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TECHNICAL REPORT

Soil management practices for sustainable agro-ecosystems

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Abstract A doubling of the global food demand projected for the next 50 years poses a huge challenge for the sustainability of both food production and global and local environments. Today's agricultural technologies may be increasing productivity to meet world food demand, but they may also be threatening agricultural ecosystems. For the global environment, agricultural systems provide both sources and sinks of greenhouse gases (GHGs), which include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). This paper addresses the importance of soil organic carbon (SOC) for agro-ecosystems and GHG uptake and emission in agriculture, especially SOC changes associated with soil management. Soil management strategies have great potential to contribute to carbon sequestration, since the carbon sink capacity of the world's agricultural and degraded soil is 50–66% of the historic carbon loss of 42–72 Pg (1 Pg=10^{15} g), although the actual carbon storage in cultivated soil may be smaller if climate changes lead to increasing mineralization. The importance of SOC in agricultural soil is, however, not controversial, as SOC helps to sustain soil fertility and conserve soil and water quality, and organic carbon compounds play a variety of roles in the nutrient, water, and biological cycles. No-tillage practices, cover crop management, and manure application are recommended to enhance SOC storage and to contribute to sustainable food production, which also improves soil quality. SOC sequestration could be increased at the expense of increasing the amount of non-CO_2 GHG emissions; however, soil testing, synchronized fertilization techniques, and optimum water control for flooding paddy fields, among other things, can reduce these emissions. Since increasing SOC may also be able to mitigate some local environmental problems, it will be necessary to have integrated soil management practices that are compatible with increasing SOM management and controlling soil residual nutrients. Cover crops would be a critical tool for sustainable soil management because they can scavenge soil residual nitrogen and their ecological functions can be utilized to establish an optimal nitrogen cycle. In addition to developing soil management strategies for sustainable agro-ecosystems, some political and social approaches will be needed, based on a common understanding that soil and agro-ecosystems are essential for a sustainable society.

Keywords Soil carbon sequestration · Greenhouse gas emission · Soil management · Sustainable agriculture · Cover crop

Introduction

The exponential growth of the global population has placed increased demands on agriculture to produce more food. The world's population has grown by one billion people in the past 12 years, exceeding 6 billion in 2000, and is projected to reach 9 billion by 2050 (Brown 2004). More than 90% of this growth has taken place in developing countries, in sharp contrast to Western Europe, North America, and Japan, where the population growth is small or stagnant. Increasing demand for food has resulted in increased soil distur-

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bance, increased fossil fuel consumption to produce agricultural products, and increased biomass burning.

The technologies developed since the 1960s to revolutionize agriculture may be increasing productivity to meet world food demand, but they may also be threatening agricultural ecosystems. For instance, chemical-based pesticides and insecticides initially allowed farmers to reduce their losses from harmful insects and disease. But they began to fail as pests developed resistance, and the chemicals left toxic residues in our water, soil, and food (Nierenberg and Halweil 2005). In addition, soil managers became overdependent on chemical fertilizers to replace or enhance soil nutrients, which also degraded soil and water quality (Stamatiadis et al. 1999). For the global environment, agriculture provides both a source and a sink of greenhouse gases (GHGs), which include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

Generally, agriculture in Japan is considered as a minor source of the total global GHGs (about 2–3%; Sakai 2002), but this is not necessarily the case with agriculture elsewhere in the world. At the same time, the growing world population requires that agricultural production be increased without increasing GHG emissions or environmental degradation. The solution to sustaining food production is not to rely on new chemicals or fertilizers, but, rather, to develop new approaches to farming that utilize the knowledge of farmers and make sophisticated uses of their environment.

As local environmental quality becomes increasingly degraded by agricultural practices, the importance of protecting and restoring soil resources is being recognized by the world community (Lal 1998, 2001; Barford et al. 2001). The sustainable management of soil received strong support at the Rio Summit in 1992, as well as in Agenda 21 (UNCED 1992), the UN Framework Convention on Climate Change (UNFCCC 1992), Articles 3.3 and 3.4 of the Kyoto Protocol (UNFCCC 1998), and elsewhere. These conventions are indicative of recognition by the world community of the strong link between soil degradation and desertification on the one hand, and loss of biodiversity, threats to food security, increases in poverty, and risks of accelerated greenhouse effects and climate change on the other.

Proper soil management has great potential to contribute to carbon sequestration, since the carbon sink capacity of the world's agricultural and degraded soil is 50–66% of the historic carbon loss of 42–72 Pg ($1 \text{ Pg}=10^{15}$ g) of carbon (Lal 2004). Carbon sequestration implies transferring atmospheric CO_2 into long-lived pools and storing it securely so that it is not immediately re-emitted. Soil organic carbon (SOC) stocks, through the addition of high amounts of biomass to the soil, cause minimal soil disturbance, conserve soil and water, improve soil structure, enhance activity and species diversity of soil fauna, and strengthen the mechanism of elemental cycling (Lal 2004).

The maintenance and improvement of soil quality in cropland is critical to sustaining agricultural productivity and environmental quality for future generations. Soil management practices that improve soil quality through enhancing SOC stock will become more noticeable, since soil management determines the level of food production, and, to a great extent, the state of the global environment, and the current pressure on the land resources of the world is enormous. This paper addresses soil management strategies, including tillage systems, crop rotation, cover crops, and manure application, and their effects on SOC accumulation, with the goals of contributing toward sustaining food productivity, improving local environmental quality, and adapting to climate change.

Soil organic carbon and soil quality

Soil is an essential natural resource that provides several important ecological functions, e.g., (1) a medium for plant growth, (2) a regulator and partitioner of water flow in the environment, and (3) an environmental buffer in the formation, attenuation, and degradation of natural and xenobiotic compounds. Management that causes a decline in soil quality reduces these functions; however, proper soil management can be expected to restore ecosystem functions that have become degraded. SOC, which is a very reactive, ubiquitous component in soils, is an important soil quality indicator that influences the productivity and physical well-being of soils.

Soil organic matter (SOM), which includes a vast array of carbon compounds originally created by plants, microbes, and other organisms, helps to maintain soil fertility and plays a variety of roles in the nutrient, water, and biological cycles (Tiessen et al. 1994; Reeves 1997). SOM is also critical for its function of supporting crop growth naturally, and provides a place for water, air, and biological ecosystems to exist in the soil.

Declines in SOC caused by the cultivation of soils have been studied in many long-term experiments (Grace and Oades 1994; Golchin et al. 1995). In cultivated land, the restoration of organic matter tends to decrease, while soil respiration tends to increase, resulting in a considerable carbon loss compared with forests (Buyanovsky et al. 1987). In addition, when soils are tilled, SOC is decomposed faster because of changes in water, aeration, and temperature conditions. The amount of organic matter lost after clearing a wooded area or tilling native grassland varies according to the kind of soil, but most organic matter is lost within the first 10 years (Buyanovsky et al. 1987).

The loss of SOC under cultivation can mainly be attributed to the loss of the labile C fraction (Wadman and de Haan 1997), which is very important for supplying nutrients to plants (Magdoff 1998). Kapkiyai et al. (1999) also indicated that the labile fraction is crucial for the interpretation of soil fertility changes and that it could be potentially used as a soil quality indicator.

Because SOC is reactive to soil management practices, long-term studies have consistently shown the benefits of manuring, adequate fertilization, and crop rotation for maintaining agronomic productivity by increasing C input into the soil (Duff et al. 1995; Mitchell et al. 1996; Reeves 1997). Differences in C and N inputs deriving from the management system, including manure addition, inorganic N fertilization, and crop residue management (plowing under vs. burning), are reflected in changes in SOC and soil N in wheat/fallow rotation (Fig. 1). Duff et al. (1995) suggested that soil N fertilization would increase SOC stock compared with unfertilized plots, but without the addition of manure, SOC decreased significantly for over 50 years. Crop residue burning in this agro-ecosystem caused a particularly serious decline of SOC, although burning had been practiced in commercial fields until recent years (Reeves 1997). Decreasing SOC causes low soil fertility and low cation exchange capacity, resulting in additional fertilizer input to maintain economical yield.

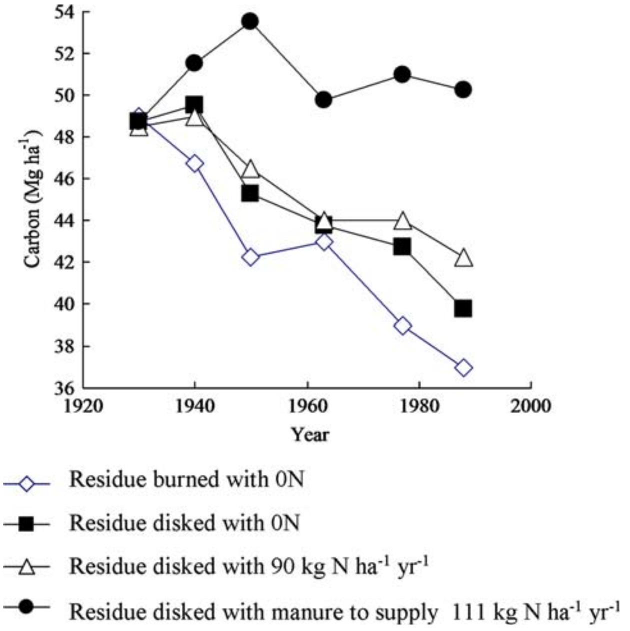

Fig. 1 Soil organic carbon (SOC, 0–30-cm depth) from a long-term residue management study (1931–1990) in winter wheat/summer fallow production system, Pendleton, OR, USA, as affected by amendment and residue management (modified from Duff et al. 1995)

In general, an increase in SOC increases crop yield response and conserves water quality, thus, improving soil quality. A study of soils in Michigan, USA, demonstrated potential crop-yield increases of about 12% for every 1% of organic matter (Magdoff 1998). Quiroga et al. (2006) found that crop yield was related to soil texture, and in similar textures, yield depends on the total SOM content. Increasing the SOM content for crop periodicity significantly increased nitrate availability. The protection it provides to water quality, which increases the organic content in soil, is significant, as the percentage of organic content is directly related to the water-holding capacity of the soil. For example, Hudson (1994) reported that increasing the organic matter content by 1% would be able to ensure that the soil could hold 160 m^3 of water needed by plants in a 1 ha × 1 foot depth. Soil with insufficient organic matter may not be able to hold enough water or supply an environment for beneficial microbes.

Certainly, SOC provides many benefits, but it can also have negative environmental and crop production impacts. For example, increasing the SOM content increases the application requirements of many soil-incorporated pesticides (Stevenson 1972; Ross and Lembi 1985). As SOM increases from about the 1–3% range to the 3–5% range, soil-incorporated pesticide allocation rates needed to retain efficiency commonly rise by 20–100%. In soil sample clay fractions with 11% pesticide allocation rates, SOM had 68% of the atrazine sorption affinity in the organic fraction (Laird et al. 1992; Barriuso et al. 1994).

Furthermore, Clancy (1986) and Hallberg (1987) noted that the increased use of synthetic insecticides, fungicides, and herbicides increases the probability of people being exposed to toxic hazards. 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. In addition, high levels of SOM and manure have been linked to greater P solubility in the water if soil is easily eroded (Robinson and Sharpley 1995; Sharpley and Smith 1995). These findings suggest that, as SOC stock increases, other soil management strategies will be required to conserve environment quality.

Soil carbon sequestrations in cropland

Cultivated soils (cropland) also store great amounts of organic carbon; they are one of the sinks of atmospheric CO_2. Plant biomass and soils store about 500 Pg and 1,100 Pg C, respectively, on the global scale; carbon stored in soils is mainly in the form of SOM (IPCC 1996). As for the carbon dynamics of cropland, crops accumulate carbon, resulting in CO_2 fixation by photosynthesis and carbon consumption by respiration. Part of the net crop carbon accumulation is removed through the harvesting process, while other types of crop residues, including litter and roots, remain in the cropland. These crop residues are decomposed to CO_2 (through mineralization) or transformed to SOM in the soil by microbial decomposition, with the mineralization strongly dependent on the C:N ratio.

Grain crop residues show high C:N ratios and yield high amounts of litter, which increases the SOM content in the soil. Leguminous crops also produce considerable litter, but their residues have low C:N ratios. Brassica crops produce small amounts of litter and the C:N ratio of their residues is low. These low C:N residue-producing crops result in quick decomposition of residues in the soil (Komatsuzaki 1999).

One of the major factors in carbon loss from croplands is soil respiration, including microbial decomposition and root respiration. The soil respiration rate is influenced by soil type, climatic conditions, amount and quality of organic matter input, and soil management (Magdoff 1998). Other processes of soil carbon loss are CH_4 emission from paddy fields, and the leaching of organic carbon, such as root exclusion. Much remains to be learned about the leaching of organic carbon from cropland.

The SOM is both a raw material for and a product of biological activity in soils. Increased SOM can enhance the diversity of the prokaryote community, as well as biomass (Weil and Magdoff 2004). Prokaryotes are an enormous component of the biological carbon pool in the Earth's carbon cycle. Whitman et al. (1998) estimated the number of prokaryotes and the total amount of their cellular carbon on Earth to be 4×10^{30}–6×10^{30} cells and 350–550 Pg of C, respectively. Thus, the total amount of prokaryotic carbon is 60–100% of the estimated total carbon in plants (562 Pg) and the inclusion of prokaryotic carbon would nearly double the estimated amount of carbon stored in living organisms, i.e., 900–1,100 Pg of C (Whitman et al. 1998; Shively et al. 2001).

Prokaryotes also possess a vast metabolic diversity and, thus, contribute to all aspects of carbon cycling in agricultural soil. Globally, agricultural soils account for less than one-fourth of the SOC pool (Wood et al. 2000), and SOC levels are usually related to climate, topography, and soil texture. Wood et al. (2000) reported that soils in North America, Asia, and Europe are considerably richer in SOC (12.2, 12.6, and 14.6 kg C m^{-2}, respectively) than in sub-Saharan Africa (7.7 kg C m^{-2}). In agricultural soil, not only do prokaryotes account for most of the biological carbon pool, but they also contain about ten times as much of these nutrients as plants do, and represent the largest pool of these nutrients in living organisms (Whitman et al. 1998). This portion of the SOM pool is most readily amenable to management by agriculturalists, and agricultural soil management has to be considered as a serious option for helping balance anthropogenic GHG emissions.

However, there are some difficulties involved with increasing or decreasing SOC, and continuing on an indefinite basis by using the same soil management or land use practices. In their latest report, Bellamy et al. (2005) announced that carbon loss from soils across England and Wales over the survey period (1978–2003) occurred at a mean rate of 0.6% $year^{-1}$. They found that the relative rate of carbon loss increased with soil carbon content and was more than 2% $year^{-1}$ in soils with carbon content greater than 100 g kg^{-1}. Because the relationship between the rate of carbon loss and soil carbon content is irrespective of land use, they concluded that the carbon loss was linked to climate change. However, after examining the data, Schulze and Freibauer (2005) disputed this observation, concluding that the land-use factor played a primary role and climate variation was, apparently, only a secondary factor.

Alternatives for carbon storage in cropland

Carbon balance in croplands is used to calculate the difference between the amount of organic matter input and the carbon loss by soil respiration and other losses. Although the applicability of these options might differ according to the soil type and region, recommended management practices for soil C sequestration in cropland are as follows: (1) adopting conservation tillage, surface-residue management, and mulch farming; (2) cultivating crops with deep-root systems; (3) developing and cultivating plants with high lignin content, especially in residues and roots; (4) eliminating summer fallow and incorporating legumes and other appropriate cover crops in rotation; (5) applying animal manure and non-toxic anthropogenic biosoil;

(6) enhancing biological N fixation; and (7) increasing crop biomass production (Follett et al. 2005).

Evidence acquired over the past several years has been increasingly indicating that certain fractions of SOC are likely to respond more rapidly than total soil C to land use change and management. SOM is divided into labile and non-labile materials. It has been shown that the C and N present in particulate organic matter (POM) can accumulate rapidly under land management systems that minimize soil disturbance and may also provide an early indicator of change in C dynamics and total soil C under different land use and management practices (Cambardella and Elliot 1992; Franzluebbers and Arshad 1997; Franzluebbers and Stuedemann 2002).

The rate of increase in SOC stock, through land-use change and adopting recommended management practices, follows a sigmoid curve that attains the maximum 5–20 years after the adoption of recommended management practices, and continues until SOC attains another equilibrium (Lal 2004). In addition, the amount of organic carbon stored in paddy soils is greater than in upland soils because of different biochemical processes and mechanisms, specifically caused by the presence of floodwater in paddy soils (Katoh 2003).

Soil management practices directly affect the SOC pool by changing the carbon balance of input and output SOC. A comparison of soil management practices that increase soil carbon stocks is shown in Table 1.

Tillage practices

The conventional tillage system in Japan starts with plowing to a depth of 30 cm with a moldboard plow or cultivating to a depth of 15 cm for rotary tillage in the fall or spring. Soils are then disked or cultivated in the spring once or twice to further break down aggregates and smooth the soil surface before planting (Gu et al. 2002). These treatments ensure the germination of crop seeds and enhance the mineralization of SOM; however, many scientists and farmers have recently recognized that the conventional tillage system decreases SOM and increases the potential for soil erosion by wind and water (Magdoff 1998).

Conservation tillage systems, including no-till, leave more surface residues because the soil is not turned over. These systems create less potential for soil erosion and, therefore, conserve SOM. Many studies of ecosystems under long-term management involving conventional tillage (CT) and no-tillage (NT) practices have demonstrated that tillage causes a substantial decrease of SOM content and mineralization of carbon (Elliott et al. 1994; McCarty et al. 1995; Six et al. 1999). Johnson et al. (2005) summarized 44 studies regarding conservation tillage and showed that the rate of SOC storage in NT compared to conventional tillage has been significant, but variable, averaging 0.4±0.61 Mg C ha^{-1} $year^{-1}$.

Crop residue from above- and below-ground components is an essential input of C for maintaining or

Table 1 Evaluation of soil management practices to increase carbon stocks

Treatment	Effect on OM input (changes to primary production and/or supplied to the soil)	Effect on OM output (rate of mineralization)	Other positive effects	Negative secondary environmental effects	Additional carbon stock (Mg C ha^{-1} $year^{-1}$)	Reference
No-till	Slightly low production, slightly low level of OM conversion into humus	Low rate (increased protection of OM due to improve soil aggregate)	Erosion control, reduced fuel consumption	Slightly low production use of pesticide, emission of N_2O to be confirmed	0.07–0.33	Robertson et al. (2000), Arrouays et al. (2002)
Crop rotation	Increase OM input	Increases soil respiration	Breaks the insect and pest cycle	None	0.05–0.25	Lal (2004)
Cover cropping	Annual production and increase OM returned (crop not harvested)	Increases soil respiration	Scavenging residual nutrients, erosion control, reduces fertilizer consumption	Possible emission of N_2O	0.15–0.25	Arrouays et al. (2002), Lal (2004)
Manure application	Exogenous OM input increases production by the addition of nutrients	Increases soil respiration	Improves soil productivity	N leaching and N_2O emission if excessive inputs occur	0.05–0.15	Robertson et al. (2000), Lal (2004)

OM=organic matter

building SOC. By increasing cropping intensity (periods for crop growth in a year) to more effectively utilize the available water and sunlight, more C can potentially be produced for yields and biomass, as well as for residues, resulting in more C as an input to the soil. For example, Franzluebbers and Arshad (1997) reported that soil organic C to a depth of 0.2 m increased with cropping intensity as a result of greater C input, and was 10–30% greater under NT than under CT, with the resulting sequestration of crop-derived C input into SOC at 22% under NT and 9% under CT. Accumulation of SOC at the soil surface was a result of surface placement of crop residues and the lack of soil disturbance that kept residue isolated from the rest of the soil profile.

Increases in the SOC rate after adopting NT can also show great differences depending on soil properties, climatic conditions, and the degree of stratification of SOC. Franzluebbers (2002) examined increases in the SOC rate after adopting NT, and found that decreasing mean annual precipitation and temperature tended to increase SOC within a certain soil depth increment, irrespective of tillage treatment (Fig. 2). The data also suggested that increases of SOC in NT were smaller in large stock SOC soil than small stock soil.

Japanese soils, especially Andisols, usually show great SOC stock, which ranges from 30 to 60 g kg^{-1} (Kusaba 2001); therefore, there would be little increase in SOC by adopting NT. Sakai et al. (1988) reported that there was no significant difference in SOC content between NT and CT for upland field production in a 7-year experiment. On the other hand, after adoption of the NT system, SOC accumulation in paddy fields occurs earlier and increases to a greater extent compared with upland fields. Ito (2002), for example, reported a 63% increase in SOC at 0–2 cm in the top soil layer four years after adopting the no-till system for paddy fields compared with the conventional tillage system in Furukawa, Japan. These results suggest that paddy fields have greater potential to conserve SOM because the decomposition of organic matter occurs more slowly under flooded conditions.

Cover crops

Cover crops are grown in addition to primary cash crops for the purposes of erosion control, organic N enrichment, conservation of SOM, scavenging soil residual N, and nematode control (Komatsuzaki 2004). Ismail et al. (1994) evaluated the long-term effects of tillage in continuous corn cropping with a rye (*Secale cereale* L.) cover crop in Kentucky, USA. SOC in the top 30 cm did not change from 1975 to 1980, but increased substantially from 1980 to 1989. Komatsuzaki and Mu (2005) evaluated the effects of tillage in continuous field rice cropping with rye and hairy vetch (*Vicia villosa* Roth) cover crops in the Kanto region of Japan. SOC in the top 0–2.5 cm increased compared with winter fallow two years after adopting cover cropping; however, other soil layers did not change (Fig. 3).

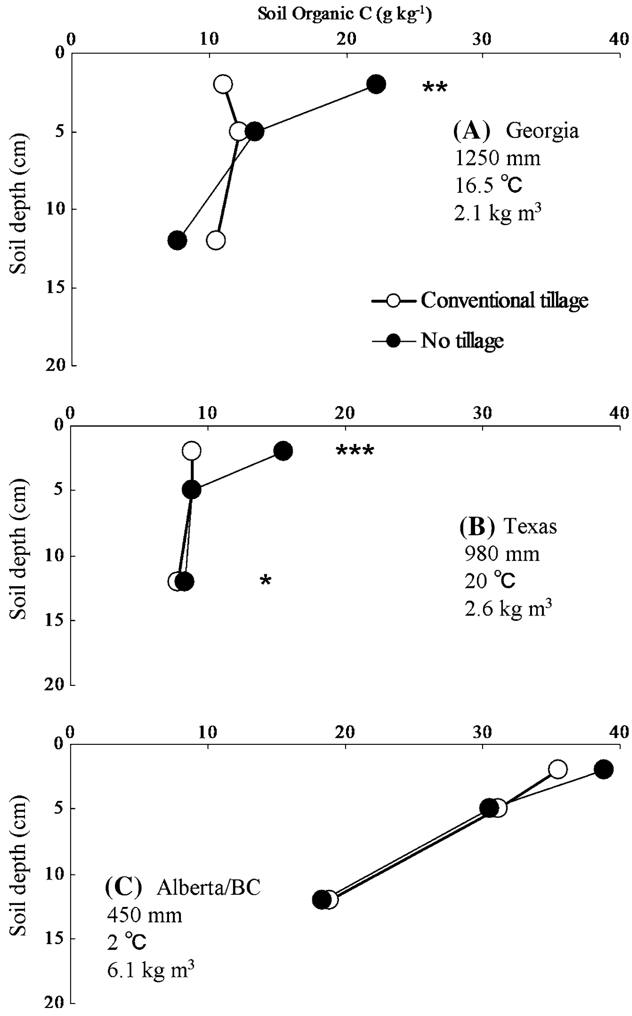

Fig. 2 SOC depth distribution under conventional and no-tillage in Georgia (millet/clover/cotton/rye rotation for 4 years), Texas (wheat/soybean rotation for 10 years), and Alberta/British Columbia (small-grain crop rotation for 7 years). Each location is shown with mean annual precipitation, temperature, and average SOC concentration; *, **, and *** indicate significance between the tillage systems within $P \leq 0.1$, $P \leq 0.01$, and $P \leq 0.001$, respectively (modified from Franzluebbers 2002)

The potential long-term impact of cover crops on SOC was illustrated by Lee et al. (1993) using the EPIC model on typical "Corn Belt" soil. A twofold increase in SOC was primarily related to input associated with cover crop dry matter accumulation, suggesting that long-term cover crops could help offset SOC loss, and maintain soil quality, due to intensive tillage.

Cover crop dry matter accumulation is strongly associated with species and management. For grass cover crops, the dry matter accumulation depends on soil N availability, which is dependent on the amount of residual soil N, as well as the mineralization rate, while leguminous cover crops show little difference in dry matter accumulation dependent on residual soil N availability (Wagger and Mengel 1988; Gu et al. 2004).

Cover crop residues decomposed from crimson clover (*Trifolium incarnatum* L.), hairy vetch, and rye winter cover crop were examined by Wagger (1989), and the results indicated greater C mineralization from residues with narrower C:N ratio and lower concentration of cellulose and lignin. The concentrations of cellulose and lignin are greater in grasses and more mature plant materials than in legumes and young plant tissue. Therefore, cover crop selection and management strongly influence the amount of carbon input to the soil and carbon release from residues, resulting in varying ability to accumulate in SOC pools.

The tillage system may also be an important factor in managing cover crop residue that is decomposed in the soil. Research is being conducted to evaluate the use of fall-planted cover crops, including rye and hairy vetch in various tillage systems in the Kanto region of Japan (Komatsuzaki and Mu 2005).

Manure application

Nutrient supplies via animal manure and organic by-products are expected to increase SOC by increasing C input from enhanced plant productivity and crop residue returned to the soil. Manure application in modern cropping systems is known to sustain or increase SOC. In addition, manure application is considered valuable for nutrient management and the improvement of soil quality. In red–yellow podzolic soils in Toyohashi, Japan, changes in the SOM content of sweet corn and cabbage rotation have been compared under different types of nutrient management and manure input by Katoh (2003). It was reported that the upland soil reached an equilibrium level of C input and mineralization within five years, and the 10–20 Mg ha^{-1} manure input produced a somewhat lower accumulation rate compared with 30–40 Mg ha^{-1} manure input, suggesting that over 30 Mg ha^{-1} manure input per year is required for enhancing SOM accumulation (Katoh 2003). In the same study, the sequestration estimate with 10, 20, 30, and 40 Mg ha^{-1} manure input was 0.1, 0.6, 1.2, and 1.9 Mg ha^{-1} year^{-1}, respectively (Fig. 4).

Manure addition may not be entirely beneficial, as increased production of CH_4 and N_2O emission can occur (Yagi 2002). Although manure application may lead to increased N_2O emission, high N fertility may occur, regardless of the N source. Proper management, such as avoiding excess manure application and optimizing the application timing to synchronize with crop uptake, will ensure the most positive effects of manure addition on SOC storage and GHG emission (Johnson et al. 2005).

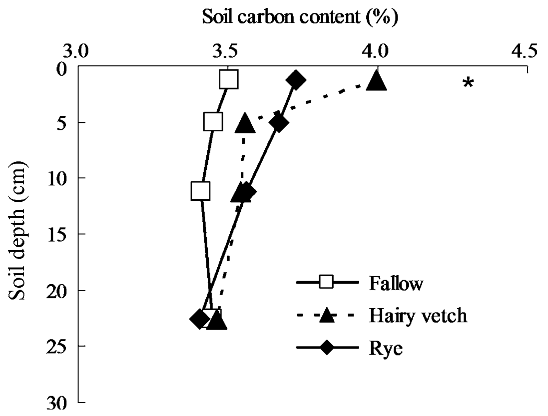

Fig. 3 Changes in SOC content in relation to cover cropping in continuous field rice cultivation in 2004 in the Kanto area of Japan. The experiment was started in 2002; * indicates significant difference (P>0.05) between treatments (modified from Komatsuzaki and Mu 2005)

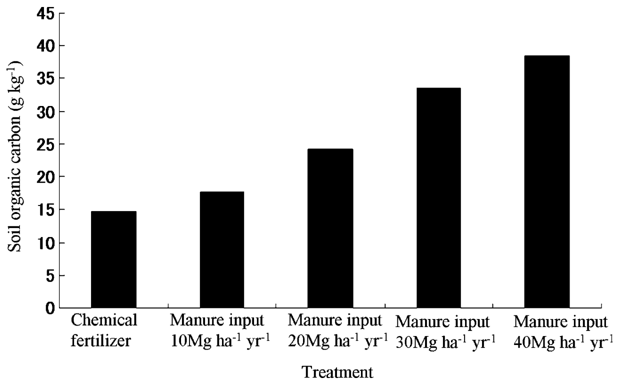

Fig. 4 Changes in SOC content with continuous different nutrient management and manure input to sweet corn and cabbage rotation in Toyohashi, Japan. The experiment was started in 1981; the data shows the average from 1985 to 1994 (modified from Katoh 2003)

Non-CO_2 GHG emissions from farming practices

Agricultural soils are a major source of atmospheric nitrous oxide (N_2O), and they can be a sink or source of atmospheric methane (CH_4). Nitrous oxide and methane account for about 6% and 19%, respectively, of the anthropologically derived greenhouse effect (IPCC 1996). Global emissions of N_2O and CH_4 are directly related to land use and soil management practices (Eichner 1990; Lemon et al. 1991), because between one half and two thirds of all anthropogenic N_2O and one third of all anthropogenic CH_4 are thought to come from cropland soil (IPCC 2001).

Soil management practices significantly affect N_2O and CH_4 emissions, and changes to these emissions can also affect the impact of agriculture on global warming, as can the use of crop production inputs, such as fertilizer, lime, and fuel (Robertson et al. 2000). Alternative soil management practices for enhancing SOC storage might be especially useful for promoting non-CO_2 GHG emissions through farming practices.

N_2O production in cropland soil and alternative practices

The production of N_2O in soils is due mainly to nitrifying and denitrifying microorganisms (Conrad 1996). During nitrification, N_2O can be formed by the oxidation of nitroxyl (NOH) or the reduction of nitrite (NO_2^-) under low oxygen concentration (Fig. 5). As indicated below, N_2O is an intermediate in bacterial denitrification, which is the anaerobic reduction of nitrate (NO_3^-) to nitrogen gas (N_2) (Davidson 1991):

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

The production of N_2O may also be caused by other microorganisms, e.g., during dissimilatory reduction of nitrate to ammonium, nitrate reduction to nitrite, and nitrate assimilation (Smith and Zimmerman 1981; Bleakly and Tiedje 1982). The mechanism of N_2O production by these bacteria and their role in N_2O production in soil require extensive study.

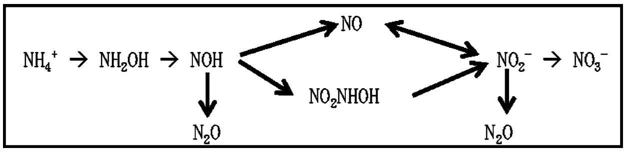

Fig. 5 N_2O production during nitrification (modified from Kinney et al. 2005)

It is clear that denitrification is a function of eukaryotes as well as bacteria (Bollag and Tung 1972; Shoun et al. 1992; Tsuruta et al. 1998). Many fungi lack N_2O-reductase, so N_2O is the major product of fungal denitrification (Shoun et al. 1992). Recently, Laughlin and Stevens (2002) demonstrated that fungi were responsible for most of the N_2O production in a grassland soil. In their study, streptomycin and cycloheximide were used as the bacterial and fungal inhibitors, respectively, to measure N_2O flux from the soil. They observed that cycloheximide decreased the N_2O flux by 89%, while streptomycin decreased the flux by 23%, suggesting that fungal denitrification could be of ecological significance. Very recently, Spokas et al. (2006) also performed such inhibitor studies to elucidate potential mechanisms of N_2O production following chloropicrin fumigation in soil. Their results suggest that 20% of the N_2O production was from bacteria and 70% from fungi.

The production of nitrous oxide by soil microbes is known to be controlled by soil type, pH, maturity of vegetation, microbial biomass content, and SOC content (Scott et al. 2002). N_2O emission is greater in upland fields than in paddy fields because aerobic conditions promote N_2O production through denitrification by microbes. In particular, nutrient-rich soils with abundant organic C under wet soil conditions provide the most ideal conditions for denitrification (Franzluebbers 2005). With no-till cultivation, there is increased surface residue, which can result in wetter soil, and these conditions have been implicated in increased production of N_2O (Lal 1995). Therefore, it is possible that soil management resulting in SOC sequestration could also result in increased N_2O emission.

Robertson et al. (2000) measured gas flux and other sources of global warming potential in corn–wheat–soybean rotations managed with conventional chemical inputs and tillage, with conventional inputs and no tillage, with reduced chemical inputs, and with no chemical input (i.e., organically). The latter two treatments included a winter legume cover crop following the corn and wheat portions of the rotations to provide nitrogen, and mechanical cultivation to control weeds. Soil N_2O emission under NT was 7.7% higher than under CT. Increased N_2O emission with NT represented a small offset (3.6%) of the SOC gain that occurred during 10 years of NT.

To minimize N_2O emission from agricultural practices, soil managers may be able to adopt such methods as precision fertilizer application based on soil and plant testing (Brown et al. 2005), minimizing the fallow period to avoid high rates of decomposition (Scott et al. 2002), and optimized split application using precision farming techniques (Sehy et al. 2003). Sehy et al. (2003) reported that precision fertilizer application can achieve a 7% and 40% reduction of N_2O emission in high-yielding and low-yielding areas, respectively (Table 2). Mosier et al. (1998) speculated that it would be possible to reduce synthetic fertilizer applications to the field by 20% without loss of fertility through the use of these soil management practices. This percentage does not assume any improvements in the techniques of application or of the fertilizer formation itself, but merely the wider application of techniques that are already well established. Scott et al. (2002) predicted that, in the context of moderate climate change, improvements in fertilizer application efficiency would make it possible to reduce the total agricultural soil N emissions to the 1995 level, which is about 20% below the projected baseline values.

Production and consumption of CH_4 in cropland

Methane is another agent of the carbon transfer pathway between the atmosphere and the soil. In Japan, CH_4 emission from paddy fields accounts for 55% of the total Japanese CH_4 emissions, while that from paddy fields worldwide accounts for 16% of the total world CH_4 emissions (Sakai 2002). Methane is removed from the atmosphere primarily by chemical oxidation and a small portion (about 10%) is converted to CO_2 via methanotrophic bacteria (Shively et al. 2001). In soil environments, methane can either be released or consumed, depending on the microbial community and soil moisture conditions (Schütz et al. 1990; King 1997). Under anaerobic conditions, CH_4 is produced by methanogenic prokaryotes (methanogens) at the final stage of organic matter decomposition, whereas under aerobic conditions, microbial oxidation of CH_4 prevails over CH_4 production.

Table 2 Cumulative N_2O emission, amount of N applied, corn yield, and N_2O loss per yield compared between uniform and site-specific precision fertilizer applications depending on previous yield levels in Munich, Germany (data are shown in mean±standard deviation; data modified from Sehy et al. 2003)

	High-yielding area		Low-yielding area	
	Uniform	Precision	Uniform	Precision
N_2O emission ($kg\ N_2O–N\ ha^{-1}$)	5.5±0.5	5.4±0.7	3.5±0.6	2.3±0.7
N fertilizer ($kg\ N\ ha^{-1}$)	150	175	150	125
Yield ($Mg\ ha^{-1}$)	19.3±2.6	20.9±2.1	17.7±1.5	18.2±1.6
N_2O per yield ($kg\ N_2O–N\ Mg^{-1}$)	0.28±0.02	0.26±0.04	0.20±0.03	0.12±0.02

Three different pathways to CH_4 production are found in methanogens: (1) the reduction of CO_2; (2) the disproportionality of methanol and methylamines; and (3) the fermentation of acetate (Ferry 1993). All of these reactions occur under strictly anaerobic conditions. The active CH_4-emitting soils include all kinds of water-saturated wetlands and flooded rice fields. In such anoxic soils, O_2 diffusion from the atmosphere is limited and, thus, favors the activities of fermenting bacteria and, finally, of methanogens. In well-aerated soils, by contrast, microbial oxidation of CH_4 with O_2 to CO_2 prevails over CH_4 production and, thus, causes soils to become a sink for atmospheric CH_4 (Conrad 1995). Methanotrophs oxidize CH_4 as their carbon and energy source, and assimilate into cell material some of the carbon from the formaldehyde level:

$$CH_4 \rightarrow CH_3OH \rightarrow HCHO \rightarrow HCOOH \rightarrow CO_2$$

On the basis of this mechanism, various methods of flooded paddy field management affect CH_4 emission, which occurs through the aerenchyme of rice plants. CH_4 flux shows a maximum from afternoon towards evening in a day, and at the late growth stage of rice in the year (Yagi 2002). Previous studies demonstrated the effects of soil management practices on CH_4 emission, e.g., method of water management, timing and amounts of straw application, and type and rate of nitrogen fertilizer (Yagi 2002).

Among the management options for mitigating CH_4 emission in paddy fields, mid-season drainage, intermittent irrigation, improved infiltration, sulfate fertilizer application, and soil oxidation have the greatest potential (Yagi 2002). While some of the mitigation options may cause increased N_2O emission (for example, mid-season drainage can reduce CH_4 emission), N_2O emission occurs under aerobic conditions during drainage. Nishimura et al. (2004) reported that mid-season drainage over seven days causes increased N_2O emission; therefore, short-term drainage in mid-season is recommended to mitigate CH_4 emission and prevent N_2O emission. Consequently, appropriate flooding control and nutrient management may mitigate CH_4 and other GHG emissions.

Cropland soil can absorb CH_4 gases, as CH_4 consumption mainly occurs in upland fields, in sharp contrast with flooded paddy fields. Flessa et al. (2002) reported that the total CH_4 uptake in a potato field during the growing season was 295–317 g ha^{-1}, and most of the total CH_4 uptake (<86%) occurred on a ridge. Hansen et al. (1993) observed that soil compaction from a bulk density of 1.2–1.3 Mg m^{-3} by tractor traffic reduced the CH_4 oxidation rate by 52%.

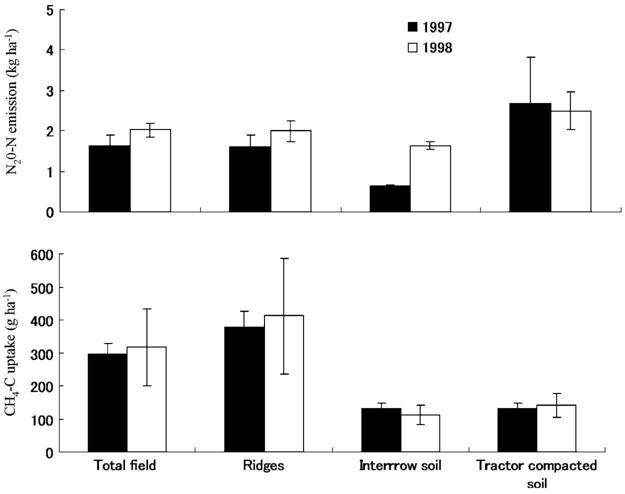

Fig. 6 Cumulative N_2O and CH_4 flux from the ridge, uncompacted interrows, and entire field for the potato growing season in Munich, Germany. The *vertical bars* indicate the standard deviations (modified from Flessa et al. 2002)

The reduced CH_4 uptake of compacted soil can be explained by the reduced diffusion of atmospheric CH_4 into the soil. However, Flessa et al. (2002) concluded that optimum soil physical conditions and structure were more important for decreasing N_2O emission and increasing CH_4 uptake, and soil compaction would have the opposite effect (Fig. 6).

Soil management for adapting to climate change

The Kyoto Protocol allows signatory countries listed in Annex II to subtract from their national GHG emission any sequestration induced by "additional human activities." These activities principally target the uptake of carbon in biomass and the soil. Agricultural soils are involved in these activities, and the amounts deductible under the terms of the agriculture section of Article 3.4 are not, in principle, limited; each country determines the levels it will undertake to ensure, but its claimed results for sequestration must be verified by an independent method (Watson et al. 2000).

Many researchers have noted that cropland has a great capacity for absorbing carbon produced from the burning of fossil fuels (Schütz et al. 1990; Katoh 2003; Franzluebbers 2005; Johnson et al. 2005; Su 2007). Lal (2004) estimated that cultivated soil can accumulate 0.4–0.8 Pg C year^{-1} if recommended farming practices are adopted, such as no-till, crop rotation, cover cropping, and manure application.

Many reports have stated that forestry, pasture, and land conservation can be effective for storing the carbon pool in the soil (e.g., Drinkwater et al. 1998; Toyota et al. 2006). The invasion of woody vegetation into deserts, grasslands, and savannas is generally thought to help increase the amount of carbon stored in those ecosystems. However, Jackson et al. (2002), in their report on a woody plant invasion along a precipitation gradient (200–1,100 mm year^{-1}), made by comparing carbon and nitrogen budgets and soil $\delta^{13}C$ profiles between six pairs of adjacent grasslands, suggested a clear negative relationship between precipitation and changes in SOC when grasslands were invaded by woody vegetation, with drier sites gaining and wetter sites losing. Goodale and Davidson (2002) reported that the replacement of grassland by afforestation, which is occurring on a large scale in the United States, may be locking up considerable amounts of carbon. However, this carbon sink may be much smaller than previously estimated because the net balance of SOC would be strongly affected by regional conditions, as well as by plant inputs, erosion, leaching, and decomposition by microbes.

On the other hand, there are indications that deep-rooted grasses might enhance SOC stock compared with reforestation. Hungate et al. (1997) reported that increased CO_2 concentration not only increased grassland ecosystem carbon uptake, but it also greatly increased carbon partitioning to rapidly cycling carbon pools below ground. Furthermore, in Ohio, Akala and Lal (2001) reported that pasture treatment increased SOC from 9.2 to 55.4 Mg ha^{-1} after 25 years, and forest treatment increased SOC from 14 to 48.4 Mg ha^{-1} after 21 years, suggesting that grassland and pasture treatments would increase SOC stock as much as forest management would. These findings have stirred much debate about the contribution of additional human intervention, such as reforestation and land use management, towards enhancing SOC stock through plant and soil ecosystems.

Cox et al.'s (2000) results from a fully coupled, three-dimensional carbon–climate model indicated that carbon cycle feedbacks could significantly accelerate climate change during the twenty-first century. They also found that, under a "business as usual" scenario, the terrestrial biosphere acts as an overall carbon sink until about 2050, but turns into a source thereafter. Ciais et al. (2005) reported that, while the United Kingdom accomplished its goal for reducing carbon dioxide emission from fossils fuels, this success has been wiped out by the acceleration of carbon emissions from the soil brought about by the heat and drought of 2003. Their report suggested that fertile soil may become an emission source once the SOC has sufficiently accumulated. Furthermore, the actual carbon storage in cultivated soil may be smaller if climate change leads to increasing mineralization, as a significant fraction of relatively labile SOC is clearly subject to temperature-sensitive decomposition. These reports have noted that the resulting concentration of SOC may possibly increase global warming.

The contribution of soil carbon pool enhancement to reducing the rate of enrichment of atmospheric concentration is debatable, and adopting agricultural soil as a carbon sink would reduce the obligation to cut emissions of carbon dioxide from fossil fuel combustion (Oberthür and Ott 1999). It would be risky to try to accumulate carbon dioxide emissions from fossil fuels into agricultural soil, because there is no guarantee that the soil carbon will remain there for centuries of farming.

The importance of SOM in agricultural soil is, however, not controversial, as soil management is a principle for ensuring the sustainability of agriculture. Oldeman (1994) reported that, from 1945 to 1994, approximately 17% of vegetated land had undergone human-induced soil degradation and loss of productivity, often from poor fertilizer and water management, soil erosion, and shortened fallow periods. Continuous cropping and inadequate replacement of nutrients removed in harvested materials or lost through erosion, leaching, or gaseous emissions deplete fertility and cause SOM levels to decline, often by 50% or more (Matson et al. 1997).

Such human-induced soil degradation may intensify global warming, which, in turn, may strongly affect SOM decomposition. For example, Knorr et al. (2005) claim that rising temperatures brought about by climate change will cause microorganisms in the world's soils to decompose organic matter more rapidly, releasing extra CO_2 and accelerating climate change.

Over the short term, increasing CO_2 in the atmosphere could enhance plant growth through CO_2 fertilization, thus, removing some of the excess CO_2 (Giardina and Ryan 2000). However, current models predict that, in the longer term, rising temperatures will speed up the decomposition of organic carbon in soil, releasing CO_2 into the atmosphere in excess of any carbon sequestered in the soil, and adding to climate change (Knorr et al. 2005). Some reports have pointed out that non-labile SOC is more sensitive to temperature than labile SOC, implying that the long-term positive effects of soil decomposition in a warming world may be even stronger than that predicted by global models (Davidson and Jansens 2006).

In addition, many studies have found that the sensitivity of POM-C to soil use and management, and the proportion of POM-C in SOC increase as sand content increases (Liang et al. 2003; Su 2006). However, Japanese upland soils usually have low sand content. Therefore, while SOM in upland soils could be gradually increased by adopting recommended farming practices, SOM decomposition may be significantly affected by global warming (Hayashi and Koyama 2003).

In contrast, the soil in paddy fields, which account for half of the Japanese cropland, has low aluminum and high clay mineral content, and is in an anaerobic condition due to flooding, resulting in maintenance of the SOM pool with decreasing SOM decomposition (Nishio 2005). However, Hayashi and Koyama (2003) reported that SOM in paddy soils would decompose 5.8–7.8% faster with a 2°C increase in temperature and indicated that paddy soils would be much more sensitive than upland soils to global warming.

As global warming progresses, the depletion of SOC stock from the root zone will strongly affect soil productivity and environmental quality. Farming practices which tend to accumulate carbon in the soil almost always engender other environmental benefits, including reduced erosion, improvements in soil and water quality, economies in fossil energy, and greater biodiversity. SOC stock should be considered not only as a means to reduce atmospheric CO_2 levels, but also as a natural resource that can be managed to ensure global food security and promote environmental conservation.

Strategies of soil management for sustainable agro-ecosystems

Much information on the properties of SOC has been obtained from long-term studies. SOC has become the most important indicator of soil quality and agronomic sustainability because of its impact on other physical, chemical, and biological indicators of soil quality (Reeves 1997). Long-term studies have consistently shown the benefit of manure, adequate fertilization, and crop rotation on maintaining agronomic productivity by increasing C input into the soil (Mitchell et al. 1996; Reeves 1997). The soil management strategy to maximize the benefits from SOC will require intelligent compromises in order to achieve agronomical sustainability.

However, the decline of SOM content in Japanese cropland has also been noticeable, decreasing by 5% between 1960 and 2000 because of the reduced application of manure during that time (Kusaba 2001). Complete residue removal for seed bed preparation, reducing manure application, single and continuous cropping, and the elimination of winter crops have significantly reduced organic matter input to cropland, and the enhancement of soil respiration by increasing N fertilizer application is resulting in a significant decline of SOM in these fields.

Moreover, the high humidity and relatively high temperatures during the summer growing season in Japan enhance soil respiration associated with SOM breakdown, and, thus, result in considerable carbon loss from soils. Most of the soils in Japanese upland fields show some acidity, high aluminum content, and low phosphorus availability, and the labile SOM rapidly decomposes due to the enhanced microbial decomposition when soils are tilled. On the other hand, non-labile SOM retards microbial decomposition because it joins with aluminum ions, resulting in low N mineralization of SOM (Nishio 2005). Current soil management techniques pose a threat to agricultural ecosystems, as farmers are likely to apply more fertilizer to their fields than what is recommended.

The recent actions of the Japanese government to develop more environmentally friendly farming practices and the importance of surplus reduction have led to a widespread interest in organic farming and environmental conservation farming. Conservation farming, which is supported by the Japanese government, is practiced on 16% of all agriculture land in Japan (Ministry of Agriculture, Forestry and Fisheries of Japan 2001). Under conservation management, traditional agronomic methods are combined with modern farming techniques, and conventional inputs such as synthetic pesticides and fertilizers are excluded or reduced. Soil fertility is built up not with synthetic inputs, but with cover crops, compost, and animal manure. This policy places greater emphasis on SOM management by promoting alternative soil management practices, such as manure application or crop residue management.

While SOM in the soil has many benefits for agroecosystems, increased SOM can even mitigate some problems associated with soil management. For example, during the fallow season, a fertile soil sometimes causes nutrients, such as NO_3^-, to leach into groundwater (Miura and Ae 2005). Even with organic agriculture, the soil may cause nitrate leaching, depending on soil management, because it is difficult to synchronize the N mineralization from manure, compost, or crop residues with the crop growth (Rodrigues et al. 2006).

Maeda et al. (2003) reported that sweet corn cultivation in Andisols showed significant N leaching from a manured plot compared with a no-fertilizer plot, and there was no difference in nitrate leaching between the manured plot and the chemical fertilizer plot. In this regard, soil management strategies for sustainable agriculture should focus on not only increasing SOM in the soil, but also on the uptaking or stocking of soil residual nutrients in such a way as to prevent excess nutrient leaching into the groundwater.

At one time, Japanese upland fields were mostly used to produce grain, soybeans, and sweet potatoes, but farmers have shifted to vegetable production without field crop rotation. This type of cultivation has dramatically influenced the nitrogen input and nitrogen uptake by crops in the field, resulting in widespread nitrate leaching into the groundwater, as vegetable crops use nitrogen much less efficiently than field crops.

Nishio (2005) reported that the nitrate concentration in groundwater was often over 10 ppm, and the highest concentration was observed in a vegetable production area (over 77 ppm). Nitrate leaching mainly occurs in spring and autumn, when there is much precipitation and relatively little evaporation, resulting in a downward movement of soil water. Most vegetable and field crop production occurs in spring to summer or autumn to winter, resulting in a relatively sparse vegetation cover of fields during early spring and early autumn, when nutrient leaching is most prominent.

Nitrate concentration in food crops and vegetables is also decreasing food quality, as high N in the soil can increase crude protein concentration, but decrease the nutritional value of that protein (Schuphan 1974). In addition, methemoglobinemia (blue-baby syndrome), various cancers, and birth defects have been listed as possibly being associated with exposure to elevated nitrate levels in food (Weyer 2001). Since nitrogen from organic fertilizer sources is often released slowly and is, therefore, less readily available to plants than that from chemical sources, many studies have speculated that conventional fertilizing practices could possibly result in a higher crude protein content, but poorer quality protein than organic practices (Finesilver 1989).

However, even organic farming may promote excess nitrate concentration due to the accumulation of soil residual nutrients from long-term organic material input. In Reinken's (1986) 6-year field study, there were no differences between organic and non-organic methods detected in total-N or protein (fresh weight basis) in a number of vegetables and three varieties of apples. Furthermore, Nakagawa et al. (2003) reported that there was no difference in nitrate concentration of production crops and that there were high concentrations in both organic and conventional produce, suggesting that organic farming may, essentially, be plagued by the same excess of soil residual nutrients that plagues conventional farming.

The strategy of soil management for sustainable agro-ecosystems should be compatible with increasing SOM to improve the soil quality for sustaining food productivity and to control soil residual nutrients that aggravate environmental problems. To control soil residual nutrients by increasing SOC, it will be necessary to employ fertilization techniques to synchronize with crop growth using post-planting application and soil testing to determine the optimum fertilizer application for the expected SOM and organic material mineralization. These techniques will usually reduce chemical or organic nutrient inputs to the soil; however, for high-quality, high-yield crop production, there would still likely be soil residual nutrients, despite the introduction of such techniques, because more nutrients are required than what the crops can absorb from the soil.

The cultivation of cover crops is a more attractive alternative, since cover crops have been shown to prevent N leaching to groundwater by accumulating excess soil N (Wagger and Mengel 1988; Gu et al. 2004). This system works well following rice, corn, potato, soybean, and most vegetable crops, because the range of planting dates for grass cover crops is wider than that of legume cover crops (Komatsuzaki 2004).

Cover cropping is the only technique for improving the N cycle in cultivated soil that scavenges the soil residual N and turns it into nutrients for subsequent crops. Komatsuzaki and Mu (2005) reported that rye cover crops accumulated soil N as the soil residual N level increased (Fig. 7a). The soil inorganic N distribution showed that the inorganic N concentration at a 60–90-cm depth layer was significantly low for rye compared with hairy vetch and fallow at cover crop growth termination (Fig. 7b), and this soil inorganic N reduction was observed to occur year-round (Fig. 7c).

Cover crop systems also reduce the nitrate concentration in vegetable crops, since cover crop residue enhances N immobilization and reduces excess N during the crop growing season (Komatsuzaki and Muranaka 2005). Komatsuzaki et al. (2005) reported that millet was a significant summer cover crop for potato–broccoli rotation, because broccoli following millet showed low nitrate concentration, high ascorbic acid concentration, and high sugar content compared with the following fallow in summer (Fig. 8). This suggests that cover crops may be able to contribute to the scavenging of soil residual N and improve broccoli food quality across the entire fertilizer application system.

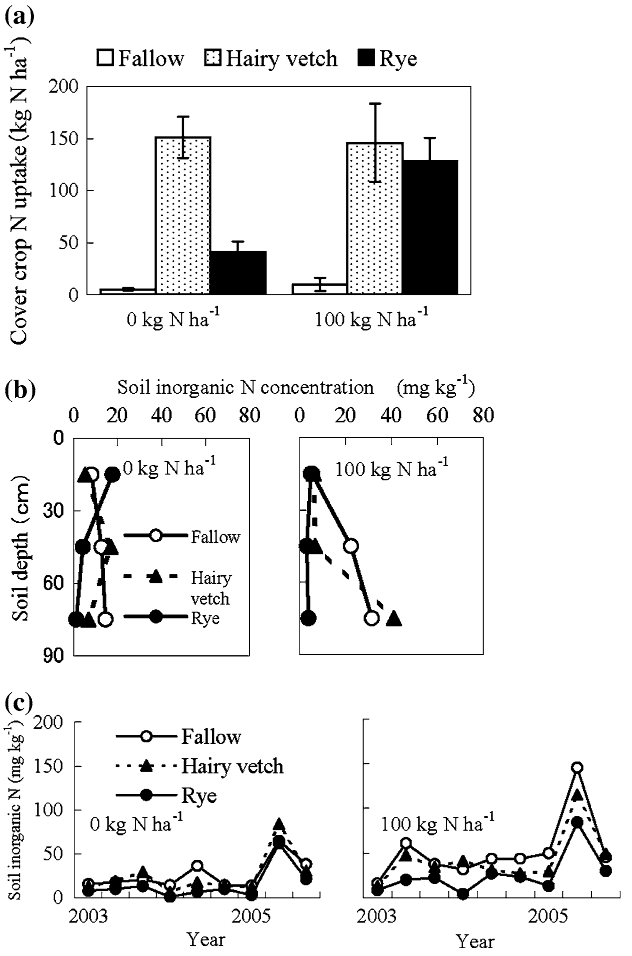

Fig. 7a–c Effect of cover crop species on cover crop N recovery (**a**), soil residual nitrogen distribution (**b**), and soil residual N changes in 60–90-cm depth layer (**c**) in no-till field rice production compared between different N applications. Data from 2004 are shown in **a** and **b**, data for 2003–2005 in **c** (modified from Komatsuzaki and Mu 2005)

Cover crops have many other benefits as well, such as supplying organic matter, adding biological fixed nitrogen, suppressing weeds, and breaking pest cycles (Peet 1996; Magdoff 1998; Sarrantonio 1998). They may also be able to enhance soil ecological diversity and perform activities to improve soil health.

Farmers grow crops or raise livestock to feed their family or to sell to earn a living in a market economy that is becoming increasingly global and competitive. Although soil management strategies for sustainable agro-ecosystems may be benefitting the public as a whole, there may be little or no direct benefit to the farmer. Therefore, when developing a soil management strategy for sustainable agro-ecosystems, some political and social approaches will be needed.

First, political assistance and incentives should be provided to encourage the introduction of integrated soil management practices that can increase SOM

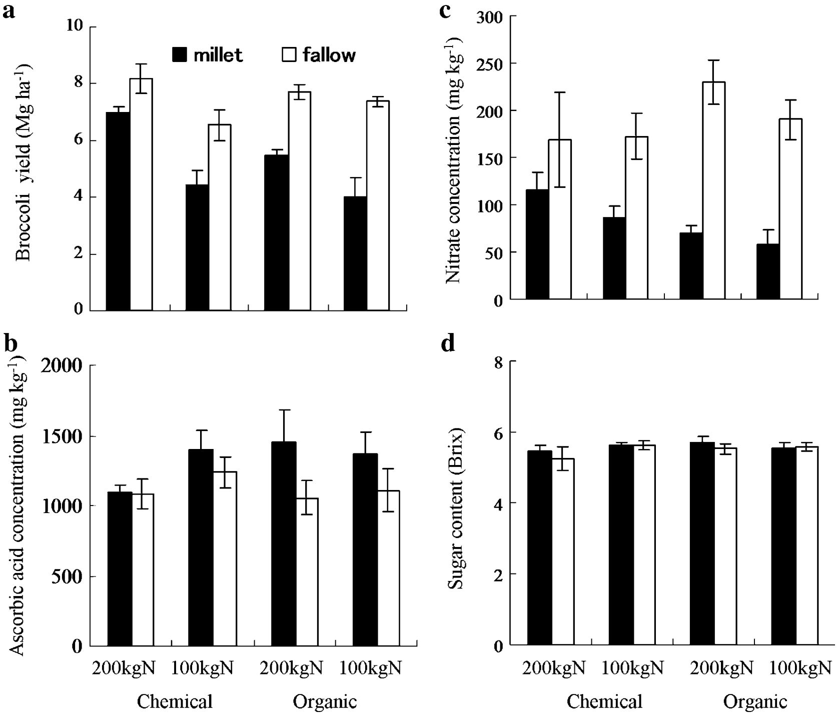

Fig. 8a–d Broccoli yield (**a**), ascorbic acid concentration (**b**), nitrate concentration (**c**), and sugar content (**d**) in broccoli heads and their relation to summer cover crop. Broccoli was grown following millet as a cover crop or fallow treatment at different fertilizer applications (fertilizer type=chemical and organic; input rate=200 kg N ha^{-1} and 100 kg N ha^{-1}) in Ibaraki, Japan. The *vertical bars* indicate the standard error (modified from Komatsuzaki et al. 2005)

management and control soil residual nutrients. For example, the city of Ushiku, located in the northern part of the Kanto area of Japan, implemented a cost sharing program in 2004, in which the city will share the cost for cover crop seed that farmers use in their crop rotation. This program has succeeded in preventing N leaching and in protecting the soil from wind erosion (Suzuki and Komatsuzaki 2006).

Next, social support, such as volunteer activities in conservation farming, is needed, as rapidly ageing Japanese farmers are managing soil, which is a non-renewable resource, for the next generation. For example, the government of the city of Abiko near Tokyo and various nonprofit organizations are encouraging local residents to assist farmers with conservation farming. Such volunteer activities are helping farmers who introduce conservation farming practices to eliminate synthetic chemical inputs to their farming. Political and social incentives are much more important when they are based on the common understanding that soil and agro-ecosystems are essential for sustaining society.

Conclusions

Concern for soil management will become more common and more noticeable because further increases in agricultural output are essential for promoting equity and maintaining global political and social stability. Soil organic carbon (SOC) has the potential to improve soil structure, provide essential plant nutrients, and play an important role in pollution prevention, groundwater protection, and the enhancement of biodiversity. However, SOC is reactive and an increase in SOC may also have negative impacts on local environments if the soil is not managed properly. Therefore, balanced and integrated increases in the SOC pool, mitigation of non-CO_2 emissions, and the control of soil residual nutrients based on location-specific recommendations will contribute to long-term productivity and adequate economic returns, and help to ameliorate environmental issues.

However, since increases in SOC cause nutrient loss during the fallow season due to microbial decomposition, cover cropping will be a critical tool to control and scavenge soil residual nutrients while maintaining high levels of SOC. To meet the growing demand for and pressures on land and water resources, it will be necessary to develop and adopt eco-specific, eco-friendly, and system-based soil management practices. Research, extension of credit, and other support services will need to be reoriented to help farmers better understand the systems and make appropriate decisions for soil management.

References

Akala VA, Lal R (2001) Soil organic carbon pools and sequestration rates in reclaimed minesoils in Ohio. J Environ Qual 30(6):2098–2104

Arrouays D, Balesdent J, Germon JC, Jayet PA, Soussana JF, Stengel P (2002) Increasing carbon stocks in French agricultural soils? Scientific Assessment Unit for Expertise, the French Institute for Agricultural Research (INRA), Paris, France. Available online at http://www.inra.fr/actualites/rapport-carbone/synthese-anglais.pdf

Barford CC, Wofsy SC, Goulden ML, Munger JW, Pyle EH, Urbanski SP, Hutyra L, Saleska SR, Fitzjarrald D, Moore K (2001) Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest. Science 294(5547):1688–1691

Barriuso E, Laird DA, Koskinen WC, Dowdy RH (1994) Atrazine desorption from smectites. Soil Sci Soc Am J 58(6):1632–1638

Bellamy PH, Loveland PJ, Bradley RI, Lark RM, Kirk GJD (2005) Carbon losses from all soils across England and Wales 1978–2003. Nature 437(7056):245–248

Bleakley BH, Tiedje JM (1982) Nitrous oxide production by organisms other than nitrifiers or denitrifiers. Appl Environ Microbiol 44(6):1342–1348

Bollag JM, Tung G (1972) Nitrous oxide release by soil fungi. Soil Biol Biochem 4:271–276

Brown LR (2004) Outgrowing the Earth. Earth Policy Institute, Washington, DC

Brown L, Scholefield D, Jewkes EC, Lockyer DR, del Prado A (2005) NGAUGE: a decision support system to optimise N fertilisation of British grassland for economic and environmental goals. Agric Ecosyst Environ 109(1–2):20–39

Buyanovsky GA, Wagner GH, Gantzer CJ (1987) Soil respiration in a winter wheat ecosystem. Soil Sci Am J 50(2):338–344

Cambardella CA, Elliott ET (1992) Particulate soil organic matter changes across a grassland cultivation sequence. Soil Sci Soc Am J 56:777–783

Ciais P, Reichstein M, Viovy N, Granier A, Ogée J, Allard V, Aubinet M, Buchmann N, Bernhofer C, Carrara A, Chevallier F, De Noblet N, Friend AD, Friedlingstein P, Grünwald T, Heinesch B, Keronen P, Knohl A, Krinner G, Loustau D, Manca G, Matteucci G, Miglietta F, Ourcival JM, Papale D, Pilegaard K, Rambal S, Seufert G, Soussana JF, Sanz MJ, Schulze ED, Vesalaand T, Valentini R (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437(7058):529–533

Clancy KL (1986) The role of sustainable agriculture in improving the safety and quality of the food supply. Am J Alternative Agric 1(1):11–18

Conrad R (1995) Soil microbial processes involved in production and consumption of atmospheric trace gases. Adv Microbial Ecol 14:207–250

Conrad R (1996) Soil microorganisms as controllers of atmospheric trace gases (H_2, CO, CH_4, OCS, N_2O, and NO). Microbiol Rev 60(4):609–640

Cox MC, Betts RA, Jones CD, Spall SA, Totterdell IJ (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408(6809):184–187

Davidson EA (1991) Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In: Rogers JE, Whitman WB (eds) Microbial production and consumption of greenhouse gases: methane, nitrogen oxides, and halomethanes. American Society for Microbiology, Washington, DC, pp 219–235

Davidson EA, Jansens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440(7801):165–173

Drinkwater LE, Wagoner P, Sarrantonio M (1998) Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396(6708):262–265

Duff B, Rasmussen PE, Smiley RW (1995) Wheat/fallow systems in semi-arid regions of the Pacific NW America. In: Barnett V, Payne R, Steiner R (eds) Agricultural sustainability: economic, environmental and statistical considerations. Wiley, Chichester, UK, pp 87–109

Eichner MJ (1990) Nitrous oxide emissions from fertilized soils: summary of available data. J Environ Qual 19(2):272–280

Elliott ET, Burke IC, Monz CA, Frey SD, Lyon DJ, Paustian K, Collins HP, Halvorson AD, Huggins DR, Paul EA, Turco RF, Cole CV, Hickman MV, Blevins RL, Frye WW (1994) Terrestrial carbon pools: preliminary data from the Corn Belt and Great Plains regions. In: Doran JW, Coleman DC, Bezdicek DF, Stewart BA (eds) Defining soil quality for a sustainable environment. SSSA special publication no. 35. Soil Science Society of America, Madison, Wisconsin, pp 179–191

Ferry JG (1993) Methanogenesis: ecology, physiology, biochemistry and genetics. Chapman and Hall, New York

Finesilver T (1989) Comparison of food quality of organically versus conventionally grown plant foods. Ecological Agriculture Projects Office, McGill University, Quebec, Canada. Available online at http://eap.mcgill.ca/Publications/EAP38.htm

Flessa H, Ruser R, Schilling R, Loftfield N, Munch JC, Kaiser EA, Beese F (2002) N_2O and CH_4 fluxes in potato fields: automated measurement, management effects and temporal variation. Geoderma 105(3):307–325

Follett RF, Shafer SR, Jawson MD, Franzluebbers AJ (2005) Research and implementation needs to mitigate greenhouse gas emissions from agriculture in the USA. Soil Till Res 83(1):159–166

Franzluebbers AJ (2002) Soil organic matter stratification ratio as an indicator of soil quality. Soil Till Res 66(2):95–106

Franzluebbers AJ (2005) Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. Soil Till Res 83(1):120–147

Franzluebbers AJ, Arshad MA (1997) Particulate organic carbon content and potential mineralization as affected by tillage and texture. Soil Sci Soc Am J 61(5):1382–1386

Franzluebbers AJ, Stuedemann JA (2002) Particulate and non-particulate fractions of soil organic carbon under pastures in the Southern Piedmont USA. Environ Pollut 116(Suppl 1):S53–S62

Giardina CP, Ryan MG (2000) Evidence that decomposition rates of organic carbon in mineral soil do not vary with temperature. Nature 404(6780):858–861

Golchin A, Clarke P, Oades JM, Skjemstad JO (1995) The effects of cultivation on the composition of organic matter and structural stability of soils. Aust J Soil Res 33(6):975–993

Goodale CL, Davidson EA (2002) Uncertain sinks in the shrubs. Nature 418(6898):593–594

Grace P, Oades JM (1994) Long-term field trials in Australia. In: Leigh RH, Johnson AE (eds) Long-term experiments in agriculture and ecological science. CAB International, Wallingford, UK, pp 53–81

Gu S, Komatsuzaki M, Moriizumi S, Takahashi M, Ikeda M (2002) Cover crop species and mowing treatment affect the performance of rotary tollage (in Japanese). Jpn J Farm Work Res 37:13–23

Gu S, Komatsuzaki M, Moriizumi S, Mu Y (2004) Soil nitrogen dynamics in relation to cover cropping (in Japanese). Jpn J Farm Work Res 39(1):9–16

Hallberg GR (1987) Agricultural chemicals in ground water: extent and implications. Am J Alternative Agric 2(1):3–15

Hansen S, Mæhlum JE, Bakken LR (1993) N_2O and CH_4 fluxes in soil influenced by fertilization and tractor traffic. Soil Biol Biochem 25(5):621–630

Hayashi Y, Koyama O (2003) Impact on agriculture, forestry and fishery. In: Harasawa H, Nishioka H (eds) Global warming: potential impact on Japan (in Japanese). Kokon-syoin, Tokyo, Japan, pp 133–179

Hudson BD (1994) Soil organic matter and available water capacity. J Soil Water Conserv 49(2):189–194

Hungate BA, Holland EA, Jackson RB, Chapin FS, Mooney HA, Field CB (1997) The fate of carbon in grasslands under carbon dioxide enrichment. Nature 388(6642):576–579

IPCC (1996) IPCC second assessment: climate change 1995. Cambridge University Press, Cambridge, UK

IPCC (2001) Climate change 2001: the scientific basis. Intergovernmental Panel on Climate Change. Available online at http://www.grida.no/climate/ipcc_tar/wg1/index.htm

Ismail I, Blevins RL, Frye WW (1994) Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci Soc Am J 58(1):193–198

Ito T (2002) Soil and plant nutrition science newly developed from field study: acquisition and analysis of data from a new viewpoint. 6. Influence of no-tillage on soil properties and crop growth (in Japanese). Jpn J Soil Sci Plant Nutr 73:193–201

Jackson RB, Banner JL, Jobbàgy EG, Pockman WT, Wall DH (2002) Ecosystem carbon loss with woody plant invasion of grassland. Nature 418(6898):623–626

Johnson JMF, Reicosky DC, Allmaras RR, Sauer TJ, Venterea RT, Dell CJ (2005) Greenhouse gas contributions and mitigation potential of agriculture in the central USA. Soil Till Res 83(1):73–94

Kapkiyai JJ, Karanja NK, Qureshi JN, Smithson PC, Woomer PL (1999) Soil organic matter and nutrient dynamics in a Kenyan nitisol under long-term fertilizer and organic input management. Soil Biol Biochem 31(13):1773–1782

Katoh T (2003) Carbon accumulation in soils by soil management, mainly by organic matter application: experimental results in Aichi prefecture (in Japanese). Jpn J Soil Sci Lant Nutr 73:193–201

King GM (1997) Responses of atmospheric methane consumption by soils to global climate change. Glob Change Biol 3(4):351–362

Kinney CA, Mandernack KW, Mosier A (2005) Laboratory investigations into the effects of the pesticides mancozeb, chlorothalonil, and prosulfuron on nitrous oxide and nitric oxide production in fertilized soil. Soil Biol Biochem 37(5):837–850

Knorr W, Prentice IC, House JI, Holland EA (2005) Long-term sensitivity of soil carbon turnover to warming. Nature 433(7023):298–301

Komatsuzaki M (1999) Cropping system and rotation. In: Endo O (ed) Sustainable agriculture system management (in Japanese). Nourin Toukei Kyoukai, Tokyo, Japan

Komatsuzaki M (2004) Use of cover crops in upland fields (in Japanese). Jpn J Farm Work Res 39(3):157–163

Komatsuzaki M, Mu Y (2005) Effects of tillage system and cover cropping on carbon and nitrogen dynamics. In: Proceedings and abstracts of ecological analysis and control of greenhouse gas emission from agriculture in Asia. Ibaraki, Japan, pp 62–67

Komatsuzaki M, Muranaka K (2005) Organic broccoli production utilizing summer cover crop (in Japanese). Jpn J Farm Work Res 40(1):17–26

Komatsuzaki M, Ishida M, Ozaki Y (2005) Improving soil residual nitrogen leaching using summer cover crops (in Japanese). Jpn J Farm Work Res 40(Extra issue 1):101–102

Kusaba T (2001) Development of soil diagnosis research (in Japanese). J Agric Sci 56(1):7–12

Laird DA, Barriuso E, Dowdy RH, Koskinen WC (1992) Adsorption of atrazine on smectites. Soil Sci Soc Am J 56(1):62–67

Lal R (1995) Global soil erosion by water and carbon dynamics. In: Lal R, Kimble J, Levine E, Stewart BA (eds) Soils and global change. CRC Press, Boca Raton, Florida, pp 131–142

Lal R (1998) Soil erosion impact on agronomic productivity and environment quality. Crit Rev Plant Sci 17(4):319–464

Lal R (2001) World cropland soils as a source or sink for atmospheric carbon. Adv Agron 71:145–91

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304(5677):1623–1627

Laughlin RJ, Stevens RJ (2002) Evidence for fungal dominance of denitrification and codenitrification in a grassland soil. Soil Sci Soc Am J 66(5):1540–1548

Lee JJ, Phillips DL, Lui R (1993) The effect of trends in tillage practices on erosion and carbon content of soils in the US corn belt. Water Air Soil Pollut 70(1–4):389–401

Lemon KM, Katz LA, Rosenberg NJ (1991) Uncertainties with respect to biogenic emissions of methane and nitrous oxide. Discussion paper ENR92-03, report for Climate Resources Program, Resources for the Future, Washington, DC

Liang BC, McConkey BG, Schoenau J, Curtin D, Campbell CA, Moulin AP, Lafond GP, Brandt SA, Wang H (2003) Effect of tillage and crop rotations on the light fraction organic carbon and carbon mineralization in chernozemic soils of Saskatchewan. Can J Soil Sci 83(1):65–72

Maeda M, Zhao B, Ozaki Y, Yoneyama T (2003) Nitrate leaching in an Andisol treated with different types of fertilizers. Environ Pollut 121(3):477–487

Magdoff F (1998) Building soils for better crops, 2nd edn. University of Nebraska Press, Lincoln, Nebraska

Matson PA, Parton WJ, Power AG, Swift MJ (1997) Agricultural intensification and ecosystem properties: human-dominated ecosystems. Science 277(5325):504–509

McCarty GW, Meisinger JJ, Jenniskens FMM (1995) Relationships between total-N, biomass-N and active-N in soil under different tillage and N fertilizer treatments. Soil Biol Biochem 27(10):1245–1250

Ministry of Agriculture, Forestry and Fisheries of Japan (2001) Annual report on food, agriculture and rural areas in Japan. Available online at http://www.maff.go.jp/hakusyo/kaigai/ehakusyo2001.pdf

Mitchell CC, Arriaga FJ, Entry JA, Novak JL, Goodman WR, Reeves DW, Rungen MW, Traxler GJ (1996) The old rotation, 1896–1996: 100 years of sustainable cropping research. Alabama Agricultural Experiment Station Bulletin, Auburn University, Alabama, pp 1–26

Miura N, Ae N (2005) Possibility of leaching of organic nitrogen in a field under heavy application of organic matter: model experiment using soil columns. Jpn J Soil Sci Plant Nurtur 76:843–848

Mosier AR, Duxbury JM, Freney JR, Heinemeyer O, Minami K (1998) Assessing and mitigating N_2O emissions from agricultural soils. Climatic Change 40(1):7–38

Nakagawa S, Tamura Y, Yamamoto H, Yoshida K, Yoshimoto T (2003) Quality comparison of carrots (*Daucus carota* L.)

fertilized organically or chemically, with differences in growth eliminated. Jpn J Soil Sci Plant Nurtur 74:45–53

Nierenberg D, Halweil B (2005) Cultivating food security. In: Renner M, French H, Assadourian E (eds) State of the world 2005. W.W. Norton, New York, pp 62–77

Nishimura S, Sawamoto T, Akiyama H, Sudo S, Yagi K (2004) Methane and nitrous oxide emissions from a paddy field with Japanese conventional water management and fertilizer application. Global Biogeochem. Cycles 18(2):GB2017. DOI: 10.1029/2003GB002207

Nishio M (2005) Agriculture and environmental pollution (in Japanese). Nou-bunn-kyo, Tokyo, Japan

Oberthür S, Ott HE (1999) The Kyoto Protocol: international climate policy for the 21st century. Springer, Berlin Heidelberg New York

Oldeman LR (1994) The global extent of soil degradation. In: Greenland DJ, Szabolic I (eds) Soil resilience and sustainable land use. CAB International, Wallingford, UK, pp 99–118

Peet M (1996) Chapter 1: soil management. In: Peet M (ed) Sustainable practices for vegetable production in the south. Pullins, Newburyport, Massachusetts, pp 1–28

Quiroga A, Funaro D, Noellemeyer E, Peinemann N (2006) Barley yield response to soil organic matter and texture in the Pampas of Argentina. Soil Till Res 90:63–68

Reeves DW (1997) The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Till Res 43(1):131–167

Reinken G (1986) Six years comparison between biodynamic and conventional growing of vegetable and apples. In: Vogtmann H, Boechncke E, Fricke I (eds) The importance of biological agriculture in a world of diminishing resources. Verlagsgrruppe, Witzenhausen, Germany, pp 164–174

Robertson GP, Paul EA, Harwood RR (2000) Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289(5486):1922–1925

Robinson JS, Sharpley AN (1995) Release of nitrogen and phosphorus from poultry litter. J Environ Qual 24(1):62–67

Rodrigues MA, Pereira A, Cabanas JE, Dias L, Pires J, Arrobas M (2006) Crops use-efficiency of nitrogen from manures permitted in organic farming. Eur J Agron 25(4):328–335

Ross MA, Lembi CA (1985) Applied weed science. Macmillan, New York

Sakai N (2002) The relationship between circulation of carbon and farm work: artificial production and reduction of carbon dioxide and methane (in Japanese). Jpn J Farm Work Res 37(4):251–258

Sakai N, Sunohara W, Yonekawa S, Tsunoda K (1988) Assessment of no-tillage farming IV: soil changes and root growth (in Japanese). Jpn J Farm Work Res 23(1):25–32

Sarrantonio M (1998) Building soil fertility and tilth with cover crops. In: Clark A (ed) Managing cover crops profitably, 2nd edn. Sustainable Agriculture Network, Beltsville, Maryland, pp 16–24

Schulze ED, Freibauer A (2005) Environmental science: carbon unlocked from soils. Nature 437(7056):205–206

Schuphan W (1974) Nutritional value of crops as influenced by organic and inorganic fertilizer treatments: results of 12 years' experiments with vegetables (1960–1972). Qual Plant Pl Fds Hum Nutr 23(4):333–358

Schütz H, Seiler W, Rennenberg H (1990) Soil and land use related sources and sinks of methane (CH4) in the context of the global methane budget. In: Bouwman AF (ed) Soils and the greenhouse effect. Wiley, New York, pp 269–285

Scott MJ, Sands RD, Rosenberg NJ, Izaurralde RC (2002) Future N_2O from US agriculture: projecting effects of changing land use, agricultural technology, and climate on N_2O emissions. Glob Environ Change 12(2):105–115

Sehy U, Ruser R, Munch JC (2003) Nitrous oxide fluxes from maize fields: relationship to yield, site-specific fertilization, and soil conditions. Agric Ecosyst Environ 99(1–3):97–111

Sharpley AN, Smith SJ (1995) Nitrogen and phosphorus forms in soils receiving manure. Soil Sci 159(4):253–258

Shively JM, English RS, Baker SH, Cannon GC (2001) Carbon cycling: the prokaryotic contribution. Curr Opin Microbiol 4(3):301–306

Shoun H, Kim DH, Uchiyama H, Sugiyama J (1992) Denitrification by fungi. FEMS Microbiol Lett 73(3):277–281

Six J, Elliot ET, Paustian K (1999) Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci Soc Am J 63(5):1350–1358

Smith MS, Zimmerman K (1981) Nitrous oxide production by nondenitrifying soil nitrate reducers. Soil Sci Soc Am J 45:865–871

Spokas K, Wang D, Venterea R, Sadowsky M (2006) Mechanisms of N_2O production following chloropicrin fumigation. Appl Soil Ecol 31(1–2):101–109

Stamatiadis S, Werner M, Buchanan M (1999) Field assessment of soil quality as affected by compost and fertilizer application in a broccoli field (San Benito County, California). Appl Soil Ecol 12(3):217–225

Stevenson FJ (1972) Organic matter reactions involving herbicides in soil. J Environ Qual 1(4):333–343

Su YZ (2007) Soil carbon and nitrogen sequestration following the conversion of cropland to alfalfa forage land in northwest China. Soil Till Res 92(1–2):181–189

Suzuki K, Komatsuzaki M (2006) Cover crop affect wind erosion (in Japanese). Jpn J Farm Work Res 41(Extra issue 1):151–152

Tiessen H, Cuevas E, Chacon P (1994) The role of soil organic matter in sustaining soil fertility. Nature 371(6500):783–785

Toyota A, Kaneko N, Ito MT (2006) Soil ecosystem engineering by the train millipede Parafontaria laminata in a Japanese larch forest. Soil Biol Biochem 38(7):1840–1850

Tsuruta S, Takaya N, Zhang L, Shoun H, Kimura K, Hamamoto M, Nakase T (1998) Denitrification by yeasts and occurrence of cytochrome P450nor in Trichosporon cutaneum. FEMS Microbiol Lett 168(1):105–110

UNCED (1992) Agenda 21: programme of action for sustainable development. The Rio declaration on environment and development, statement of principles. Final text of agreement negotiated by governments at the United Nations Conference on Environment and Development (UNCED), Rio de Janeiro, Brazil, UNDP, New York, pp 3–14

UNFCCC (1992) United Nations Framework Convention on Climate Change. UNFCCC, Bonn, Germany

UNFCCC (1998) Kyoto Protocol to the United Nations Framework Convention on Climate Change. UNFCCC. Available online at http://unfccc.int/resource/docs/convkp/kpeng.pdf

Wadman WP, de Haan S (1997) Decomposition of organic matter from 36 soils in a long-term pot experiment. Plant Soil 189(2):289–301

Wagger MG, Mengel DB (1988) The role of nonleguminous cover crops in the efficient use of water and nitrogen. In: Hargrove WL (ed) Cropping strategies for efficient use of water and nitrogen. Special publication no. 51. American Society of Agronomy, Madison, Wisconsin, pp 115–127

Wagger MG (1989) Time of desiccation effects on plant composition and subsequent nitrogen release from several winter annual cover crops. Agron J 81(2):236–241

Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (2000) IPCC special report on land use, land-use change and forestry. Cambridge University Press, Cambridge, UK

Weil RR, Magdoff F (2004) Significance of soil organic matter to soil quality and health. In: Magdoff F, Weil RR (eds) Soil organic matter in sustainable agriculture. CRC Press, Boca Raton, Florida, pp 1–44

Weyer P (2001) Nitrate in drinking water and human health. Center for Health Effects of Environmental Contamination, University of Iowa, Iowa. Available online at http://www.cheec.uiowa.edu/nitrate/health.html

Whitman WB, Coleman DC, Wiebe WJ (1998) Prokaryotes: the unseen majority. Proc Natl Acad Sci USA 95(12):6578–6583

Wood S, Sebastian K, Scherr SJ (2000) Pilot analysis of global ecosystems: agroecosystems. International Food Policy Research Institute and World Resources Institute, Washington, DC. Available online at http://www.ifpri.org/pubs/books/page/agroeco.pdf

Yagi K (2002) Mitigation options for methane emission in rice fields. In: Lal R (ed) Encyclopedia of soil science. Dekker, New York, pp 814–818