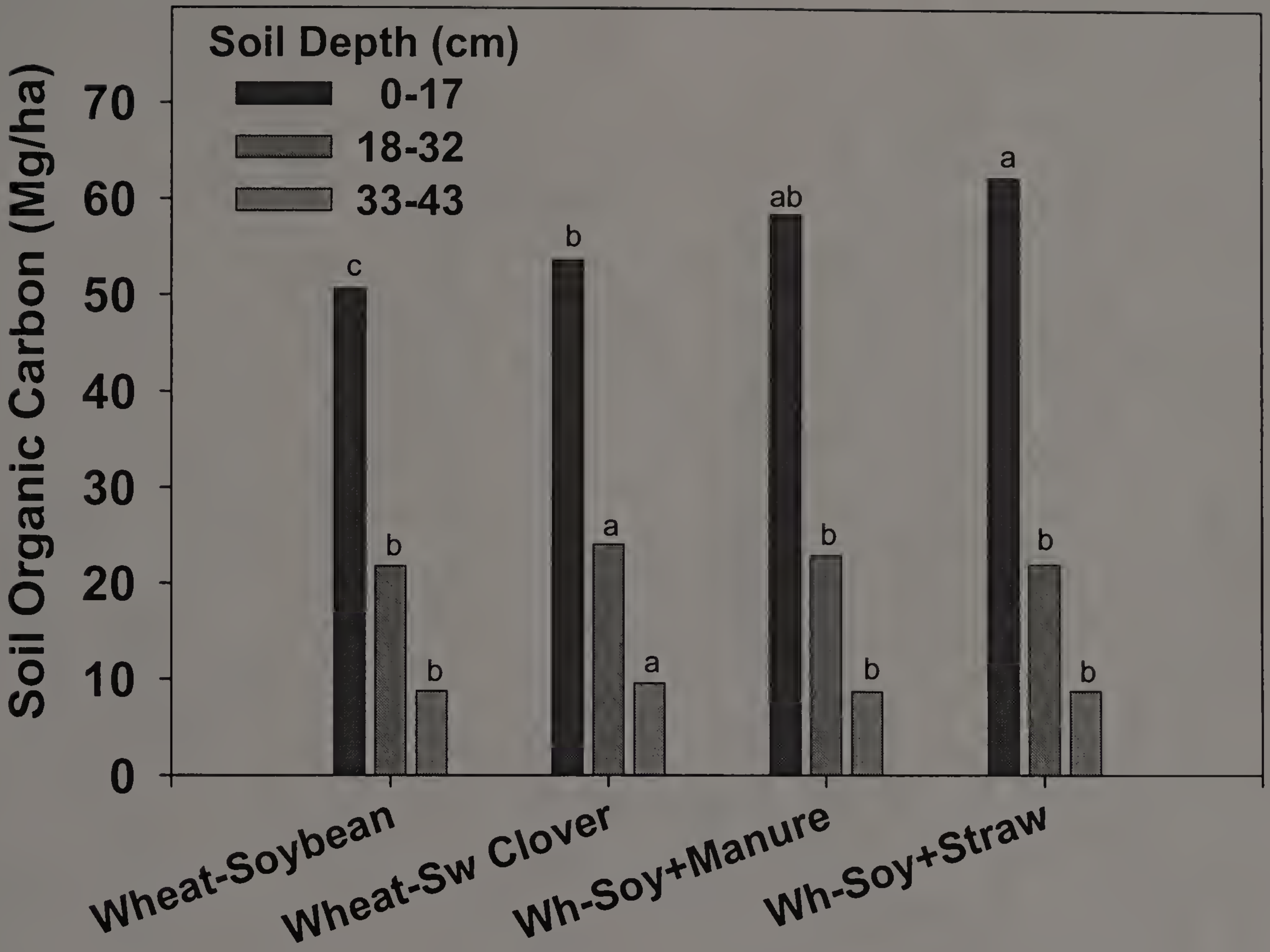

Figure 3.7 Effects of Rotation Management Systems on Soil Organic Carbon Quantity
Sw: Sweet Clover; Wh-Soy:Wheat-soybean
Means followed by the same letter in the same soil depth
are not significantly different ($P \leq 0.05$).

Table 3.1 Soil Organic Carbon Concentration and Distribution during 50 Years of Cultivation

Years of Cultivation	Soil Depth of Sampling (cm)			
	0-17	18-32	33-43	Means
	------------------------ g kg^{-1} -------------------			
0	54.4a[a]	42.4a	27.8a	41.5a
5	47.0b	34.9b	20.9b	34.3b
14	40.9b	31.3b	13.0c	28.4c
50	28.1c	12.4c	6.0d	15.5d
Means	42.6a[b]	30.2b	16.9c	

[a] Values followed by the same letter within each column for different periods of cultivation are not significantly different ($P \leq 0.05$).

[b] Values followed by the same letter within each row for different depths are not significantly different ($P \leq 0.05$).

Table 3.2 Changes in Soil Bulk Density during 50 Years of Cultivation

Years of Cultivation	Soil Depth of Sampling (cm)			
	0-17	18-32	33-43	Means
	------------------------- g cm^{-3} --------------------			
0	0.89b[a]	1.08b	1.20b	1.06b
5	0.89b	1.10b	1.21b	1.07b
14	0.90b	1.16ab	1.25b	1.10b
50	1.09a	1.22a	1.38a	1.23a
Means	0.94c[b]	1.14b	1.26a	

[a] Values followed by the same letter within each column for different periods of cultivation are not significantly different ($P \leq 0.05$).

[b] Values followed by the same letter within each row for different depths are not significantly different ($P \leq 0.05$).

Table 3.3 Changes of Soil Organic Carbon Quantity during 50 Years of Cultivation

Years of Cultivation	Soil Depth of Sampling (cm)				
	0-17	18-32	33-43	Total	Decline %†
	---------------- kg ha^{-1} ----------------				
0	82300a[a]	68600a	36800a	187700a	
5	71000b	57700b	27800b	156600b	16.6c
14	62600b	54500b	17800c	134900b	28.1b
50	52100c	22700c	9170d	83970c	55.3a
Means	67000a[b]	50900b	22900c		

[a] Values followed by the same letter within each column for different periods of cultivation are not significantly different ($P \leq 0.05$).

[b] Values followed by the same letter within each row for different depths are not significantly different ($P \leq 0.05$).

†Decline % is relative to SOC in the uncultivated soil (0-year cultivation).

Table 3.4 Effects of Rotation Management Systems on Soil Organic Carbon Concentration

Rotation System	Soil Depth of Sampling (cm)			
	0-17	18-32	33-43	Means
	---------------------- g kg^{-1}		-------------------	
Wheat-Soybean Rotation	27.1c[a]	11.8c	5.7b	14.9c
Wheat-Sweet Clover Rotation	32.2b	14.0a	6.4a	17.5b
Wheat-Soybean Rotation with Addition of Pig Manure	33.0b	12.4b	5.7b	17.0b
Wheat-Soybean Rotation with Addition of Wheat Straw	36.6a	12.1b	5.7b	18.1a

[a] Values followed by the same letter within each column for different treatments are not significantly different ($P \leq 0.05$).

Table 3.5 Effects of Rotation Management Systems on Soil Bulk Density

Rotation System	Soil Depth of Sampling (cm)			
	0-17	18-32	33-43	Means
	---------------------- g cm^{-3} ------------------			
Wheat-Soybean Rotation	1.11a[a]	1.23a	1.40a	1.24a
Wheat-Sweet Clover Rotation	0.98b	1.15b	1.37a	1.17a
Wheat-Soybean Rotation with Addition of Pig Manure	1.04a	1.23a	1.39a	1.22a
Wheat-Soybean Rotation with Addition of Wheat Straw	1.10a	1.21a	1.41a	1.24a
Means	1.06c[b]	1.21b	1.39a	

[a] Values followed by the same letter within each column for different treatments are not significantly different ($P \leq 0.05$).

[b] Values followed by the same letter within each row for different depths are not significantly different ($P \leq 0.05$).

Table 3.6 Effects of Rotation Management Systems on Soil Organic Carbon Quantity

Rotation System	Soil Depth of Sampling (cm)				
	0-17	18-32	33-43	Total Amount	Increase %†
	------------------ kg ha^{-1} -----------------				
Wheat-Soybean Rotation	50600c[a]	21800b	8800b	81300c	
Wheat-Sweet Clover Rotation	53600b	24100a	9600a	87300b	7.5
Wheat-Soybean Rotation with Addition of Pig Manure	58400ab	22900b	8700b	90000b	10.7
Wheat-Soybean Rotation with Addition of Wheat Straw	62300a	22000b	8800b	93100a	14.5
Means	56200a[b]	22700b	9000c		

[a] Values followed by the same letter within each column for different treatments are not significantly different ($P \leq 0.05$).

[b] Values followed by the same letter within each row for different depths are not significantly different ($P \leq 0.05$).

†Increase % is relative to SOC in the wheat-soybean rotation.

CHAPTER 4

EFFECTS OF LONG-TERM CONTINUOUS CROPPING, TILLAGE, AND FERTILIZATION ON SOIL ORGANIC CARBON AND NITROGEN CONTENTS IN CHINESE MOLLISOLS

Abstract

Cultivation and tillage practices alter soil properties and often lead to decline of soil quality. Adoption of appropriate agricultural management systems, however, may maintain soil productivity. This research examined the effects of long-term continuous cropping, tillage, and fertilization on soil organic carbon (C) and nitrogen (N) contents of black soils in China. Soil samples from 11-year tillage, 11-year continuous cropping, and 16-year fertilization experiments were analyzed. Soil organic carbon (SOC) and N declined with soil depth in all treatments. Compared with a wheat-corn-soybean rotation, continuous cropping of wheat, corn, or soybean reduced SOC and N contents, particularly SOC content. Continuous cropping of corn reduced SOC more than that of soybean or wheat in top soil layers. Moldboard plowing significantly reduced SOC and N contents whereas integrated tillage (i.e., moldboard plow for wheat, deep tillage (sub-soiling) for soybean, and rotary tillage for corn) increased SOC and N relative to conventional tillage. Use of chemical fertilizers (N, P, and K) along with return of crop residues resulted in a substantial increase in SOC and N in top layers of the soil. It is proposed that the best management for maintaining soil productivity in the study area would be crop rotation along with the integrated tillage and addition of crop residues and chemical fertilizers.

Introduction

Crop rotation, tillage, and fertilization are the most common practices in agricultural production altering soil properties such as nutrient status and soil organic carbon (SOC) content. These changes can affect availability of nutrients and soil productivity. Traditional cropping systems, tillage, and intensive monoculture with little organic matter return are considered as a worst-case scenario for SOC storage because of relatively low C inputs and promotion of organic matter decomposition (Busscher et al., 2000). Tillage accelerates organic C oxidation by improving soil aeration, increasing contact between soil and crop residues and exposing aggregate-protected organic matter to microbial attack (Beare et al., 1994). Long-term no-till systems accumulate nutrients in the soil surface, whereas moldboard and chisel plows distribute nutrients uniformly through the tillage depth due to soil mixing (Karlen et al., 1991). Crops grown in rotation often produce a higher quantity of plant dry matter than those grown in monoculture (Copeland and Crookston, 1992). For example, continuous cultivation of cereal crops showed substantial losses of SOC and N (Dalal and Henry, 1988; Campbell et al., 1991; Paustian et al., 1992). Several studies have indicated that management practices such as crop rotation and application of manure could lead to improved soil conditions, particularly with respect to increased organic matter contents (Tyler et al., 1983; Hill, 1990; Havlin et al., 1990). In addition, long-term studies have consistently demonstrated the benefit of application of manure, and adequate fertilization, and crop types for maintaining agronomic productivity by increasing organic C inputs into the soil (Reeves, 1997).

Black soils (Mollisol), the most fertile and productive soils in China, are distributed mainly in the Songnen Plain, Heilongjiang and Jilin Provinces of Northeast China, with a total acreage of 6 million ha and 4.4 million ha under cultivation. These areas contain 84 to188 Mg organic carbon ha^{-1} and thus can be a large source or sink of atmospheric CO_2 (Liu et al., 2003) depending on agricultural practices. However, intensive cultivation has led to deterioration of soil properties, SOC loss, and associated yield suppression. In this paper, we investigated the effects of long-term continuous cropping, tillage, and fertilization on soil organic C and N contents of those black soils.

Materials and Methods

The research was conducted on Hailun Agro-Ecological Experimental Station, Chinese Academy of Sciences, Heilongjiang Province, China. This station is one of the 29 key stations in Chinese Ecological Research Network Program, in which several long-term experiments were initiated. The research site (47°26′N, 126°38′E, altitude 240 m) is in the North Temperate Zone and Continental Monsoon Area (cold and arid in winter, hot and rainy in summer) and has an average annual temperature of 1.5 °C and a frost-free period of 124 days. The average annual precipitation is 530 mm with 65% in June, July and August. The soil in the area is a typical black soil with a moderate thickness (30 to 40 cm) of Mollic epipedon (i.e., A horizon). The texture of the black soils in the study area is silty clay loam or silty clay, each with about 40% clay. Soil pH determined in distilled water (1:5 V/V) was neutral (7.0±0.1). The detailed experiments are presented below.

- **Experiment I: Continuous Wheat, Corn or Soybean Cultivation**

Long-term experiment plots were established in 1991, with an initial purpose to assess the impact of continuous cropping on yield and quality decline of different crops. The main crops of the region, spring wheat, corn and soybean, were selected in this experiment, and a common used crop rotation, wheat-corn-soybean, was adopted as a standard treatment.

Plot size was 77 m^2 with 10 rows in each plot (row size was 0.7m x 11m). The experiment was a complete randomized block design with three replications. Four treatments were: a) wheat-corn-soybean rotation; b) continuous wheat; c) continuous corn; and d) continuous soybean. Chemical fertilizers were applied as follows: 84 kg diammonium phosphate $ha^{-1}$and 168 kg urea ha^{-1} in wheat; 150 kg di-ammonium phosphate ha^{-1} and 225 kg urea ha^{-1} (half as basal application and half as side-dressing) in corn; and 150 kg diammonium phosphate ha^{-1} in soybean. For all treatments, crop residues (straw) were removed after harvest, which is a normal practice by local farmers. Plots were tilled with a disc harrow for wheat at 18 cm and for soybean at 25 cm, and corn plots were not tilled. The field population was 5,000,000 plants ha^{-1} for wheat, 60,000 plants $ha^{-1}$for corn, and 300,000 plants $ha^{-1}$for soybean. Sowing, weed control, and harvesting were done by hand.

- **Experiment II: Soil Tillage Systems**

Soil tillage experiment plots also were established in 1991. All plots adopted the wheat-corn-soybean rotation but were treated with different tillage methods after harvest. Plot size was 336 m^2 (10m x 33.6m) with three replications. The detailed treatments are shown in Table 4.1.

- **Experiment III: Fertilization Systems**

This experiment was initiated in 1986. Four fertilization treatments were: a) control (no addition of fertilizers and manure); b) manure application (80% harvested grain was fed to pigs and straw was broken into small pieces and placed into the sty. The decomposed, mixed manure and residues were applied annually to the original plots where the grain and straw came from); c) chemical fertilizer application: nitrogen fertilizer at the N rate 127 kg ha^{-1} (urea) with P application at the rate of 120 kg ha^{-1}(superphosphate) and K at the rate of

60 kg ha^{-1} (potassium sulphate); d) combination of treatment b and c at their respective rates. Treatment c was considered as an optimum fertilizer management practice to maintain soil productivity in the area. The size of each plot was 22.4 m^2 (4 m x 5.6 m) with three replications. Crop rotation was wheat, corn, and soybean for all treatments. Nitrogen fertilizer (urea) was not used when soybean was planted in rotation. Soil samples were collected from five depths (0-15 cm, 16-30 cm, 31-50 cm, 51-70 cm and 71-90 cm) in each plot in October 2001. Crop residues were removed from the surface before the samples were taken. All samples (15 per plot at each depth) were mixed to form one composite soil sample. The composite samples were air-dried and sieved (2-mm) before analysis. Total soil organic C and N were measured by an elemental analyzer (Xing et al., 1994; Xing, 1997). Total microbial C of top soil in continuous cropping was determined by the chloroform fumigation method (Dalal et al., 1991). Experimental data were analyzed by analysis of variance, and Duncan's multiple range tests were performed using SAS software (SAS Institute, 1996).

Results and Discussion

Continuous Wheat, Corn or Soybean Cultivation

For all treatments, the contents of SOC and N declined with depth, which is normal and consistent with other studies (Xing and Dudas, 1992; Mikhailova et al., 2000), but decreased markedly below the 30 cm depth (Figures 4.1 and 4.2). The marked decline may be due to the plow depth, above which plowing could mix organic matter. The decline of SOC was greater than that of soil N. On average, N content at the 71 to 90 cm was 46% of that at the 0 to15 cm, and the carbon content was only 32% (Tables 4.2 and 4.3).

Crop types affected the decline of SOC and N in the soil profile. Relative to the rotation, continuous cropping of all three crops reduced soil C and N contents at all depths in the profile with an exception of N content in continuous wheat (Table 4.3). These results are similar to those reportedly by Mikhailova et al. (2000). Continuous wheat had the least impact on soil C and N contents. This result may be due to a relatively higher total microbial C in the soil for this crop. The total microbial C of topsoil layer was 533 mg kg^{-1} in continuous wheat and was 429 mg kg^{-1} in the crop rotation, but was only 350 mg kg^{-1} for continuous corn and 398 mg kg^{-1} for continuous soybean (Figure 4.3). Thus, continuous corn and soybean not only reduced SOC and N but also led to the decline of soil biological activity. Collins et al. (1992) also reported a greater amount of soil organic matter and soil microbial biomass in continuous wheat than in a wheat-fallow rotation after 58 year. Soil from continuous soybean had a greater decline in SOC and N contents at the 51 to 70 cm and 71 to 90 cm depths than other treatments. This effect may be due to the tap root system of soybean and to harmful impacts of continuous cropping on soybean root nodules and nitrogen fixation (Liu and Herbert, 2002). In regard to the average SOC and N contents of the five soil layers, 11-year continuous corn, soybean, and wheat resulted in 10%, 11% and 5.3% decline of SOC, respectively compared with the regular rotation; and continuous cropping resulted in a 6.5% decline for N in corn or soybean but no decline in wheat (Tables 4.2 and 4.3). These results indicate that if continuous corn, soybean, or wheat is to be adopted, an average annual decline rate of soil carbon in the 0 to 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. Other research has shown that a decline in SOC significantly reduced the N supply and resulted in deterioration of soil physical conditions (Stevenson, 1994). Therefore, it is important to maintain proper levels of SOC by crop rotation, as it may potentially provide more available soil N through increases in SOC and microbial biomass. The reason for microbial biomass increase by continuous wheat is not clear.

- **Soil Tillage Experiments**

For all tillage treatments, profile distributions of SOC and N content (i.e., declining with depth) were similar to that of continuous cropping (Tables 4.4 and 4.5). After 11 year of different tillage operations, integrated tillage had the highest levels of SOC and N in the upper soil layer (Figures 4.4 and 4.5). Moldboard plowing had the lowest level for the average SOC and N contents in the profile, with the largest reduction being in the top two layers (Tables 4.4 and 4.5). The soil C and N contents at 16 to 30 cm in the rotary plowing and conventional tillage were higher than in the 0 to 15 cm depth, indicating that more root residues possibly were incorporated into this layer. This result is consistent with mixing of organic matter by plowing but opposite to the results with no-tillage practice or conservation tillage (Dalal et al., 1991; Arshad et al., 1990; Ding et al., 2002). Conservation tillage tends to accumulate SOC at soil surface due to lack of mixing. Although the profile average contents of soil C and N were relatively high in conventional tillage, the contents at the 0 to 15 cm depth were low. Overall, integrated tillage appears effective to maintain SOC and, maybe, soil productivity (Figures 4.4 and 4.5). It has been suggested that soil organic matter is the heart to sustaining agricultural productivity (Reeves, 1997).

- **Fertilization Experiments**

Again, SOC and N declined with depth as for the cropping and tillage experiments (Figures 4.6 and 4.7). After 16 yr of different fertilization treatments in the crop rotation, the profile average SOC content (0 to 90 cm) was only 0.9%, 4.1%, and 8.6% higher for manure, chemical fertilizers, and manure plus fertilizers, respectively, compared to no fertilizer application or control (Table 4.6). However, SOC at the 0 to 15 cm soil layer was 6.2%, 7.7%, and 9.3 % greater from manure, chemical fertilizers, and manure plus fertilizers, respectively, than with no fertilizer application. These results indicate that the annual decline rate of soil C at the 0 to 15 cm without fertilizer was not very high (<0.58%/year) when the crop rotation was used. These results are in line with the data from some 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 Johnston, 1997).

Manure alone did not increase the N content in the soil profile compared to that of no fertilizer application in the crop rotation (Figure 4.7). Chemical fertilizers and manure plus fertilizers significantly increased N contents, especially at the 0 to 15 cm and 16 to 30 cm soil layers (Table 4.7). Francioso et al. (2000) also reported that SOC and N differed significantly after 22 yr for all their treatments, where the amendments with cattle manure markedly increased the SOC and N contents while with the 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 yr. This long-term experiment further indicated that crop rotation did play an important role in maintaining soil fertility and that crop residue alone could not maintain SOC levels obtained in no-tillage soils. Similar result was reported by Bruce et al. (1995). Reeves (1997) suggested that soil organic matter can be preserved only by ley rotations with reduced tillage frequency. Our results fully support this conclusion. Additions of chemical fertilizers or manure were essential to soil sustainability if tillage is employed.

Conclusions

In general, soil C and N contents decreased with soil depth regardless of treatments but were concentrated near the soil surface (0-30 cm). For continuous cropping, all crops (wheat, corn, and soybean) significantly reduced SOC compared to the crop rotation for all horizons examined. Continuous wheat had the least impact on SOC and N. For tillage experiments, integrated tillage (Tables 4.4 and 4.5) showed higher SOC and N contents, particularly at the surface layer (0-15 cm). For the fertilizer treatments, manure plus chemical fertilizers provided the highest level of SOC and N. Crop rotation alone could not maintain SOC and N levels. We conclude that long-term crop rotation with integrated tillage and additions of manure and chemical fertilizers appears to be a viable method for maintaining SOC and N contents and improving soil quality in the study area.

Table 4.1 Methods of Soil Tillage after Harvest for Each Crop during the Rotation

Methods	Wheat	Corn	Soybean
Conventional Tillage	Moldboard plowed to a depth of 20 cm, disked and harrowed, and ridges formed	No plowing	Disked and harrowed, and then the soil leveled
Moldboard Plowing	Moldboard plowed to a depth of 20 cm, disked and harrowed, and ridges formed	Moldboard plowed to a depth of 20 cm, disked and harrowed, and ridges formed	Moldboard plowed to a depth of 20 cm, disked and harrowed, and field leveled
Rotary Plowing	Rotary plowed to a depth of 5 cm and ridges formed	Rotary plowed to a depth of 5 cm and ridges formed	Rotary plowed to a depth of 5 cm and field leveled
Deep Tillage	Harrowed, and then deep chisel plowed to loosen the soil to a depth of 28 cm, and ridges formed	Deep chisel plowed to loosen the furrow to a depth of 28 cm, while keeping the ridge unchanged	Harrowed, and then deep chisel plowed to loosen the soil to a depth of 28 cm, and field leveled
Integrated Tillage	Moldboard plowed to a depth of 20 cm, disked and harrowed, and ridges formed	Deep chisel plowed to loosen the furrow to a depth of 28 cm, while keeping the ridge unchanged	Rotary plowed to a depth of 5 cm and field was leveled

Table 4.2 Effects of Continuous Cropping on Soil Organic Carbon in the Profile

Cropping System	Depth in soil profile (cm) 0-15	16-30	31-50	51-70	71-90	Mean
	----------g kg^{-1}					----------
Crop Rotation	29.86a[a]	27.12a	18.18a	12.76a	9.38a	19.46a
Continuous Wheat	27.36b	26.48b	17.07b	12.08b	9.09b	18.42b
Continuous Corn	25.54d	24.91c	16.54c	12.14b	8.35c	17.50c
Continuous Soybean	26.17c	25.10c	17.23b	10.82c	7.53d	17.37c
Mean	27.23a[b]	25.90b	17.26c	11.95d	8.59e	

[a] Values followed by the same letter within each column for different treatments are not significantly different ($P \leq 0.05$).

[b] Values followed by the same letter within each row for different depths are not significantly different ($P \leq 0.05$).

Table 4.3 Effects of Continuous Cropping on Soil Nitrogen in the Profile

Cropping System	Depth in soil profile (cm)					
	0-15	16-30	31-50	51-70	71-90	Mean
	---------- g kg^{-1} ----------					
Crop Rotation	2.63a[a]	2.41ab	1.75a	1.36a	1.15a	1.86a
Continuous Wheat	2.58a	2.54a	1.77a	1.39a	1.18a	1.89a
Continuous Corn	2.31c	2.30b	1.60b	1.27b	1.20a	1.74b
Continuous Soybean	2.45b	2.30b	1.69ab	1.20b	1.00b	1.73b
Mean	2.49a[b]	2.39b	1.70c	1.31d	1.13e	

[a] Values followed by the same letter within each column for different treatments are not significantly different ($P \leq 0.05$).

[b] Values followed by the same letter within each row for different depths are not significantly different ($P \leq 0.05$).

Table 4.4 Effects of Different Tillage Methods on Soil Organic Carbon in the Profile

Tillage Methods	Depth in soil profile (cm)					
	0-15	16-30	31-50	51-70	71-90	Mean
	$g\ kg^{-1}$					
Conventional Tillage	24.81c[a]	26.57c	16.39a	11.35a	7.46a	17.32a
Moldboard Tillage	22.39e	21.94e	15.03c	8.47c	7.80b	15.13b
Rotary Tillage	24.55d	27.91a	15.18b	8.61d	7.41c	16.73ab
Deep Tillage	25.39b	25.12d	13.50e	9.30c	7.28d	16.12b
Integrated Tillage	27.69a	27.60b	14.29d	10.74b	8.40a	17.74a
Mean	24.97a[b]	25.83a	14.88b	9.69c	7.67d	

[a] Values followed by the same letter within each column for different treatments are not significantly different ($P \leq 0.05$).

[b] Values followed by the same letter within each row for different depths are not significantly different ($P \leq 0.05$).

Table 4.5 Effects of Different Tillage Methods on Soil Nitrogen in the Profile

Tillage Methods	Depth in soil profile (cm)					
	0-15	16-30	31-50	51-70	71-90	Mean
	---------------------------------- g kg^{-1} ---------------------------					
Conventional Tillage	2.33b[a]	2.55b	1.70a	1.32a	1.08ab	1.80a
Moldboard Tillage	2.10c	2.09d	1.61b	1.15b	1.07b	1.60e
Rotary Tillage	2.37ab	2.41b	1.51c	1.18b	1.08ab	1.71c
Deep Tillage	2.36b	2.25c	1.49c	1.19b	1.13a	1.68d
Integrated Tillage	2.42a	2.37b	1.48c	1.29a	1.13a	1.74b
Mean	2.32a[b]	2.33a	1.56b	1.23c	1.10d	

[a] Values followed by the same letter within each column for different treatments are not significantly different ($P \leq 0.05$).

[b] Values followed by the same letter within each row for different depths are not significantly different ($P \leq 0.05$).

Table 4.6 Effects of Fertilization Systems on Soil Organic Carbon in the Profile

Fertilization System	Depth in soil profile (cm)					
	0-15	16-30	31-50	51-70	71-90	Mean
	------------------------------ g kg^{-1} ------------------------------					
No Fertilizers	30.35d[a]	28.29c	20.99a	11.29d	7.69c	19.72c
Manure Application	32.33c	28.51c	17.99c	12.51b	8.26b	19.90c
Chemical Fertilizers	32.70b	30.79b	18.42b	11.66c	9.05a	20.82b
Manure + Fertilizers	33.17a	32.69a	18.37b	13.79a	9.02a	21.41a
Mean	32.11a[b]	30.07a	18.94b	12.31c	8.51d	

[a] Values followed by the same letter within each column for different treatments are not significantly different ($P \leq 0.05$).

[b] Values followed by the same letter within each row for different depths are not significantly different ($P \leq 0.05$).

Table 4.7 Effects of Fertilization Systems on Soil Nitrogen in the Profile

Fertilization System	Depth in soil profile (cm)					
	0-15	16-30	31-50	51-70	71-90	Mean
	---------- g kg^{-1} ----------					
No Fertilizers	2.65b[a]	2.51b	2.02a	1.26b	1.07b	1.90b
Manure Application	2.65b	2.54b	1.73c	1.43a	1.06b	1.88b
Chemical Fertilizers	2.92a	2.77a	1.83b	1.29b	1.18a	2.00a
Manure + Fertilizers	2.86a	2.87a	1.82bc	1.46a	1.11b	2.02a
Mean	2.76a[b]	2.67a	1.85b	1.36c	1.11d	

[a] Values followed by the same letter within each column for different treatments are not significantly different ($P \leq 0.05$).

[b] Values followed by the same letter within each row for different depths are not significantly different ($P \leq 0.05$).

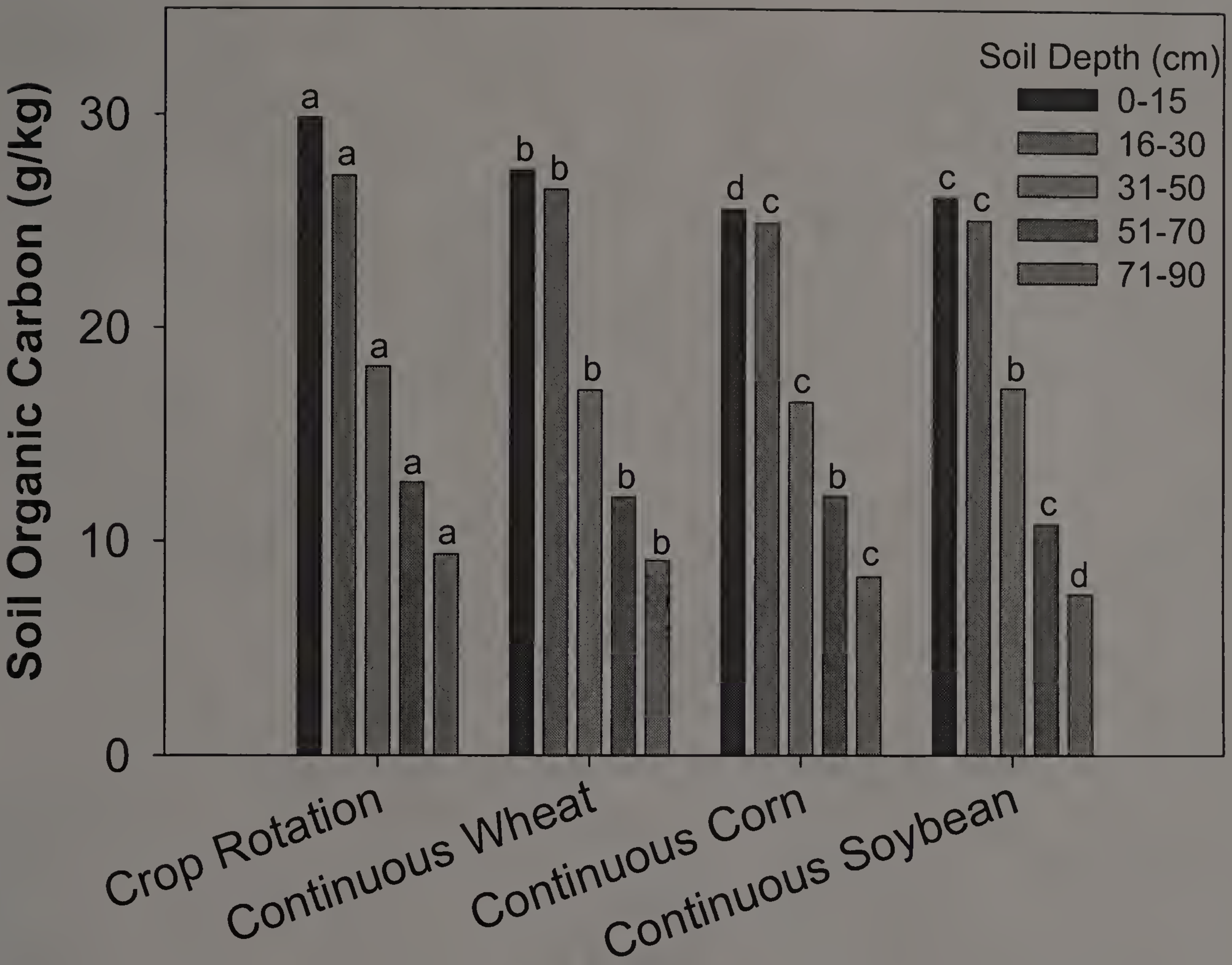

Figure 4.1 Effects of Continuous Cropping on Soil Organic Carbon in the Profile
Means followed by the same letter in the same soil depth
are not significantly different ($P \leq 0.05$).

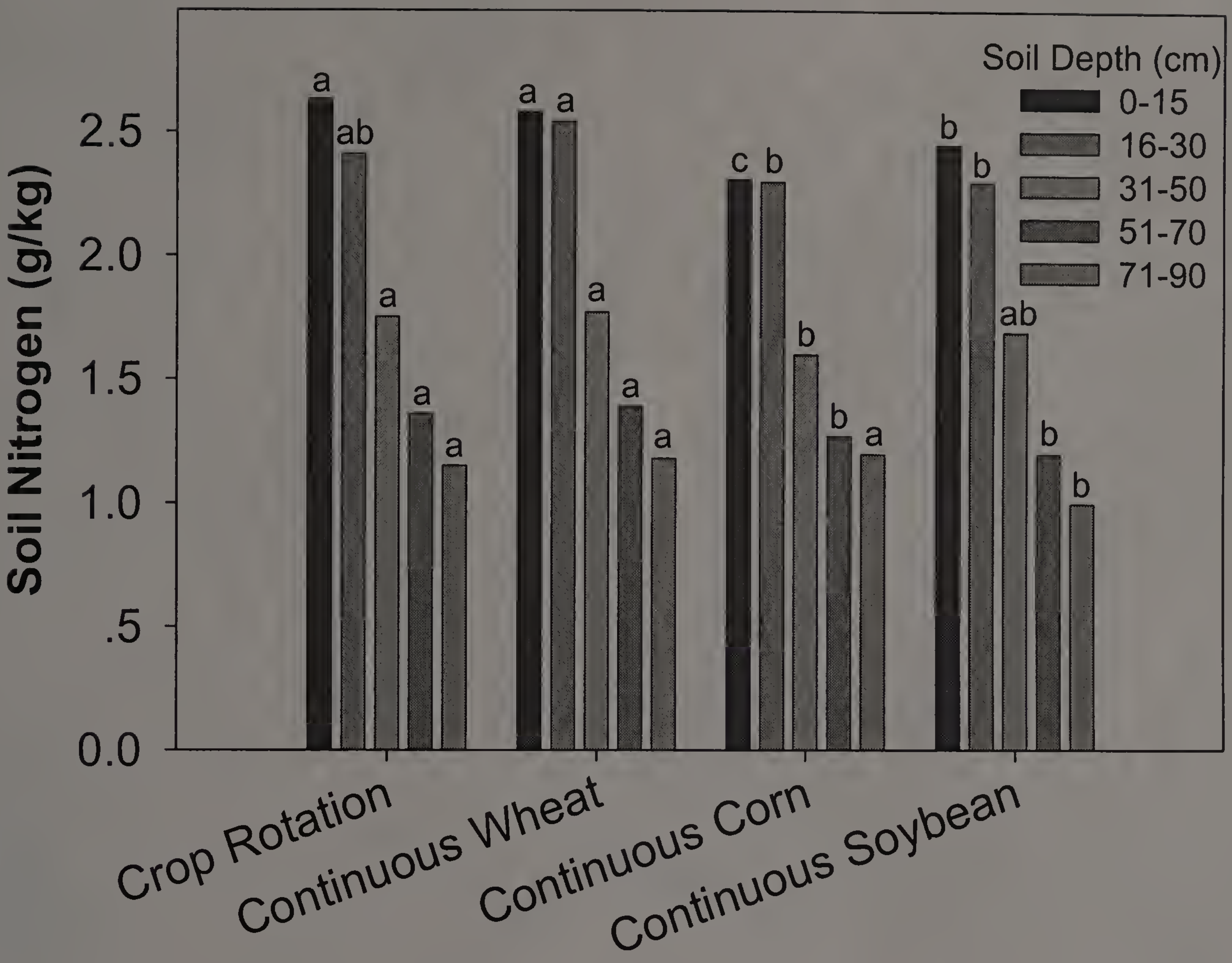

Figure 4.2 Effects of Continuous Cropping on Soil Organic Nitrogen in the Profile
Means followed by the same letter in the same soil depth
are not significantly different ($P \leq 0.05$).

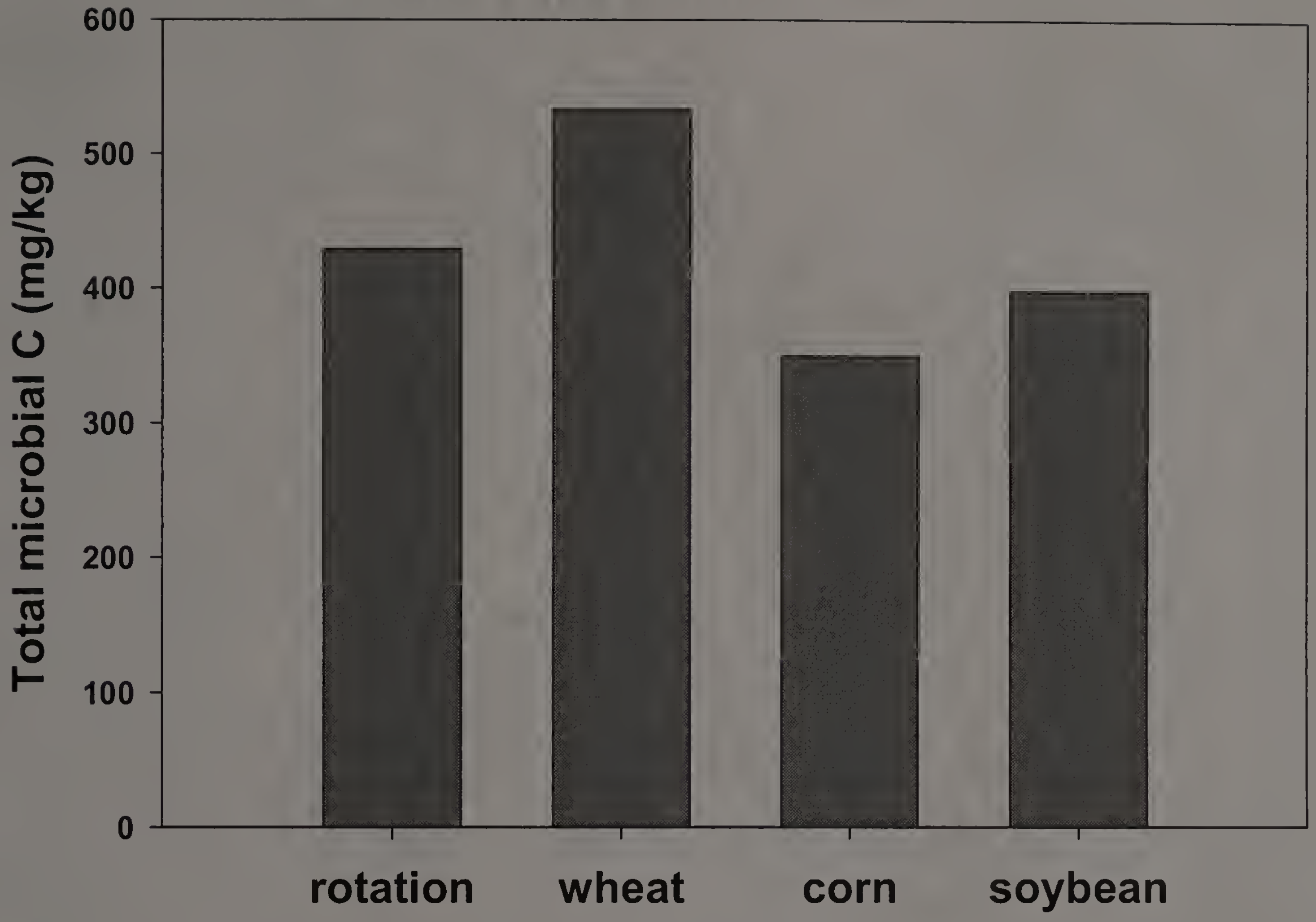

Figure 4.3 Effects of Continuous Cropping on Total Microbial C over a 11-Year Period

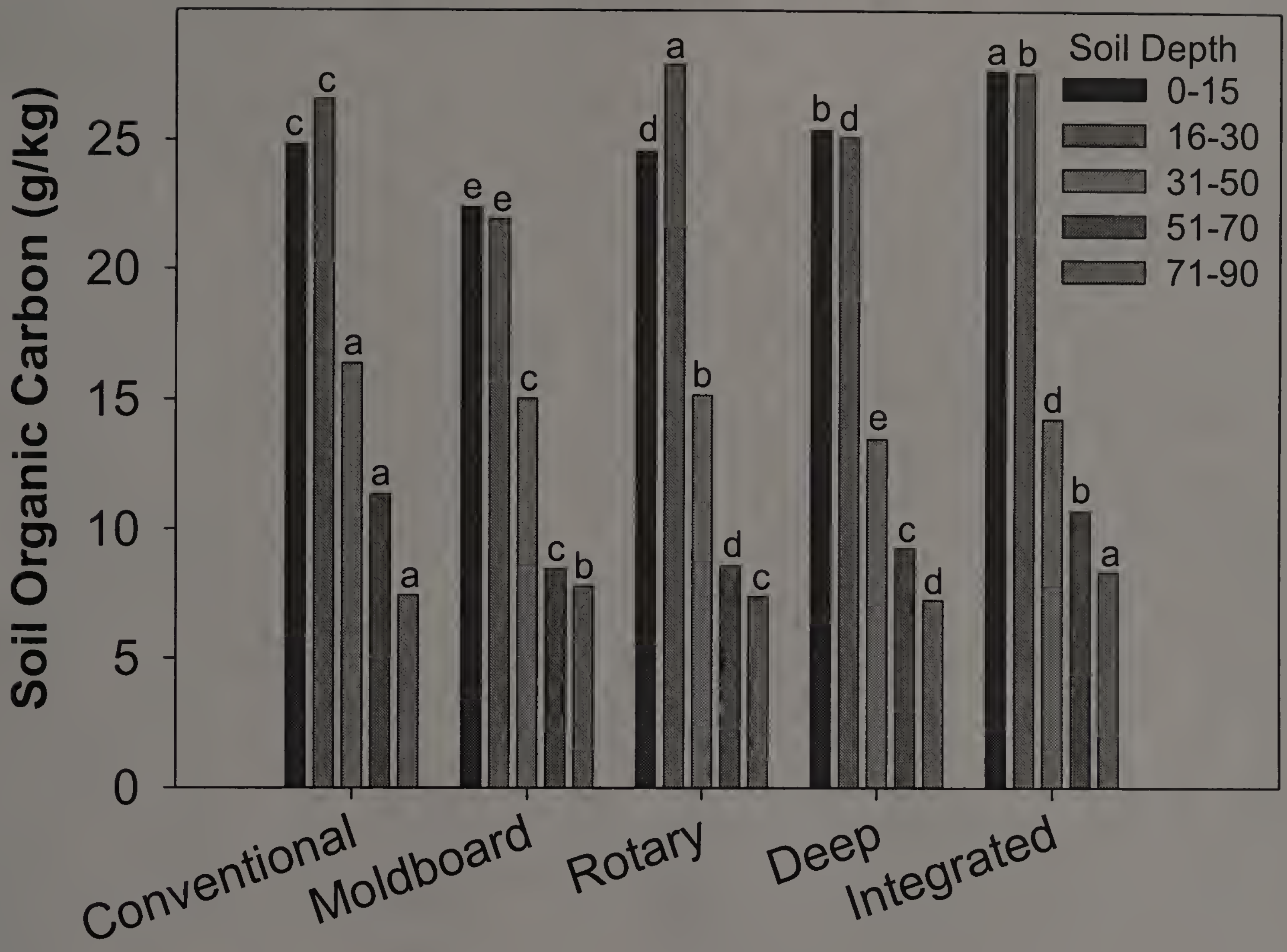

Figure 4.4 Effects of Different Tillage on Soil Organic Carbon in the Profile Means followed by the same letter in the same soil depth are not significantly different ($P \leq 0.05$).

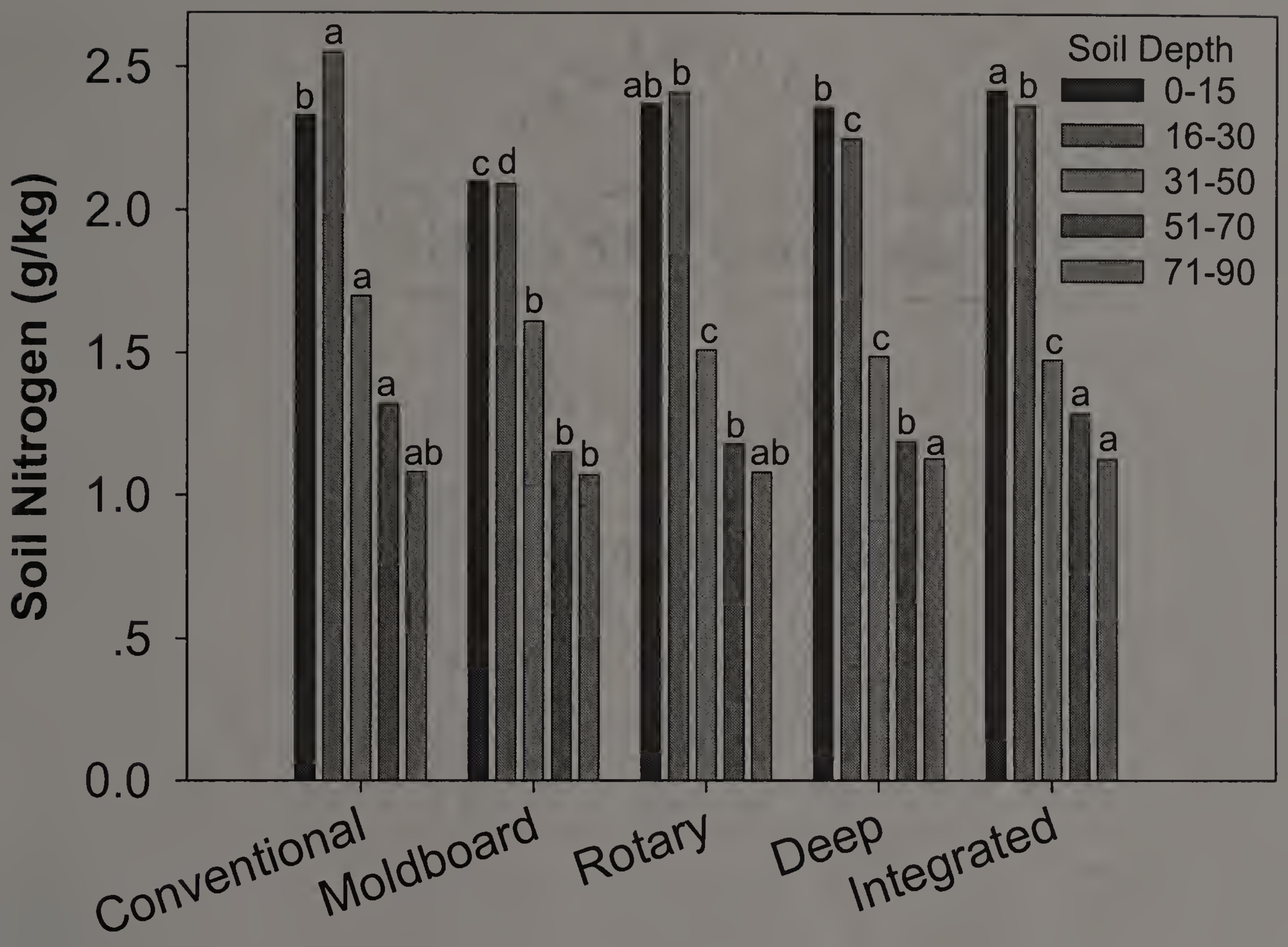

Figure 4.5 Effects of Different Tillage on Soil Organic Nitrogen in the Profile
Means followed by the same letter in the same soil depth
are not significantly different ($P \leq 0.05$).

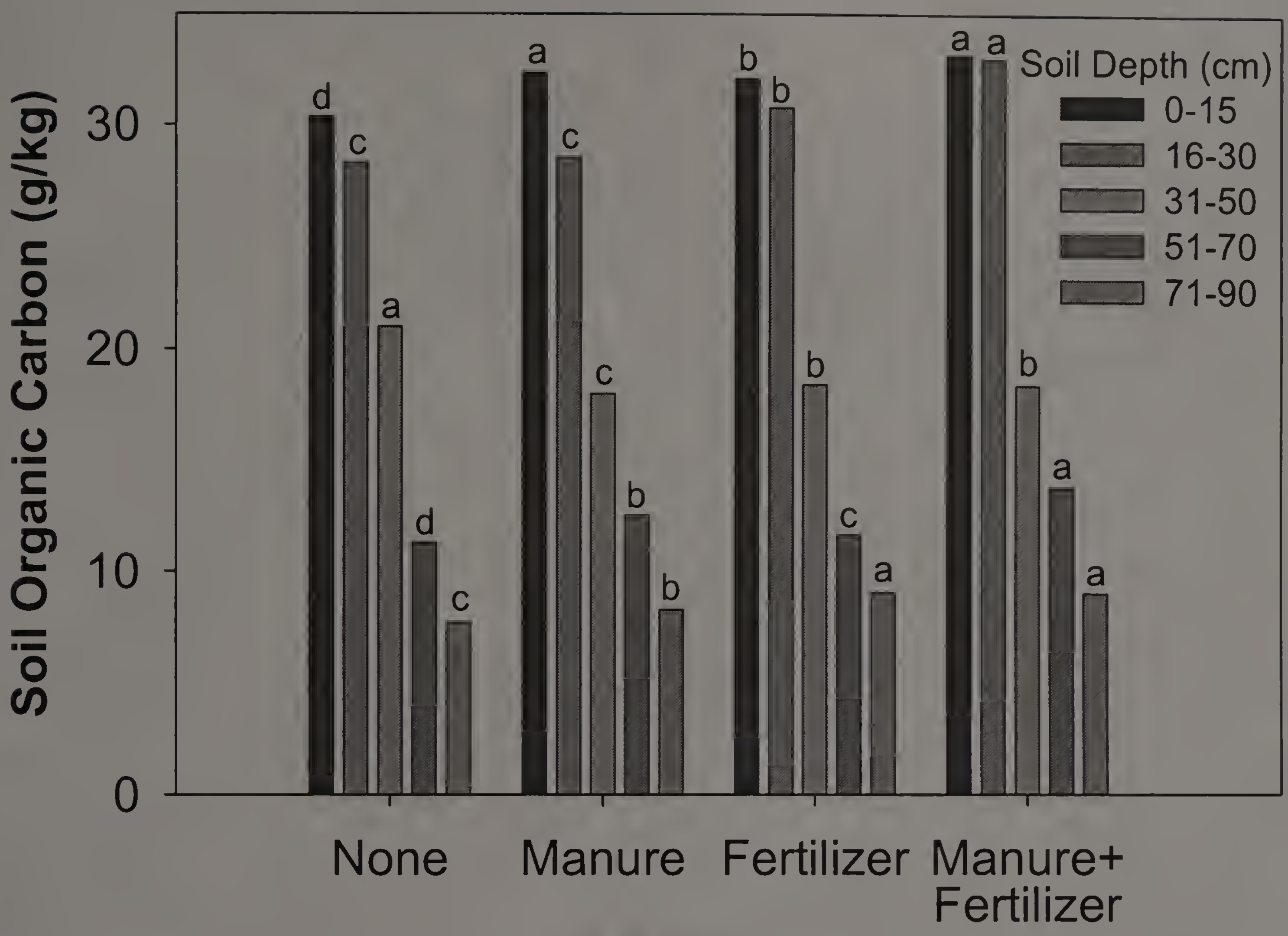

Figure 4.6 Effects of Fertilization Systems on Soil Organic Carbon in the Profile
Means followed by the same letter in the same soil depth
are not significantly different ($P \leq 0.05$).

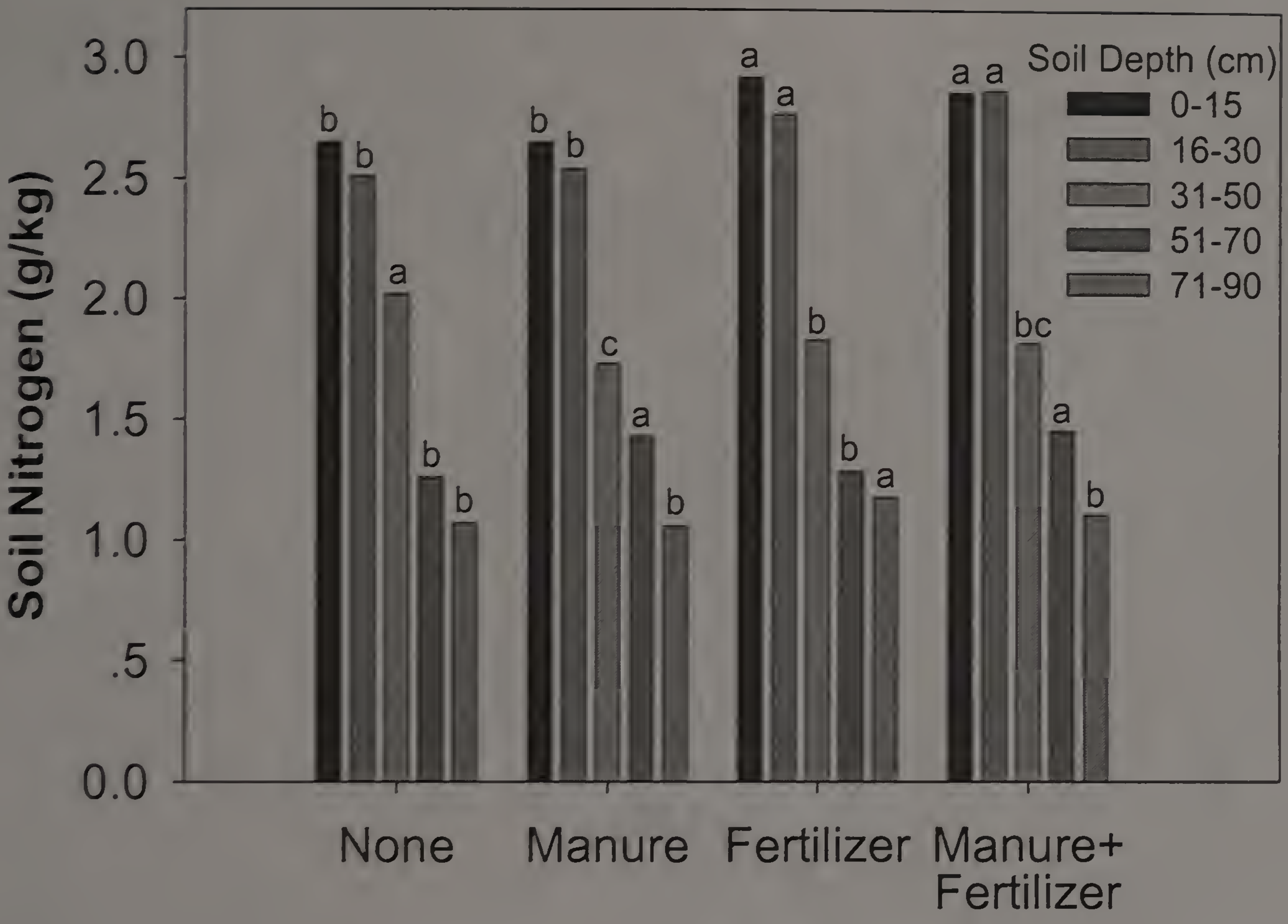

Figure 4.7 Effects of Fertilization Systems on Soil Organic Nitrogen in the Profile
Means followed by the same letter in the same soil depth
are not significantly different ($P \leq 0.05$).

CHAPTER 5

EFFECTS OF CONTINUOUS SOYBEAN ON SOIL CHATACTERISTICS AND CROP PRODUCTIVITY IN NORTHEAST CHINA

Abstract

Soybean is the main crop in Northeast China. The sown acreage and total yield now account for 33% and 44%, respectively of the nation's total production. Continuous soybean is the main practice used by farmers in the region because of relatively higher economic benefits, farmers' preferences and natural agro-ecological conditions suited for the culture of this crop. However, continuous culture of soybean may result in yield decline and quality deterioration. This paper firstly reviews aspects of research on continuous soybean cropping for soybean biology and yield in Northeast China. Growth and development, including changes of root nodule number and LAI are described, and reduction in yield and seed quality is discussed. The effects on physiological and biochemical processes are reviewed, and roles of root diseases, insect pests, and root exudates or plant residuals are discussed. Our results on changes of soil rhizosphere microbes, some enzymes and soil properties are presented. Finally, farm practices for alleviating effects on yield reduction are provided, and a diagram of the interaction among factors involved in continuous soybean yield reduction is presented.

Introduction

Soybean is one of the main crops in Northeast China. Since the early 1980's, farmers' interest in growing soybean in the Northeast has increased dramatically, where sown acreage and total yield now accounting for 33% and 44% respectively of the nation's total. There are several reasons leading farmers to plant soybean in this region, higher economic benefit, farmers' preferences for growing this crop, and natural agro-ecological conditions suited to soybean culture. For instance, in some areas farmers have no other crop choice since the soil in early spring is often too wet or waterlogged, for early seeding of alternative crops such as spring wheat. On these marginal or poorly drained soils a normal crop rotation cannot be carried out. It is well known that continuous culture of soybean results in yield decline and quality deterioration. The reasons for this are not fully clear. This paper is a summary of research results during the past fifteen years on soybean biology and soil quality changes under continuous soybean production.

Growth and development

The visible effects of continuous soybean (CS) on growth are short stature, yellowing of leaves, reduced root development at the seedling stage, and reduction of plant source activity at middle section of the plant caused by poor canopy development (Liu et al., 1990). Xu et al. (1995, 1999) compared a long-term fixed rotation with continuous cropped plots, and found that leaf area index (LAI) in three-year, two-year and one-year CS were lower than that of normal rotation soybean (NRS), with most reduction in the three-year CS. Plant height and biomass and/or dry matter accumulation of CS soybeans were also reduced compared with NRS, the effects becoming more obvious after flowering stage. The biomass accumulation rates calculated by a logistic equation for NRS, one-year, two-year CS and three-year CS were 0.79g plant^{-1}day^{-1}, 0.57g plant^{-1}day^{-1} and 0.50g plant^{-1}day^{-1}, respectively. The ratio of grain yield to maximum leaf area (used as a measure of productivity) presented the same trend, i.e. the ratio of NRS, one-year CS, two-year CS and three-year CS were 11.99g m^{-2}, 8.152 g m^{-2} and 7.89 g m^{-2} respectively (Zhang et al., 1996).

The main characteristics of poor and under-developed root growth caused by CS were reduction of fibrous branching roots, cortex ageing and decline of root nodule number (Liu et al., 1990). The average reduction in number of effective nodules was 13.4-20.5 per plant and 18.9-23.2 per plant in one-year CS and three-year CS compared to NRS (Xu et al., 1995). Wang et al.(1995a,1995b) found that CS root tap dry matter was 10.3% and 23.9% less in three-year CS and four-year CS respectively compared to NRS. However, the aboveground dry matter was 22.6% and 28.1% less than that of NRS, resulting in an increase in the root/shoot ratio. Dong et al. (1999) also indicated that root dry matter declined in CS as did root density. Zhang et al. (1996) found that CS influenced the reproductive development, and flower shedding was 121.5% and 135.5% higher in two-year CS and three-year CS respectively compared to NRS, and pod shedding was 103.2% and 114.3% respectively more than NRS. These results indicate that not only vegetative growth but also reproductive development is strongly affected by continuous cropping of soybean.

Yield and quality

Experiments conducted in five ecological regions showed that soybean yield was significantly decreased by CS, the degree of yield decline depending on cultivar, soil type and seasonal conditions (Zheng, 1999; Liu and Yu, 2000). When grown in a two-year continuous cropping field, the cv. Hefeng 35 yielded 2978 kg/ha, which was 12.8% higher than that of a local variety Hefeng 25 (Yang, 1997). Yield data from Hailun Agro-Ecological

Experiment Station, CAS from 1992 to 1998 showed the longer the period of CS, the greater the yield reduction (Xu et al., 1999). Liu and Yu (2000) indicated that the average yield reduction below that of NRS in one-year CS, two-year CS and three-year CS across different regions and years was 9.9%, 13.8% and 19% respectively (Table 5.1). However, Xu et al. (1999) showed that yield reduction of one-year CS and two-year CS was 18.6% and 35.4% respectively compared with NRS, indicating severity of the problem.

Analysis of yield components over the years of CS found the reduction in yield was mainly due to a decrease of pod and seed number per plant, and there was almost no influence on seed number per pod and weight per seed. However, when the CS extended over four years, seed size tended to become smaller (Liu et al., 1990; Zhang et al., 1996; Liu and Yu, 2000). Besides the negative effects on yield, CS also resulted in a significant increase in diseased and pest infected seeds, leading to poor seed commodity quality. The main seed diseases of CS were *Cerospora sojina, Peronospora manschurica*, *Cercospora kikuchii.* Soybean mosaic virus and *Leguminivora glycinivorella* (Liu and Yu, 2000; Xu et al., 1999). Short-term CS had no influence on soybean seed protein and oil content. But, after four-years, CS protein content increased and oil content decreased (Xu et al., 1997). These results show that both yield and seed quality are adversely affected by CS, but yield suffering most.

Changes of physiological and biochemical properties

Research found that permeability of lipid membrane, relative conductivity of ions, malondialdehyde and proline content were all increased in CS leaves, and superoxide dismutase (SOD), catalase activities and chlorophyll-a and chlorophyll-b contents were reduced. Lipid peroxidation was enhanced (Zhao et al., 1998), indicating that the cell and lipid membranes were damaged (Luo et al., 1999). Liu et al. (1997) compared the activity of glutathione peroxidase in two soybean cultivars differing in CS tolerance and found that the activity from the leaves of a resistant cultivar was much higher than that of a susceptible cultivar. Zheng et al. (1995) found rise of phenol content in CS roots, and proposed the response is an active self-protection reaction. Generally, the total sugar content in NRS roots is higher than that of CS, showing more assimilate transport and partitioning to root in NRS (Jia and Yu, 1995). Pot and field plot research show that plant P and K content in CS declined dramatically, Zn, Mo, B contents also decreased, but there was no significant change in N content (Han and Xu, 1996; Han and Xu, 1997). Liu et al. (1997) found that CS increased Ca absorption in soybean grown on a calcareous chernozem, but decreased P, K, Fe and Mn contents, resulting in an imbalance of K/Ca and decline of lipid membrane plasticity. The changes of these physiological and biochemical properties show that CS plants have to adapt by active changes to the stress environment resulting from continuous cropping.

Changes of soil properties

Liu et al. (1990) reported the declines of soil pH and of phosphatase, urease, invertase activities, but increase of sucrase and dehydrogenase activities in CS soil (Figure 5.1), and proposed that some acid compounds were deposited in CS soil, and the deterioration of soil biological activity contributed to the changes of SOC and available macronutrients (Table 5.2). Fu and Yang (1999) reaffirmed these results in their five-years of observation. Soil poly-phenol oxidase activity is an enzyme involved in the formation of organic matter. Research found that its activity was reduced in CS and resulted in the rise in soil phenol content (Jia and Yu, 1995). Jia and Yu (1995) further found a decline of polysaccharide concentration and aggregates in CS soil, and proposed that soil fertility might be affected by those changes.

Previous research proposed that the main reasons caused CS yield decline was single nutrient deficiency (Wang, 1963). Liu et al. (1990) supported this assumption through production studies. Our three-location investigation on soil properties found that after several year's continuous cropping in soybean, SOC declined dramatically. Besides, total K, available N, K and total Zn contents declined as well, but total N and P remained no change (Table 5.2). Gu et al. (1999) reported that not only the total N, P, K but also available N, P, K declined with the increase of CS years. However, soil nutrient monitoring in a long-term fixed plots shows that there was no significant change for total N, P, K and available N, P, K, and there was also no appreciable change for the microelements such as Zn, Mn and B in CS soil compared with NRS soil (Han and Xu, 1996). Han et al. (1998) even found an increase in Zn and Mn content in CS soil. Our research indicated that CS influenced soil organic-inorganic complex and soil structure, and that water stable aggregates were damaged in this system. Yin et al. (1996) reported a decline in the amount of total microbial C at flowering in CS. Ji (1995) found that there was a great difference between water content of the CS and NRS plants during the growing season, proposing that water is the main factor influencing CS yield. Han and Xu (1997) did not however find this result. Zuo et al. (1997) indicated that water stress has a great negative effect on soybean yield than does continuous cropping. CS has complex influence on the soil properties, and it appears that there is no consistent basis for this for different soils.

Changes in the micro-organisms in the rhizosphere

There are three groups of microbes in the soil rhizosphere fungi, bacteria and actinomyces. Yu et al. (1988) and Liu et al. (1990) examined changes of these in CS. They showed that the number of bacteria in CS was significantly lower than in NRS, whereas fungi were more numerous, resulting in a decline of bacteria/fungi ratio, which imbalances the microbe of NRS and may cause the soil fertility to decline (Table 5.3). The changes of microbe number may be closely related to the change of soil pH during several years' culture of soybean as indicated in Table 5.2, because bacteria favor nearly neutral or slightly alkaline conditions, whereas fungi favor more acid conditions (Gliessman, 1998). A higher bacteria/fungi ratio is consistent with higher soil fertility, whereas a lower ratio favoring fungi is consistent with a low fertility soil. Xu et al. (1995) analyzed the dynamics of fungi during CS growth seasons, founding that the numbers of fungi in one-year CS and three-year CS were respectively 3.2%-21.8%, 18.0%-35.5% more than in NRS. Among the fungi, *Penicillium* and *Botriyis* were dominant. *Rhizoctonia* was found in CS soil, but not in NRS. Wang et al. (1989) also identified *Fusarium* and *Penicillium* as dominant fungi in CS. Hu et al. (1996) analyzed microbial communities in CS soil and reported the occurrence of *Penicillium purpurogenum*. Soybean is known to be inhibited strongly by *P. purpurogenum*. An inoculation experiment with crude crystals extracted from *P. purpurogenum* injured the root system in 5μg ml^{-1} solution, and primary roots were severely necrosised and secondary roots were almost stunted by higher concentrations. A 200μg ml^{-1} solution resulted in the death of seedlings within two weeks. Up to now, the three dominant fungi identified from CS rhizosphere soil are *Fusarium oxysporum, Gliocladium roscum* and *Fusarium semitectum*, and all of which infected soybeans and inhibited growth to some extent. The increase and influence of fungi in the CS soil rhizosphere demonstrates that CS is not sustainable unless countermeasures are taken to deal with the increase.

Changes of root diseases/ pest insects and biotic factors

The main diseases and pest insects in CS plants are soybean cyst nematode (*Heterodera glucines*), root rot (*Pythium* spp., *Fusarium* spp., *Rhizoctonia* spp.) and root flies (*Ophimyia shibatsuj kata*). Their infection or attack results in root rot, less fibrous root branching, fewer nodules and lower nitrogen fixation. Xu and Wang (1995) found in pot experiments that CS seedlings grow normally in sterilized soil, without any sign of growth inhibition. Yield in sterilized soil was much higher than that of control and thus they proposed that the main reason for CS yield decline was the effects of diseases and insect pests. Han and Xu (1997) supported this view in terms of less nutrient uptake caused by root system diseases.

Soybean root left in the soil after harvest could provide crop nutrients after decomposition. However, the residual could also inhibit successive soybean growth. Wang et al. (1995a) found that an extract of decomposed root material, watered to pots, inhibited germination of soybean seed and strongly inhibited growth. The allelopathy phenomenon, from application of extracted root residual, affected soybean seedling roots through inhibition of radicle elongation (Wang et al., 1995b). They identified the extracts as being in three groups with an inhibition ranking of acid components>neutral components>saline components, and the inhibition rate being 37.8%, 32.3% and 29.5% respectively. Han et al. (1999) reported that the water-extracted solution (0.05 dry weight ml^{-1}, 0.10 dry weight ml^{-1}) from aboveground plant soybean fractions during the flowering to pod-setting stage, also inhibits seed germination. Yan et al. (1998) indicated that water and ethanol-extracted CS soil solutions all strongly inhibit seed germination. Han et al. (1999, 2000) isolated many root exudates from soybean, including acids, acetone, aldehydes, phenols, esters, benzene and hydrocarbons, and found that only those exudates extracted from two-week old seedlings have inhibitory effects on soybean seed germination. These results show that allelopathy strongly exists in soybean, and further in-depth research of the allelopathy phenomenon could contribute to a better understanding of the mechanism of yield decline in CS.

Interactions affecting continuous soybean

Based on previous research and our investigation, it has shown no single reason for the yield decline with continuous cropping. Rather, it has revealed many varied biological and physiological process being involved and has suggests many possible interactions among these processes. Few of these have been investigated. Figure 5.1 is a proposal to illustrate the complexity of the interactions among factors involved. However, the toxicity of plant residual and root exudates, root diseases and insect pest and change of rhizosphere microbes are three key reasons for the yield decline.

Countermeasures for continuous soybean

Since situations do not permit crop rotation, measures are required to offset the decline accompanying continuous cropping.

- **Adoption of resistant or tolerant cultivars**

The most economical and simplest way to adapt to the CS environment, is to grow resistant cultivars. Those are the nematode cyst-tolerant cultivars, No.1, No.2 and No.3, which have produced well in severely cyst nematode infested areas (Li, 1988). Other cultivars tolerant of the CS environment Hefeng 35, Hefeng 36, Kennong 7, Nenfeng 14, Heinong 37, Heinong 39 and Suinong 14 could be used with knowledge of their suitability to local conditions (Yang, 1997).

- **Control of disease and pest insects**

Main diseases are soil-born diseases for continuous soybean. Therefore, the application of adapted varieties, seed coating with fungicides and insecticides application at seeding time is required. Further, in order to maintain soybean commercial seed quality, control of other diseases occurring at later stages of growth such as leaf frog eye may be needed (Xu et al., 2000).

- **Application of P, K fertilizer, and supplement of trace elements**

Due to imbalance in nutrient absorption, deteriorated soil condition and poor root development, the application of P and K fertilizers and some trace elements (Zn, Mn, Mo, B) have been found as a way to alleviate yield decline. Trace elements could be applied either at seeding time or as a foliar spay at later stage of growth (Yu et al., 1993; Liu et al., 1992; Xu and Wang, 1995). Zhao et al. (1998) found a single application of K_2SO_4 at seeding increased CS yield by 14.1% and application of Se caused 12.9-14.5% increase in yield (Luo et al., 1999).

- **Use of suitable tillage practices**

China's soybean crop is mostly grown on permanent ridges, and ridge planting results in greater yield losses. The use of plowing, rotary tillage, deep-loosening, or creating a new ridge could help break the negative effects of CS, reduce sources of pathogens, weeds and insect pests, and stimulate root growth and development. Research has shown that these measures could increase the yield by 13.8%-44.1% (He et al., 1998).

- **Cultivation management**

Xu et al. (1998) suggested a 10%-15% increase in seed rate was one of the most effective ways to avoid yield reduction in continuous soybean. Gao et al. (1999) found application of MB-97 bio-agent increased yield by 10.6%-26.7% depending on soil types, and Hu et al. (1998) found the application of MB-97 bio-agent with integrated control on diseases, resulted in a yield of 4575kg ha^{-1} for a five-years CS in a micro-plot field study.

Conclusions

Yield decline in continuous soybean is a complex problem. It inhibits growth and development, causes changes in physiological and biochemical processes, and results in yield/quality decline. The main reasons are severe root diseases and insect pests, toxicity of residual and root exudates, change of rhizosphere microbes and imbalance of the soil environment or deterioration of soil properties, so the changes of soil quality account for the major part of the yield decline. Integrated approaches involving use of resistant cultivars, control of diseases and insect pests, application of P and K fertilizers and trace elements, use of appropriate tillage and culture management, can alleviate CS yield reduction. However, a clearer understanding of the mechanism of both yield decline and quality changes deserve further investigation, especially how allelopathy is involved in, the causes of changes in infection in the root system by pathogens, and attach by pest insects, and what is the relationship between nutrients adsorption and root diseases. Further breeding for continuous cropping is also required.

Table 5.1 Yield of Soybean Grown under Normal Rotation and Three Durations of Continuous Cropping in Different Regions of Heilongjiang Province, China (Liu and Yu, 2000)*

Ecological regions	Normal Rotation Yield (kg ha^{-1})	One-year CS Yield (kg ha^{-1})	One-year CS Decline (%)	Two-year CS Yield (kg ha^{-1})	Two-year CS Decline (%)	Three-year CS Yield (kg ha^{-1})	Three-year CS Decline (%)
Low-wet	2450	2280	6.9	2141	12.6	2013	17.8
Black soil	2210	1990	9.9	1914	13.4	1826	17.4
Arid	1415	1221	13.7	1191	15.8	1095	22.6
Saline-alkaline	1769	1527	13.6	1470	16.7	1317	23.6
High latitude	2081	1919	7.8	1842	11.5	1763	15.3
Mean	1985	1788	9.9	1712	13.8	1609	19.0

*Data is three year average for the five regions

Table 5.2 Effects of Continuous Soybean on Soil Properties

Treatment	pH	C (%)	N (%)	P (%)	K (%)	Av. N mg kg^{-1}	Av. P mg kg^{-1}	Av. K mg kg^{-1}	Zn mg kg^{-1}	Cu mg kg^{-1}
Rotation	6.95	3.12	0.25	0.13	1.49	298	14.2	101.6	3.15	2.04
1-year soy	6.62	2.82	0.27	0.13	1.38	218	10.7	92.0	2.54	2.08
2-year soy.	6.50	2.70	0.26	0.13	1.35	224	30.4	89.9	2.87	1.79
3-year soy.	6.51	2.58	0.26	0.13	1.36	207	15.2	98.0	1.60	1.80
6-year soy.	6.50	2.56	0.26	0.14	1.33	205	18.6	93.0	1.58	1.85

Data is means for three locations

Table 5.3 Effects of Continuous Soybean on Microbe Number in the Rhizosphere (g^{-1} fresh weight)

Treatment	Number of Bacteria	Number of fungi	Ratio of bacteria/fungi
Rotation	3.24×10^8	3.8×10^4	8.52×10^3
3-year soybean	3.08×10^8	8.7×10^4	3.54×10^3
6-year soybean	2.22×10^8	2.7×10^5	8.22×10^2

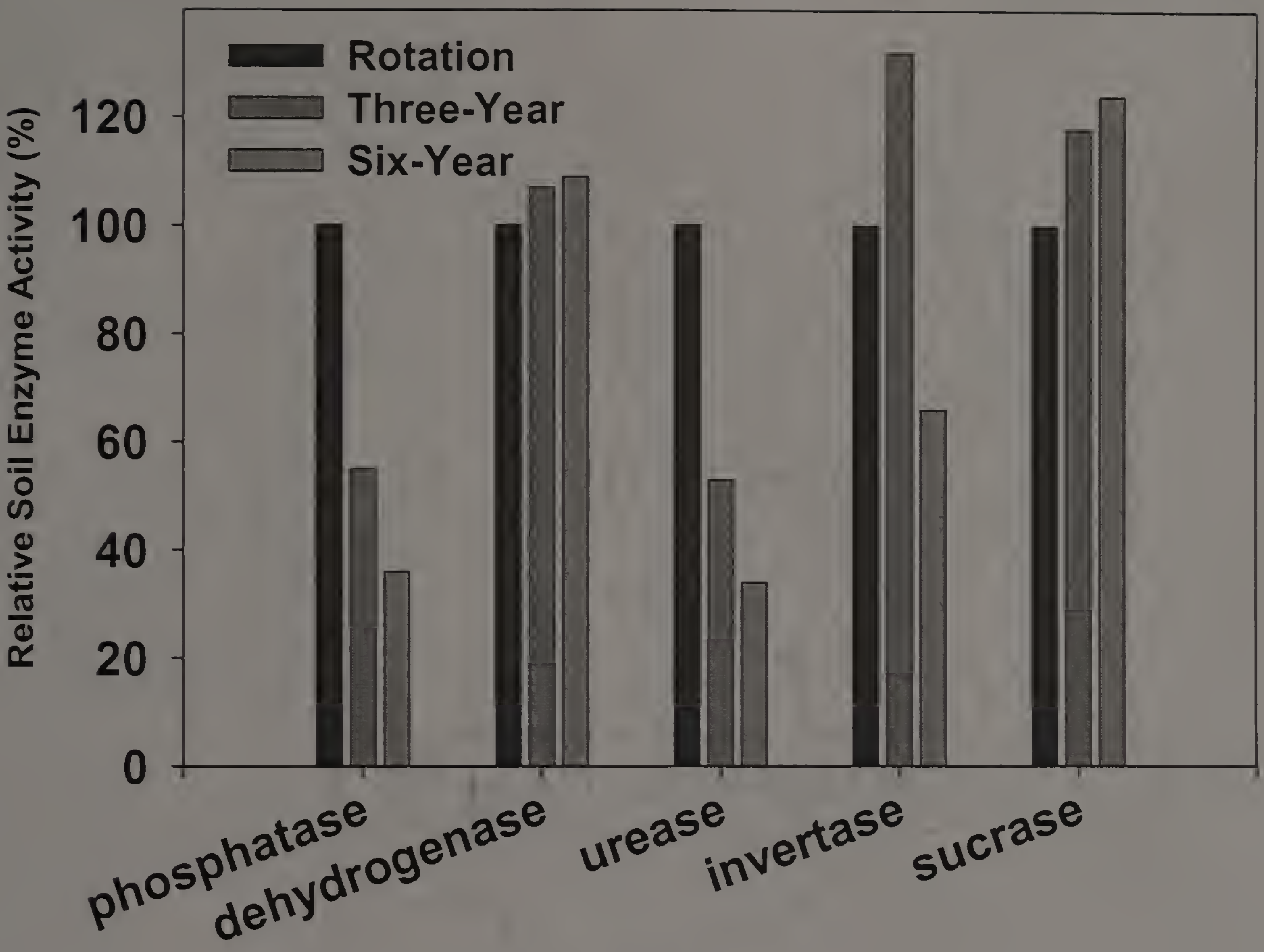

Figure 5.1 Effects of Continuous Soybean on Different Soil Enzymes Activities

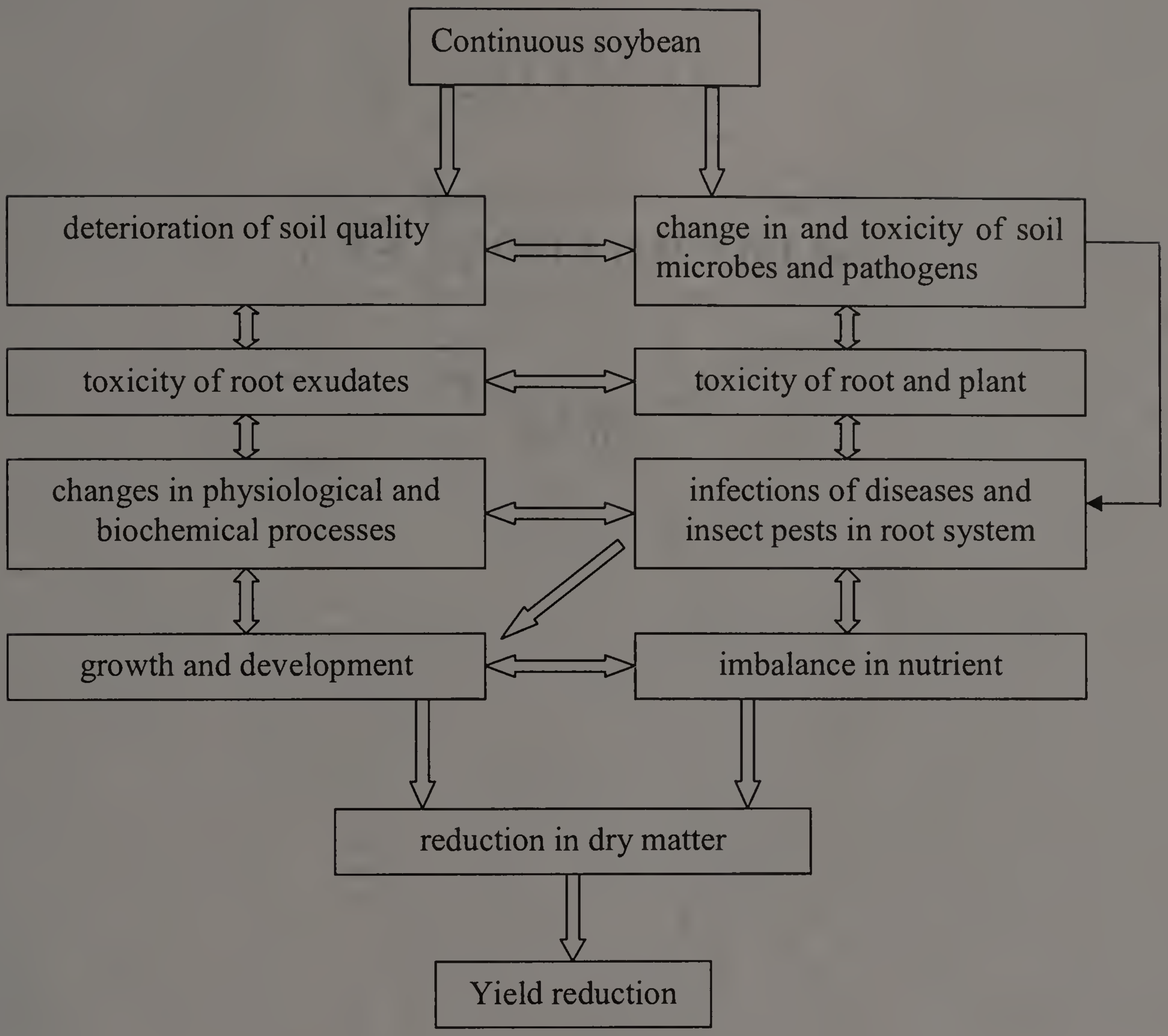

Figure 5.2 Interactions Among Factors Involved in Continuous Soybean

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