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The role of soil organic matter in maintaining soil quality in continuous cropping systems

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Abstract

Maintenance and improvement of soil quality in continuous cropping systems is critical to sustaining agricultural productivity and environmental quality for future generations. This review focuses on lessons learned from long-term continuous cropping experiments. Soil organic carbon (SOC) is the most often reported attribute from long-term studies and is chosen as the most important indicator of soil quality and agronomic sustainability because of its impact on other physical, chemical and biological indicators of soil quality. Long-term studies have consistently shown the benefit of manures, adequate fertilization, and crop rotation on maintaining agronomic productivity by increasing C inputs into the soil. However, even with crop rotation and manure additions, continuous cropping results in a decline in SOC, although the rate and magnitude of the decline is affected by cropping and tillage system, climate and soil. In the oldest of these studies, the influence of tillage on SOC and dependent soil quality indicators can only be inferred from rotation treatments which included ley rotations (with their reduced frequency of tillage). The impact of tillage per se on SOC and soil quality has only been tested in the 'long-term' for about 30 yrs, since the advent of conservation tillage techniques, and only in developed countries in temperate regions. Long-term conservation tillage studies have shown that, within climatic limits: Conservation tillage can sustain or actually increase SOC when coupled with intensive cropping systems; and the need for sound rotation practices in order to maintain agronomic productivity and economic sustainability is more critical in conservation tillage systems than conventional tillage systems. Long-term tillage studies are in their infancy. Preserving and improving these valuable resources is critical to our development of soil management practices for sustaining soil quality in continuous cropping systems. © 1997 Elsevier Science B.V.

Keywords: Sustainable agriculture; Soil management; Crop rotation; Crop residues; Soil carbon; Soil physical properties; Long-term experiments; Conservation tillage; Soil quality

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1. Introduction

The United Nations Environment Programme (UNEP) sponsored project, Global Assessment of Soil Degradation (GLASOD) estimates that 38% of all agricultural land has undergone anthropogenic soil degradation (Oldeman, 1992). About 20% is moderately degraded, i.e., farming is still possible but soil productivity is greatly reduced to the extent that major inputs are required to restore the soil to full productivity. Another 6% is strongly degraded, i.e., with such low productivity that farming is not possible without major capital investments and engineering inputs. Developing countries are unlikely to have the necessary capital to restore these soils. Oldeman (1992) defined soil degradation as the process which lowers the current and/or future capacity of soils to produce goods or services. Conversely, Lal referred to soil quality in terms of the capacity of the soil to produce economic goods and services and to regulate the environment (Lal, 1993). Many researchers have defined and refined the term soil quality (Power and Myers, 1989; Larson and Pierce, 1991; Parr et al., 1992; Lal, 1993; Pierce and Larson, 1993; Doran and Parkin, 1994; Acton and Gregorich, 1995; Karlen et al., 1997). As scientists, policy makers, and the general public have become more environmentally conscious, definitions of soil quality have expanded from being associated only with productive potential to the soil acting as an environmental buffer; protecting watersheds and groundwaters from agricultural chemicals and industrial and municipal wastes, and sequestering carbon that would otherwise contribute to global climate change.

Maintaining and improving soil quality is crucial if agricultural productivity and environmental quality are to be sustained for future generations. Increased inputs and technologies in modern agricultural production systems can often compensate for and mask losses in productivity associated with reductions in soil quality. However, increased agricultural inputs not only reduce economic sustainability but also increase the potential for negatively impacting environmental quality (National Research Council, 1993).

Within the time scale for soil formation, humans are newcomers to the planet, appearing within the last 1 million years. Only within the last 10,000 yrs or so have humans shifted their lifestyle from hunter–gatherer to nomadic animal husbandry and finally to cultivation of domesticated crops (Harlan, 1992). At first these crops were cultured in a semi-nomadic style; land was plentiful, so when soil lost its productivity, people abandoned it in favor of new land claimed from the virgin climax vegetation (Parker, 1920). Gradually, as land became scarcer and population densities increased, agriculture evolved to continuous cropping of the same parcel of land. Early cultures soon recognized the benefit of 'resting' the land from continuous cropping using regular fallow periods as evidenced by this well known verse:

> Six years thou shalt sow thy field, and six years thou shalt prune thy vineyard, and gather in the fruit thereof; But in the seventh year shall be a sabbath of rest unto the land, a sabbath for the Lord: Thou shalt neither sow thy field, nor prune thy vineyard. That which groweth of its own accord of thy harvest thou shalt not reap, neither gather the grapes of thy vine undressed: For it is a year of rest unto the land—-Leviticus 25:3–5 (Scofield, 1945).

The fallow rotation later evolved into rotations with forage legumes. This practice has been credited as being the beginning of modern production agriculture, which in turn provided the surplus capital that resulted in the Industrial Revolution (Stinner et al., 1992). Unfortunately, modern production agriculture; highly specialized, highly capitalized, and dependent on ever increasing levels of technology, seems to have forgotten the lessons of the past (Reeves, 1994).

As recent as the development of continuous cropping is, the development of agriculture as a science is newer still. The longest running agricultural experiments (the Classicals) at Rothamsted, England were only begun in 1843 (Jenkinson, 1991). Within this fledgling science, the concept of sustainability is relatively new and the term soil quality is more recent still.

This literature review looks at long-term cropping and tillage experiments and summarizes soil management recommendations learned from these experiments. Soil organic carbon is the most often reported attribute from long-term studies and is chosen as the most important indicator of soil quality and agronomic sustainability because of its impact on other physical, chemical and biological indicators of soil quality.

2. Soil quality indicators

In just a short time from the introduction of the term, agricultural scientists have moved rapidly to develop quantifiable indicators of soil quality. Larson and Pierce (1991) developed the concept of a 'Minimum Data Set (MDS)' which could be used to monitor soil quality. They recommended a set of indicators sensitive to soil management inputs that could easily be determined from relatively standard and straightforward methodologies. A combination of physical, chemical, and biological indicators comprises their minimum data set (Table 1). Arshad and Coen (1992) listed similar physical and chemical criteria and recommended that long-term experiments (20 to 30 yrs) be conducted to determine the impact of management practices on soil quality. Doran and Parkin (1994) expanded the minimum data set listing to include biological properties, in addition to physical and chemical soil properties.

Soil biological properties are more difficult to assess than chemical and physical

Table 1
Minimum data set (MDS) of soil quality indicators proposed by Larson and Pierce, 1991

Soil quality indicator
Nutrient availability
Total organic C
Labile organic C
Texture
Plant-available water capacity
Soil structure (bulk density, K_{sat})
Soil strength (bulk density or penetration resistance)
Maximum rooting depth
pH
Electrical conductivity

properties but biological indicators are critical to characterizing soil quality (Parr et al., 1992). Research is still needed to determine what microbial indicators should be included in a minimum data set for soil quality (Turco et al., 1994). Visser and Parkinson (1992) suggested that laboratory determination of microbial process level indicators like soil organic matter (SOM) decomposition rates, microbial biomass, N cycling, and soil enzymes could rapidly assess changes in soil quality. Stork and Eggleton (1992) proposed three high-priority criteria for measuring soil quality as indexed by soil microfauna, mesofauna, and macrofauna invertebrates. These were: (1) Determination of 'keystone' or 'ecosystem engineer' species, i.e., species that are abundant or play a critical role in the food web of a community (keystone species) or that construct (ecosystem engineer) environments for other species (e.g., earthworms); (2) Determination of taxonomic diversity at the group level; and (3) Quantification of species richness of several dominant invertebrates. The utility of invertebrates as indicators of soil quality has been questioned on the basis that currently no universally acceptable criteria for bioindicator selection exists and the activity of soil fauna, e.g., earthworms, relevant to soil quality may be important but not critical (Linden et al., 1994). Linden et al. (1994) argue that earthworms, for example, may be catalysts to speed soil quality processes like infiltration and crop rooting depth, but these processes proceed in the absence of earthworms, and high quality soils exist despite the absence of this particular bioindicator.

Biological, physical and chemical indicators of soil quality are not independent determinants. As difficult as it is to develop a universally acceptable standard for each of these type indicators, it is even more complex to assimilate these components into a working whole, applicable to a diversity of soil types and agroecosystems. Soil organic matter, however, has long been recognized as a key element in soil quality. Soil organic matter is defined as 'the organic fraction of the soil exclusive of undecayed plant and animal residues' (SSSA, 1987). It is commonly estimated from determinations of organic C. Soil organic carbon (SOC)–SOM conversion factors for surface soils range from 1.724 to 2.0 (Nelson and Sommers, 1982). Soil organic carbon or SOM is integrally tied to many soil quality indicators and is arguably the most significant single indicator of soil quality and productivity (Larson and Pierce, 1991; National Research Council, 1993; Cannell and Hawes, 1994; Robinson et al., 1994). Bauer and Black (1994) actually calculated the benefit per unit SOM on soil productivity of a Typic Argiborol in North Dakota, USA. Doran and Parkin (1994) expanded and refined the MDS of Larson and Pierce (1991) and as one of their recommendations cited the need to determine the role of cropping and soil management systems on SOM and related properties. Bruce et al. (1995), in the Piedmont region of Georgia, USA identified SOC in the surface soil as the most significant soil management variable impacting crop water availability and soil erosion.

Soil C serves as the energy source for microbial processes; respiration and nutrient storage and turnover are soil quality minimum data set indicators vitally dependent on SOC. Other soil quality indicators inextricably linked to SOC are plant available water capacity (Hudson, 1994), infiltration (MacRae and Mehuys, 1985; Boyle et al., 1989; Pikul and Zuzel, 1994), aggregate formation and stability (Tisdall and Oades, 1982; Oades, 1984; MacRae and Mehuys, 1985; Burns and Davies, 1986; Boyle et al., 1989),

bulk density (MacRae and Mehuys, 1985; Soane, 1990; Ekwue and Stone, 1995; Thomas et al., 1995), soil strength (Ekwue and Stone, 1995), cation exchange capacity (CEC) (Chan et al., 1992; Mahboubi et al., 1993; Rhoton et al., 1993; Riffaldi et al., 1994), soil enzymes (Dick, 1984) and invertebrate bioindicators (earthworms) (Hendrix et al., 1992).

The interrelational role of SOC on soil structure and soil physical properties has been extensively reviewed (Tisdall and Oades, 1982; Oades, 1984; Boyle et al., 1989; Carter and Stewart, 1996) and is beyond the scope of this paper. Likewise, it is beyond the scope of this paper to review the characterization and dynamics of SOC turnover. Current characterization of SOM has moved away from definitions of fractions based solely on chemical extraction procedures to definitions based on physical fractionation as well. Physical fractionation better relates to the role SOM plays in soil structure and function (Christensen, 1992; Hassink, 1995) and has been associated with decomposition rates (Buyanovsky et al., 1994; Hassink, 1995). The reader is referred to recent reviews by numerous authors in Carter and Stewart (1996) and to Collins et al. (1997) for a thorough consideration of SOM pools, C stability and turnover, and characterization of SOC in relation to soil aggregation.

3. Sustaining soil quality: Lessons from long-term experiments

Sustainable agriculture by definition is agriculture for the long-term. According to the Third New International Dictionary of Webster (Gove, 1986), one definition of the word sustain is 'to cause to continue; (to) endure'. How can we measure whether an agricultural system, much less some attribute of it, like soil quality, is sustainable, i.e., if it will endure? Sustainability of an agricultural system should properly be measured in millenniums (Sandor and Eash, 1991), not years, decades or even centuries. The longest running agricultural experiments are no more than 150 yrs old, and in researching this review, I found that in the research climate today, any experiment carried on for seven years or more was typically described as 'a long-term experiment' when published.

Biophysical process-oriented simulation models can be used to evaluate agricultural system sustainability. However, model validities are dependent on agronomic data collection and evaluation. The more intensive and varied the database, the more reliable the model. Long-term agricultural experiments are essential to providing the empirical data necessary to evaluate sustainability of agricultural systems (Rains and Cassman, 1990; Dick, 1992; Njøs, 1994; Lal and Stewart, 1995a; Paustian et al., 1995; Steiner, 1995). 'The most convincing proof of the sustainability of any agricultural system is a long-term experiment with positive results' (Steiner, 1995). Lal and Stewart (1995b) are correct in their assessment that the critical cause–effect relationship between soil management and soil quality can only be established through long-term experiments.

3.1. Ancient agricultural sites

The longest running agricultural experiments were 154 yrs old in 1997. Although this represents two human life-spans, it is too short a time span to reliably test the effect of a

given soil management practice on sustainability. Perhaps, the most time-tested data for assessing the impact of soil management practices on agricultural sustainability and soil quality are those of Sandor and Eash (1991). They compared paired (cultivated and uncultivated) landscapes at two ancient agricultural sites, one in New Mexico, USA and another in the Colca Valley of southern Peru. Soils on both sites are Mollisols and both sites are terraced. The site in New Mexico was farmed ca. 1000 to 1150 and the Peruvian site still has terraces under cultivation, some since 1500 a.d., although some fields were abandoned at the time of the Spanish conquest of Peru (ca. 1532). The USA site was cropped predominantly to corn (*Zea mays* L.) while in Peru, a diversity of crops, including corn, potato (*Solanum tuberosum* L.), small grains, fava bean (*Vicia faba* L.), and alfalfa (*Medicago sativa* L.), were grown in rotations and intercropping systems. Manures and hearth ashes were also applied to the Peruvian soils.

At the USA site, bulk density in cultivated A horizons averaged 9% greater than in uncultivated sites and the level of soil compaction after 8 centuries of abandonment was within that reported for soils managed with machinery. The compaction and poor soil structure in the cultivated fields was attributed to loss of SOC, which averaged 46% less in cultivated A horizons than uncultivated A horizons and 35% less in cultivated B horizons compared to uncultivated B horizons. Total N and P showed similar declines under cultivation.

In Peru, both abandoned and continuously cultivated fields had greater total N, P, and SOC in the A horizon than uncultivated fields, as a result of cropping practices and amendments. There was no difference in A horizon bulk density among compared fields. Total N and SOC were actually 10% and 11% greater, respectively, in presently cultivated soils than in soils abandoned some 450 yrs ago. Compared to their uncultivated counterparts, soils continually cultivated had 47% more total N and 30% more SOC. Five centuries of cultivation in the Colca Valley has proven that humans are capable of not only maintaining but improving soil quality under continuous cultivation.

3.2. Rothamsted (UK)

Compared to retrospective study of ancient agricultural sites, classical agricultural experiments are infants, but they still constitute a valuable resource for studying the effect of management on soil quality sustainability. The long-term field studies at Rothamsted are recognized as the longest running experiments in the world. Four of the eight surviving long-term experiments are cropping experiments; two are woodlands and two are forage experiments (Jenkinson, 1991). The cropping experiments include the Broadbalk Wheat Experiment (*Triticum aestivum* L.) (started in 1843), Hoosefield Barley Experiment (*Hordeum vulgare* L.) (started in 1852), and the Hoosefield Alternate Wheat–Fallow Experiment (started in 1856). These experiments have been invaluable in determining the effect of amendments (farmyard manure vs. inorganic N, P, K, and Mg fertilizer) on SOC and for developing models of SOC turnover (Jenkinson, 1991). Annual additions of 35 mg ha^{-1} farmyard manure containing 3000 kg C, 225 kg N, 40 kg P and 210 kg K have markedly increased SOC compared to no manure additions or the use of N, P, K and Mg inorganic fertilizers. The stability of SOC in this temperate zone and soil type is illustrated by the Hoosefield experiment, where manure

additions for 20 yrs between 1852 and 1871 resulted in SOC levels that still remain greater than the unmanured control. The increased SOC for the silty clay soil at Rothamsted had no influence on cereal yields, which have been similar for manure and inorganic fertilizer treatments. However, a similar experiment on a sandy loam soil at Woburn, begun in 1876, has shown that manured treatments usually increased yields compared to inorganic fertilizers (Jenkinson, 1991) and that SOC declined under continuous cropping, even with manure additions (Powlson and Johnston, 1994). The lack of response in long-term cereal yields to SOC on the Broadbalk experiment has unfortunately led to mistaken generalizations being applied to other soils and climates regarding the importance of SOC for sustained soil productivity (Powlson and Johnston, 1994).

3.3. The Morrow plots, IL, USA

The Morrow plots, established in 1876, are the oldest agronomic research plots in the USA (Odell et al., 1982). The Morrow Plots were established to test the sustainability of a typical midwestern USA prairie soil (a silt loam, Aquic Argiudoll) under continuous cropping (Mitchell et al., 1991). Three cropping systems with corn as the hub crop remain the core of the Morrow plots. The oldest continuous corn plots in the world are the cropping system control treatment. A corn–oat (*Avena sativa* L.) (from 1876–1966) or corn–soybean [*Glycine max* (L.) Merr.] (1966 to present) rotation and a corn–oat–legume (red clover (*Trifolium pratense* L.) (1901–1953) and alfalfa (*Medicago sativa* L.) (1954–present)) rotation make up the other two cropping system treatments. In addition to cropping system variables, fertility variables, including lime, barnyard manure, residual organic and inorganic P sources, and lime–N–P–K input levels, have been added to the experiment by subdividing the cropping system plots over the years (Odell et al., 1982).

On this non-eroded prairie soil, yields have significantly increased linearly or curvilinearly regardless of treatments due to improvements in crop varieties and management practices over time. Dependent on the rotation, adequate fertilization has maintained or restored productivity. However, corn yields have been consistently lowest with monoculture and highest with the corn–oat–legume rotation, regardless of fertilizer treatment.

Soil organic matter has decreased linearly or curvilinearly under all cropping systems and fertility treatments; rates being dependent on treatment (Odell et al., 1984). The decline is greatest for continuous corn and least for the corn–oat–legume rotation and is also greater where no fertilizer amendments or manure were added to the soil. Addition of lime and N–P–K to previously unfertilized plots, beginning in 1955, increased biomass and crop residues, resulting in a reversal of SOM decline in this treatment.

In 1944, the soil in the sod border around the Morrow plots was analyzed for C and N. There is considerable variability in SOM between the eastern and western halves of the plots. Given this, and assuming that the soil in the sod border is representative of the original prairie sod in 1876, the effect of fertilization (manure, lime, and P fertilizer) and crop rotation on SOM can be seen in Table 2. Continuous corn without additions of nutrients in the form of lime, inorganic fertilizers or manures resulted in an average 52%

Table 2
Effect of crop rotation and manure addition on soil organic matter in the Morrow Plots, IL, USA, sampled in 1944 (from Odell et al., 1982)

Crop rotation and ammendment	Organic matter (Mg ha^{-1})	Nitrogen (Mg ha^{-1})
Eastern sod border, no treatment	116.0	6.26
Western sod border, no treatment	98.2	5.47
Corn–oats–clover with manure, lime and phosphorus	95.7	5.10
Continuous corn, no treatment	51.1	2.96

decrease in SOM compared to the 'original' condition. A best management practice of a corn–oat–legume rotation with lime, P and manure fertilizer additions resulted in an average 11% decrease in SOM compared to the 'original' condition after nearly 70 yrs.

The impact of rotations on soil C and structural degradation was determined from sampling in 1991 (Darmody and Norton, 1994). Cropping system induced decreases in soil C levels accompanied a concomitant decrease in aggregate size and stability in the order: Sod border > maize–oat–clover rotation > maize–soybean rotation > continuous maize. Fertilizer and lime treatments had little effect on aggregate properties or soil fabric. Despite greater biomass and accompanying C inputs with higher fertilizer inputs, the type of crop residues (both aerial and below-ground) appear most critical for maintaining stable soil structure. All management systems decreased soil C, aggregate stability and macropore continuity, as judged by sampling from the native sod border. The degradative pressures on this soil are not as great as for many soils, and plant nutrient availability seems the key to its resiliency. Nevertheless, we might ask is even an 11% decrease in SOM per century sustainable?

3.4. Sanborn Field, MO, USA

J.W. Sanborn established what would become the Sanborn Field in Columbia, MO in 1888 in order to answer farmers' questions of how cropping systems affect the soil (Upchurch et al., 1985; Brown, 1993). Nine cropping systems, using corn, oat, wheat, red clover, timothy (*Phleum pratense* L.) in continuous and 2, 3, 4, and 6-yr rotations, and four soil amendment treatments (no-amendment control, barnyard manure, inorganic fertilizer and 1/2 manure rate + 1/2 fertilizer rate) were originally tested in the experiment. Presently, the management systems include 13 cropping practices and 20 soil management treatments, including conservation and conventional tillage. Continuous wheat, corn, and timothy plots with and without 13.4 Mg ha^{-1} manure additions annually, and a 3, 4, and 6-yr rotation treatment have remained unaltered since the inception of the study.

Some of the key findings from the Sanborn Field are shown below (Anderson et al., 1990; Gantzer et al., 1991; Mitchell et al., 1991; Brown, 1993).

(1) After 100 yrs, on slopes of 0.5 to 3%, all the topsoil was eroded from continuous corn and half the topsoil was eroded from the 6-yr rotation. Maintaining soil coverage with longer term intervals of sod or ley has been found critical to reducing soil degradation from erosion with conventional tillage management.

(2) Shorter rotations generally provide greater economic returns but longer rotations were more effective in maintaining soil productivity.

(3) Decline in soil N was less rapid with longer periods of forages in the rotation and less frequent soil cultivation. A faculty member, Hans Jenny, was one of the first scientists to demonstrate that the decline in soil N from virgin prairie soil (35% in 60 yrs) reached an equilibrium based on management system.

(4) Where erosion has decreased topsoil depth, reduced water-holding capacity is the most limiting factor and additions of nutrients have limited value in restoring soil productivity.

(5) Crop rotations affects rhizosphere conditions, influencing nutrient cycling, distribution and soil physicochemical properties.

(6) Cropping systems with legume or grass leys and/or addition of barnyard manure or N fertilizer proved necessary to maintain SOM. After 100 yrs, SOM averaged 1.0% in continuous corn plots without manure or fertilizer, 2.3% with annual application of 13.4 Mg ha^{-1} barnyard manure and 1.9% with N–P–K fertilizer (Brown, 1993). Similar treatments with continuous wheat resulted in SOM concentrations of 1.4%, 2.8%, and 2.2%, respectively. Increased SOM from annual manure additions reduced bulk density by 9% when averaged across rotations, and increased saturated hydraulic conductivity (K_{sat}) by a factor of 9 compared to unfertilized plots.

3.5. The Magruder Plots, OK, USA

The Magruder Plots were established in 1892 at the University of Oklahoma in Stillwater to study fertilizer management in continuous wheat grown on a prairie soil (Udertic Paleustoll) (Webb et al., 1980). Over time, the objectives of the study broadened to include the effect of continuous wheat production and long-term fertilization on soil productivity. Six treatments have continued since its inception, although the plots were physically moved in 1947 (the top 40 cm of soil, including the subsoil were removed and relocated to another site due to campus development pressures). The six treatments include no-amendment controls, inorganic N, P, K, and lime additions and intermittent additions of stable manure (to supply 67 kg N ha^{-1} yr^{-1}). Mitchell et al. (1991) summarized the soil fertility findings from the Magruder Plots. For the first 65 yrs, wheat responded to P application only. After 65 yrs, as soil N levels decreased in the native prairie soil, N also became limiting.

Soil organic matter, and accompanying soil N, declined rapidly during the first 35 yrs and somewhat more slowly during the next 52 yrs as an equilibrium level was approached (Fig. 1). Manure application slowed but did not prevent the loss of SOM and soil N. Although manure applications resulted in a long term (1899 to 1979) wheat yield of 1.55 Mg ha^{-1} compared to 0.96 Mg ha^{-1} without fertilizer, it would seem that one of the best lessons learned from the Magruder Plots is that monocropping wheat, even with manure additions, is not sustainable as evidenced by the loss of SOM and relatively small increase in wheat yields over the long term. The 5-yr average yields from 1975–1979 are only 19% greater than the 5-yr average from 1899–1903 (Webb et al., 1980). The Magruder Plots clearly indicate that monocropping and loss of soil quality severely limit the potential of new germplasm to improve productivity.

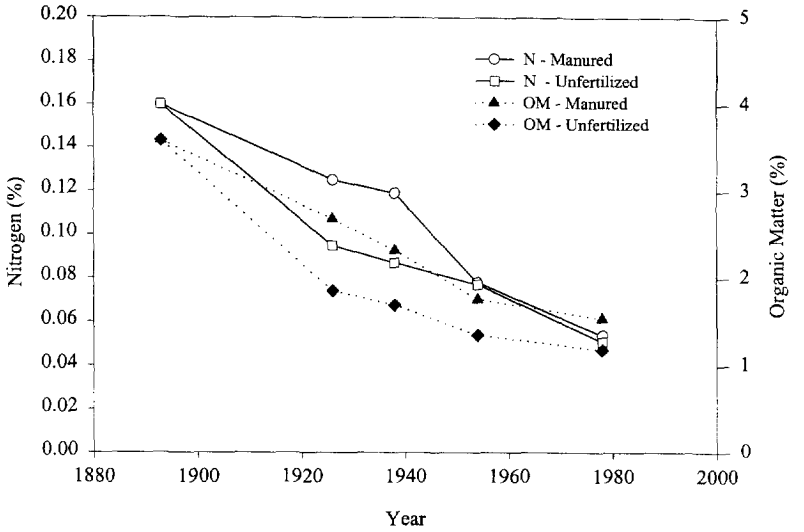

Fig. 1. Nitrogen and organic matter content of surface soil from manured and unfertilized wheat plots in the Magruder Plots, OK, USA (from Webb et al., 1980).

3.6. The Askov long-term fertilization experiment (Denmark)

Most long term study reports have concentrated on crop yields and soil fertility parameters. There are far fewer reports on soil physical properties. One exception is a recent report on physical and chemical properties of the Askov long-term fertilization experiment, initiated in 1894 on a Typic Hapludult in southern Denmark (Schjonning et al., 1994). Schjonning and colleagues sampled the 0–20 cm and 30–35 cm depths of unfertilized, farmyard manured, and inorganic N–P–K fertilized plots of a 4-yr rotation of winter wheat–beet (*Beta vulgaris* L.) or turnip (*Brassica rapa* L.)–barley–clover–grass ley (species not named) after 90 yrs. They determined textural composition, SOC, pH, CEC, particle density, and plasticity limits, uniaxial compression, drop-cone penetration resistance, annulus shear tests, and water-retention curves. In the field, they determined in situ shear strength in the plow layer.

Manure and inorganic fertilizer increased SOC 23% and 11%, respectively, over the 10.7 g kg^{-1} found in the unfertilized plots. This resulted in an increase in CEC of 17% in manured plots and 11% in N–P–K plots compared to unfertilized plots. Bulk density in 0–20 cm layer was reduced in manure and inorganic fertilizer plots. Water retention (−1.5 to −0.006 MPa) was greater in manured and N–P–K fertilized soil than in unfertilized soil, especially in the range of plant available water. The soil managed with manure was more friable at higher water contents than either the untreated soil or the soil managed with N–P–K inorganic fertilizer. Manure resulted in increased soil strengths as determined by annulus shear, drop-cone penetration, and confined uniaxial compression tests. However, in situ field techniques could not detect differences in shear strength due to soil management. In summary, the lack of fertilization and resulting

decrease in biomass returned to the soil reduced SOC and consequently diminished several physical indicators of soil quality.

3.7. The Old Rotation, AL, USA

The Old Rotation was initiated in 1896 on a Typic Hapludult at Auburn University in east central Alabama. It is the oldest continuous cotton (*Gossypium hirsutum* L.) experiment in the world, and the third oldest field crop experiment in the USA on its original site (Mitchell et al., 1991, 1996). Cropping soils to cotton is especially detrimental to soil quality because cotton is a low residue crop; it enjoys a strong economic comparative advantage and is therefore often grown in continuous monoculture; and it is predominantly (> 95%) grown using conventional rather than conservation tillage (Reeves, 1994). There are 13 plots in the Old Rotation. Rotation treatments include:

1. Continuous cotton; with (a) No N supplied, (b) With 134 kg N ha^{-1} yr^{-1}, or (c) N supplied using a winter legume cover crop of crimson clover (*Trifolium hirsutum* L.) or common vetch (*Vicia sativa* L.).
2. 2 yrs cotton—corn rotation; with (a) Winter legume, or (b) Winter legume plus 134 kg N ha^{-1} yr^{-1}.
3. 3 yrs rotation of cotton–winter legume–corn–winter cereal [wheat or rye (*Rye secale* L.)]–soybean [*Glycine max* (L.) Merr.].

Improved technology (i.e., improvements in management, equipment, varieties, fertilizers, weed control and pesticides) has increased yields in all plots but long-term yield data show the benefit of crop rotation and cover crops (Mitchell et al., 1996). Average seed cotton yields of continuous cotton without rotation, fertilizer N, or winter legume cover crops increased 16% from the first 10 yrs of the study (1896–1905) compared to the most recent 10-yr period 1986–1995 (Table 3). Yield maintenance in the absence of N from fertilizer or legumes can be explained by the fact that N removal in seed cotton is estimated at about 13.5 kg N ha^{-1} yr^{-1}, the amount determined to be deposited annually from rainfall in Alabama (C.W. Wood, personal communication). Including a winter legume in the cropping system resulted in an average 160% yield increase during the same period. Yields in the cotton—corn rotation with winter legume and inorganic N fertilizer increased 188% during the same period and the 3-yr cotton–corn–soybean rotation with alternating legume–cereal winter covers resulted in an average increase of 203%.

In 1994, we sampled the plow layer (0 to 26 cm) for differences in selected soil properties as affected by management (Table 3). Soil organic C has been substantially reduced under continuous cotton in the absence of legumes or fertilizer N. The winter legume cover crop (crimson clover and common vetch) greatly increased SOC compared to continuous cotton, with or without fertilizer N. Management systems (2- or 3-yr rotations and fertilizer N) that increase biomass and C input into the soil further increased SOC.

Physical soil quality indicators reflect differences in SOC as a result of management systems. Continuous cotton without a legume cover crop resulted in the lowest percentage water stable aggregates and K_{sat}. The 3-yr rotation, with copious residues returned

Table 3
Effect of cropping system on seed cotton yield and selected soil attributes from the Old Rotation experiment, Auburn, AL, USA (data from Reeves in Mitchell et al., 1996)

Treatment	SOC ($g\ kg^{-1}$)	[a]Penetrometer resistance (MPa)	Water stable aggregates (%)	K_{sat} (1×10^{-3} $cm\ s^{-1}$)	Mean yield 1896–1905 ($kg\ ha^{-1}$)	Mean yield 1986–1995 ($kg\ ha^{-1}$)
I: Continuous cotton						
No legume cover crop	3.9	2.9	24	1.37	896	1042
Legume cover crop	7.5	2.8	38	1.39	963	2498
Fertilizer N[b]	5.4	2.0	22	2.89	[c]	2083
II: 2 yr rotation[d]						
Legume cover crop	8.2	1.9	40	2.56	974	2565
Legume cover crop + fertilizer N	10	2	38	2.84	997	2867
III: 3 yr rotation[e]	10.1	1.9	39	3.66	829	2509

[a]Mean, averaged every 2-cm to 30-cm depth.
[b]134 kg N ha^{-1} yr^{-1}.
[c]Treatment not included in initial experiment design in 1896.
[d](yr 1) cotton–(yr 2) corn.
[e](yr 1) cotton–winter legume cover crop–(yr 2) corn–winter small grain with 67 kg N ha^{-1}–(yr 3) soybean.

to the soil from corn, clover, and rye, resulted in the lowest bulk density, penetration resistance, and greatest K_{sat}. For this highly weathered soil, management systems affect SOC, with beneficial effects on physical properties and resultant soil productivity. With thorough documentation of the first 100 yrs data from the Old Rotation (Mitchell et al., 1996), future plans are to determine if the benefits of rotations and cover crops can be enhanced by conservation tillage, as reported by other researchers based on shorter term experiments with similar soils and climates (Langdale et al., 1990; Wood et al., 1991; Bruce et al., 1995; Hunt et al., 1996).

3.8. The Glenn Innes rotation experiment (Australia)

In order to address exploitation of basaltic prairie soils in the Northern Tablelands of New South Wales by continuous cereal cropping, the New South Wales Department of Agriculture established a crop rotation experiment in 1921 with the objective of maintaining economic yields without degrading the soil (Norton et al., 1995). Seven rotation treatments using varying frequencies of corn and spring oat, with and without autumn oat, and a red clover (*Trifolium pratense* L.) ley grazed by sheep (1921–1960) or cut for hay (1961–present) comprise the test. The rotations are based on a 12-yr cycle and during the 12-yr cycle the red clover ley occupies anywhere from 0 to 60 months, dependent on rotation treatment. Total fallow periods during the cycle range from 36 to 72 months.

Corn and oat yields were improved with length of the clover ley and all crop yields were generally maintained in rotations that contained the grazed clover ley. However, after 1960 when the clover was removed as hay, crop yields declined. The authors attributed the positive effect of winter oat to its acting as a catch crop, reducing leaching

losses of nutrients and recycling them in the rotation. The beneficial effects of the clover ley were attributed to fixed-N and improved soil chemical, physical, and biological properties but no soil data were presented.

3.9. Permanent rotation trial at the Waite Agricultural Research Institute (Australia)

Kay and colleagues determined the effect of long-term (established 1925) cropping systems of continuous pasture, continuous wheat, wheat–fallow rotation, and varying phases of a 2-yr wheat–4-yr pasture rotation on tensile strength and aggregate stability of a Calcic Rhodoxeralf in South Australia (Kay et al., 1994). Soil organic C decreased with reduced frequency of pasture in the rotation and was least when a fallow period was included in the rotation. A positive linear relationship exists for both soil C and N in the 10 cm depth and frequency of pasture in rotation (Grace and Oades, 1994). Carbon in the 0–5 cm depth ranged from 31.8 g kg^{-1} in continuous pasture to 10.0 g kg^{-1} in the wheat fallow rotation. Cropping systems management resulted in stratification of SOC dependent on the intensity of cultivation (or frequency of wheat) used in the rotation. Wet aggregate stability declined in the order continuous pasture > wheat–pasture > wheat–fallow > –continuous wheat. Aggregate stability declined with depth and the decline was correlated to the decline in SOC with depth. Tensile strength increased with depth, as a result of less severe wetting events rather than changes in SOC or other soil properties with depth. Wet aggregate stability was more sensitive to rotation than tensile strength.

Grace and Oades (1994) reviewed the impact of rotations in the long-term studies at Waite and elsewhere on soil physical properties. By the 1970s, research had demonstrated the detrimental effect of summer fallow on SOM and consequent structural degradation of the Red–brown soils of southern and southeastern Australia. A rotation including 2 yrs pasture for every year of cereal was determined to be necessary to maintain soil structural stability. Structural stability of soils from the long-term trials was shown to be due primarily from polysaccharides in cropped soils as well as root systems and associated vesicular arbuscular mycorrhiza (VAM) in systems with pastures (Tisdall and Oades, 1980; Grace and Oades, 1994).

An interesting biological characteristic of soil quality reported from the Waite plots was an increase in the population of mycophagous amoebae under a pasture–pasture–wheat rotation compared to continuous wheat. The increased amoebae populations in the rotation which included pasture were associated with soil suppressive to take-all disease (*Gaeumannomyces graminis tritici*) (Chakraborty, 1983).

3.10. Westsik crop rotation experiment (Hungary)

The Westsik Crop Rotation Experiment was established in 1929 in Nyíregyháza, northeastern Hungary, to determine the long-term effects of organic manures and inorganic fertilizers on yields of rye and potato (Lazányi, 1994). Rye and potato had been grown on the sandy soil for many years before the initiation of the experiment and the soil was depleted of nutrients and organic matter. Treatment variables are various rotations of fallow, rye, potato, and lupin (*Lupinus* sp.): organic matter amendments of

lupin (harvested for grain and residue plowed, grain not harvested but plowed as green manure, or harvested for forage), rye straw as mulch or incorporated composted rye straw, farmyard manure, and rye forage—lupin green manure combinations; and rates of N, P, and K inorganic fertilizer.

Soil organic matter has declined steadily with fallowing (to about 4.4 g kg^{-1}) and has not reached equilibrium for this cropping system, soil and climate. Composted straw manure additions were effective in increasing organic matter but lupin green manure treatments maintained but did not increase organic matter under the rye–potato cropping system. The quantity of biomass from lupin green manuring was not measured. Legume crops are generally not as effective in increasing SOC as grasses, due to the amount of residue produced and the narrower C:N ratio of residues. Fertilizer additions increased crop productivity, biomass returned to the soil and consequently, soil organic matter. Additions of 26.1 Mg ha^{-1} composted straw or farmyard manure every 3 yrs is linearly increasing organic matter and has not yet reached an equilibrium. Soil organic matter in these treatments is currently in the range of 7.4 to 8.8 g kg^{-1}. Both rye and potato yields were linearly correlated positively with soil organic matter. Although lupin green manure has not increased soil organic matter, long-term rye yields are greater in rotations with lupin, indicating an effect on another soil quality parameter, i.e., soil N.

3.11. Long-term residue management experiment, OR, USA

In 1931, a study was begun to evaluate the long-term effects of inorganic N fertilizer, organic amendments, and residue management on grain yield and soil quality in a winter wheat–fallow production system in the semi-arid Columbia Plateau near Pendleton, OR, USA (Rasmussen and Parton, 1994; Duff et al., 1995). The area has been cultivated since the mid 1880s; as yields declined annual cropping gave way to a cereal grain–fallow rotation. The silt loam soils (Typic Haploxerolsl) are prone to erosion due to lack of soil coverage during winter when precipitation occurs, frozen soil during precipitation events, and sloping topography (Duff et al., 1995).

Currently, nine treatments comprise the study. They include selected combinations of: Annual applications of organic amendments, pea vines (*Pisum sativum* L., 2.24 Mg Ha^{-1}) or barnyard manure (22.4 Mg ha^{-1}); inorganic N fertilizer rates (0, 45 or 90 kg N ha^{-1}); and residue management (fall or spring burning vs. fall or spring disking).

Similar to cotton yields on The Old Rotation experiment, wheat yields have increased linearly over time due to improved germplasm and crop management technologies (Duff et al., 1995). The manure amended treatment has consistently produced the greatest yield with near equivalent yields from the 90 kg N ha^{-1} treatment. During the last 10 yrs, reported yields declined where residue is burned compared to no burning. Carbon inputs in the fall burned treatment are reduced 67% compared to no burning (Rasmussen and Parton, 1994). Differences in C and N inputs from management systems are reflected in changes in SOC and soil N (Fig. 2). Soil organic C continues to decline except where copious amounts of manure have been added. The decline in SOC and soil N is nearly linear and there was no evidence that an equilibrium has been reached after more than 100 yrs of cropping. The detrimental effect of straw burning in this agroecosystem did not manifest itself on SOC or productivity until 20 to 30 yrs later (Rasmussen and

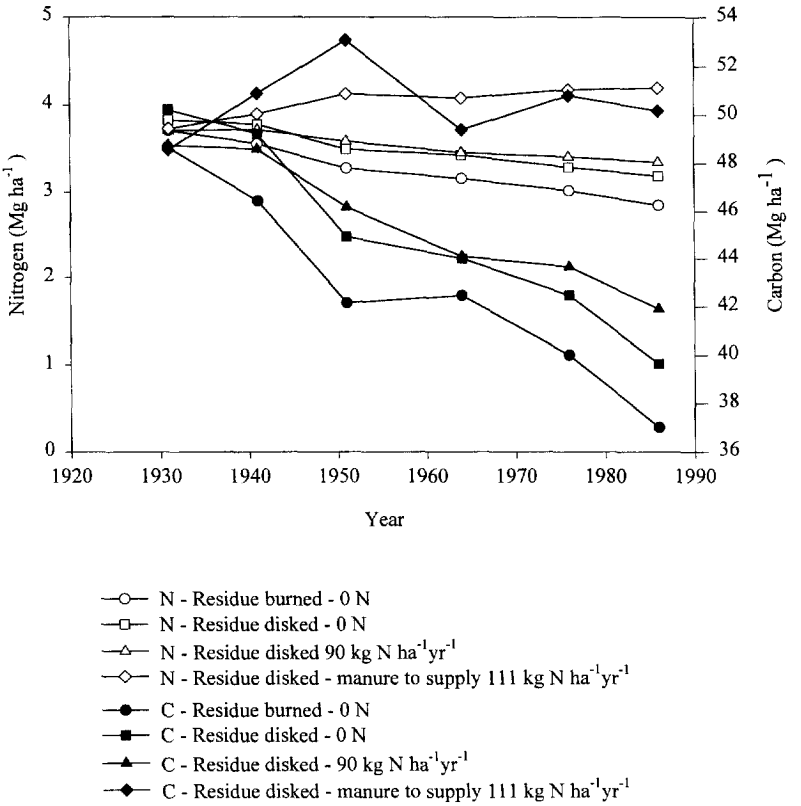

Fig. 2. Soil organic C and organic N (0 to 30 cm depth) from long-term residue management study, Pendleton, OR, USA, as affected by amendment and residue management (from Duff et al., 1995).

Parton, 1994). This underscores the importance of long-term studies; such a finding could not have been realized if this experiment had been terminated after 3 to 5 yrs, as is the common practice in research today.

3.12. Crop rotation experiment, Alberta (Canada)

A similar type experiment as in Pendleton was established at the Agriculture Canada Research Station at Lethbridge, Alberta, Canada (Bremer et al., 1994; Johnston et al., 1995). Rotations include fallow–wheat combinations (1 yr or 2 yrs) and continuous wheat with or without 80 kg N ha^{-1} yr^{-1}. A fallow–2-yr wheat rotation with annual applications of livestock manure, a fallow–2 yr wheat–3 yr–alfalfa–crested wheat grass (*Agropyron* spp.) mixed ley, and a native grass (*Agropyron* spp.) system are also included. The native grass treatment and N fertilizer treatments were added in 1985. The prairie soil is an Orthic Dark Brown Chernozemic (Typic Haploboroll) clay loam.

Bremer et al. (1994) sampled the study in 1992 to determine management effects on

total, light fraction (mineral-free, incompletely decomposed organic residues separated by a densiometric technique) and mineralizable soil organic matter. Averaged across rotation phases, total and labile organic matter (indicated by light fraction and mineralizable C and N) were increased by manure addition, ley period, native grass sod, and reductions in frequency of fallow. Light fraction organic matter was more sensitive to soil management system than total organic matter. Native grass and continuous wheat cropping systems resulted in the highest concentrations of total and labile organic matter in the 0 to 7.5 cm depth and hay production from the mixed species ley increased organic matter in the 15 to 30 cm depth. Unlike other long-term studies (Odell et al., 1982; Brown, 1993; Schjonning et al., 1994; Mitchell et al., 1996), N fertilization did not result in increased soil organic matter compared to systems with no N additions. This was explained by the lack of yield response to N, which would have increased residue inputs.

3.13. Rotation experiment, Ås (Norway)

After World War II, continuous row crop or small grain rotations became the prevalent cropping systems in southeastern Norway, with less emphasis on sod-based rotations (Uhlen et al., 1994). A study was begun in 1953 to determine the long-term effects of rotations on sustainability of cropping systems in the region. Six-year rotations were: (i) 6 yrs of cereal grains (barley, wheat and oat); (ii) 3 yrs cereal grain + 3 yrs row crops [potato, beet (*Beta vulgaris* L.), and swedes (species unknown)]; (iii) 2 yrs ley (timothy with or without red clover) + 4 yrs cereal grain; and (iv) 4 yrs ley + 2 yrs cereal grain. In addition, three fertilizer treatments were imposed: Low rate inorganic fertilizer; medium (normal recommended) rate inorganic fertilizer; and medium rate inorganic fertilizer + farmyard manure (60 Mg ha^{-1} on barley and potato). Cereal straw was incorporated or removed on the 6 yrs cereal and 3 yrs cereal + 3 yrs row crop rotations.

Rotations significantly affected the concentration of total soil C and N when sampled in 1984 (Uhlen, 1991). Treatments that increased N and C input over time, i.e., fertilizer and manure, resulted in commensurate increases in soil N and C. The row crop rotation resulted in the lowest soil C and N, averaging 32.7 g C kg^{-1} and 2.84 g N kg^{-1} with the low rate of N–P–K fertilizer. Values increased to 35.2 g C kg^{-1} and 3.06 g N kg^{-1}, respectively, with N–P–K and manure fertilization. The largest C and N concentrations were obtained in the 4-yr ley + 2-yr cereal rotation, averaging 36.5 g C kg^{-1} and 3.26 g N kg^{-1} with the low rate of N–P–K fertilizer, and 39.6 g C kg^{-1} and 3.49 g N kg^{-1} with N–P–K fertilizer + manure. Straw incorporation only slightly increased soil C and N.

Aggregate stability increased with duration of ley in the rotation and stability was least in the cereal rotation with row crops of beet, swedes and potato (Skoien, 1993). Manure also increased aggregate stability but like soil C and N, incorporation of straw had little effect on aggregate stability. Aggregate stability was linearly correlated with total soil C, however, the relationship was weak (all R^2 values < 0.36). This was attributed to the relatively high soil C concentration of this particular soil (range 29.8 to

39.5 g C kg^{-1}). This study illustrates that even on a soil with high SOM, sod-based rotations or leys are critical for maintaining soil quality.

3.14. The Ultuna long-term soil organic matter experiment (Sweden)

This experiment, established in 1956, is located in central Sweden on a Typic Eutrochrept (Gerzabek et al., 1994). Five treatments: (1) No-N, no-crop; (2) No-N with cereal (unspecified) and oil seed rape (*Brassica napus* L.); (3) Green manure (unspecified); (4) Farmyard manure; and (5) Sphagnum peat are being used to determine the long-term effects of organic amendments on soil organic matter. The organic amendments (4.0 Mg ha^{-1} yr^{-1} ash-free basis organic matter) were added to the plots in 1956, 1960, and 1963. Since 1963 they have been added biennially. Above-ground biomass is totally removed at harvest. Initial SOC averaged 15.0 g kg^{-1} and total soil N averaged 1.7 g kg^{-1}. Sampling in 1994 showed that aggregate stability increased in the order farmyard manure > peat > green manure > no-N with cropping > no-N and no-crop. Not surprisingly, increased aggregate stability was a function of SOC concentration. Although peat amendments resulted in the highest SOC (31.4 g kg^{-1}), the high C:N ratio (63:1) and resulting seven-fold reduction in microbial biomass compared to other amendments reduced the effectiveness of peat to form stable aggregates. Similar to other long-term studies reviewed previously (Odell et al., 1984; Jenkinson, 1991; Brown, 1993; Lazányi, 1994; Duff et al., 1995), steady additions of farmyard manure maintained or slightly increased SOC (16.4 g kg^{-1} average). In the absence of N fertilizer, cropping increased SOC 18% and water-stable aggregates 145% compared to no-cropping, as a result of root biomass and associated bioactivity.

3.15. Other shorter-term studies (Duration 8 to 60 yrs)

The effect of 3, 20, and 60 yrs of cultivation on selected physical and chemical properties of an Aridic Argiustoll in the Central Great Plains of northeastern Colorado, USA, was determined by Bowman et al. (1990). They sampled four contiguous sites: Native rangeland, or 3, 20, or 60 yrs of clean-tilled cropping (primarily a history of wheat–fallow rotation) for total and labile C, N, and P, particle-size analysis, pH, bulk density, CEC, and plant available water holding capacity (−0.03 to −1.5 MPa). Decreasing silt content and increasing sand content in the surface (0 to 15 cm) with years in cultivation was attributed to wind erosion. After 60 yrs of cultivation, total SOC, N, and P had declined by 55 to 63% in the surface 15 cm, with about half the decline occurring in the first 3 yrs of cultivation. Over 80% of the loss of labile C, 60% of the loss of labile N, and 60% of the organic P loss occurred during the first 3 yrs. The loss of organic matter and silt after just 3 yrs cultivation decreased CEC in the surface soil from 14.2 to 8.8 $cmol_c$ kg^{-1}. The data presented in this paper show that this sandy soil is especially vulnerable to degradation caused by the normal or standard cropping system used in this area (i.e., a clean-tilled wheat–fallow rotation).

Following approximately 50 yrs of cultivation under wheat–fallow rotation, researchers in southwestern Saskatchewan determined the effect of 24 yrs of crop rotations on SOC and N on an Aridic Haploboroll (Campbell and Zentner, 1993). Rotations included: Fallow (weed control by tillage)–1 or 2 yrs spring wheat; fallow–winter

rye–spring wheat; chemical fallow–winter wheat–winter wheat; continuous spring wheat; fallow–flax (*Linum usitatissimum* L.)–spring wheat; and spring wheat–lentil (*Lens culinaris* L.).

In this arid environment, changes in SOC were limited to the top 15 cm of soil and were greatly affected by rainfall and consequent crop yields–associated residues returned to the soil. Soil organic C, averaged over 4 samplings during the 24-yr period, ranged from 28.6 to 35.2 Mg ha^{-1}. During the first 15 yrs of rotations (following 50 yrs of wheat–fallow rotation), SOC increased in well-fertilized annually cropped rotations and was maintained in fallow rotations. However, with severe droughts during 3 of the next 9 yrs, all systems except the one containing a winter cereal failed to maintain SOC. The winter cereal system took advantage of off-season precipitation and a shorter fallow period (14 vs. 21 months) to produce more residues that maintained SOC. The fallow–flax–wheat system resulted in the lowest SOC (28.6 Mg ha^{-1}) due to low residue production by flax, greater loss of N from leaching of NO_3, and loss of flax residue from plots by wind. Soil organic C was inversely related to apparent soil N deficit (N removed in grain—fertilizer N). After only 12 yrs in the wheat–lentil system, there was a tendency for the added N from the legume to result in increased SOC and soil N compared to the monoculture wheat systems.

Researchers in Iowa, USA, determined SOC from three soil types (Typic or Aquic Hapludult) managed for 12 to 36 yrs with five rotations and two N fertility levels (Robinson et al., 1996). Rotations were: (1) Continuous corn (for grain or silage), (2) Corn–soybean, (3) Corn–corn–oat-meadow (alfalfa and red clover), and (4) Corn–oat–meadow–meadow (cut for hay). Noncropped soils under adjacent fence rows were also sampled, as was a 75-yr duration continuous corn experiment with 40 yrs of N–P–K treatments. All cropping systems had 22 to 49% less SOC than adjacent fence rows. Soil organic carbon decreased in the order corn–oat–meadow rotations > continuous corn for grain > corn–soybean > continuous corn for silage. Fertilization increased SOC 22% compared to non-fertilized treatments on the continuous corn–N–P–K experiment and the increase in SOC was linearly related to annual residue production. Although fertilization increased SOC compared to no fertilization, similar to other studies (Hageman and Shrader, 1979; Odell et al., 1984; Uhlen, 1991; Darmody and Norton, 1994; Mitchell et al., 1996), rotations were more critical to maintaining SOC than fertilizer additions.

Varvel (1994) evaluated the effect of seven cropping systems and three N fertilizer rates (dependent on crop) on total soil C and N after 8 yrs production on a Typic Argiudoll in NE, USA. Cropping systems included monocultures, 2-yr rotations and 4-yr rotations from combinations of corn, soybean, grain sorghum (*Sorghum bicolor* L. Moench), and leys of oat + clover (*Melilotus officinalis* Lam. and *Trifolium pratense* L.). Soil C and N averaged 16.9 g kg^{-1} and 1.6 g kg^{-1}, respectively, in the 0 to 7.5 cm depth at the initiation of the study. Soil C and N (0 to 7.5 cm) in the 2-yr rotations averaged 16.6 g C kg^{-1} and 1.59 g N kg^{-1}, respectively, after 8 yrs. At the end of the study, 4-yr rotations actually increased soil C and N by 7.7 and 7.5%, respectively, (to 18.2 g C kg^{-1} and 1.72 g N kg^{-1}). Soil C and N generally decreased with continuous cropping. Nitrogen fertilizer also increased soil C and N by 4.7 and 5% at the highest N rate compared to initial values. Frequency of the low residue crop, soybean, decreased

soil C and N and the oat + clover ley was especially effective in increasing soil C and N. The results of Varvel are interesting in that they suggest that rotations and adequate N fertilizer can maintain or even increase C and N, even under conventional tillage, for this prairie soil in a dry, temperate environment.

New Zealand researchers compared sets of adjacent farms that had been managed from 8 to 18 yrs conventionally or 'biodynamically' in regards to soil quality and economics (Reganold et al., 1993). 'Biodynamic' farms, like 'organic' farms, use no synthetic chemical fertilizers or pesticides. 'Unlike organic farmers, biodynamic farmers add eight specific preparations, made from cow manure, silica, and various plants, to enhance soil quality and plant life' (Koepf, 1989 in Reganold et al., 1993). Biodynamic farms typically used green manures, crop rotation, barnyard manures, composts, bone meal, fishwastes, seaweed, and rock phosphate instead of commercial N–P–K fertilizers as were used on conventional farms. In all, 16 farms were sampled, with 7 of the 16 managed as biodynamic farms. Bulk density and penetration resistance (0 to 20 cm depth) were significantly less under the biodynamic management compared to conventional farms. Soil organic C, respiration, CEC, total N, mineralizable N, ratio of mineralizable C:N, and topsoil thickness were significantly greater than on conventional farms. Extractable P and pH, however, were significantly greater on conventional farms. Unfortunately, no mention was made of specific tillage practices, crop rotations, or inputs of plant nutrients and residues–manure. Consequently, quantification of specific effects on soil quality parameters is lacking. However, the data support traditional field plot experiments that illustrate the benefits to soil quality of increased organic inputs through crop rotations and animal and green manures.

As stated earlier, cotton cropping systems typically are grown in continuous monoculture and are especially detrimental to soil quality (see The Old Rotation). Compared to other crops, few long-term studies have evaluated cotton management system effects on soil quality. Researchers in Arkansas, USA, however, conducted a long-term cotton production study for 17 yrs using winter cover crops of rye + crimson clover, hairy vetch (*Vicia villosa* Roth), rye + hairy vetch, or no cover crop (Keisling et al., 1994). The cotton was grown on an Aeric Ochraqualf using conventional tillage practices (disk-harrowing) and recommended rates of N–P–K fertilizer based on University of Arkansas soil testing recommendations. The researchers determined SOM, pH, plant nutrient concentrations, electrical conductivity, K_{sat}, water retention and bulk density from undisturbed samples from the 0 to 15 cm depth. For the most part, only data from the rye + vetch and no cover crop treatment were presented in the paper. Soil organic matter increased from 12.0 g kg^{-1} with no cover crop to 13.7 g kg^{-1} with rye + vetch. Hydraulic conductivity increased from 1.91 without cover to 4.29 cm h^{-1} with rye + vetch but there was little change in bulk density (1.35 g m^{-3} without cover and 1.30 with rye + vetch cover). The rye + vetch cover increased total porosity by 7% and plant available water (PAW, −0.01 to −1.5 MPa) by 3% compared to no cover crop. Improvements in soil quality from inclusion of a winter cover crop were likely diminished by the use of conventional tillage practices. In a corn production system in a similar climate, significant increases in SOC and improved physical and chemical properties were reported from using a winter legume cover crop after only 36 to 44 months with conservation tillage (Reeves and Wood, 1994).

Table 4
Long-term tillage experiments reviewed by Cannell and Hawes (1994)

Reference	Location	Experiment duration at report (yr)	Tillage variables	Soil properties measured
Unger, 1982	TX, USA	36	Sweep tillage, disk	SOM, aggregate size distribution, modulus of rupture, penetration resistance, clod bulk density, particle size distribution
Bauer and Black, 1981	ND, USA	25	Stubble mulch (sweep tillage), conventional tillage (moldboard plow, chisel plow, disk), native sod	SOC, total N, bulk density
Follet and Peterson, 1988	NE, USA	16	Stubble mulch, no tillage, moldboard plow, native sod	SOM, pH, total P, organic P, K, Zn, Fe, Mn, Cu, Pb, Cd, Ni, bulk density
Rasmussen and Rohde, 1988		44	Stubble mulch (disk + sweep tillage) moldboard plow	SOC, N
Mahboubi et al., 1993	OH, USA	28	Moldboard plow, chisel plow, no-tillage	SOC, CEC, bulk density, penetration resistance, K_{sat}, aggregate MWD and wet stability, available water holding capacity
Blevins et al., 1983	KY, USA	10	No-tillage, moldboard plow, native sod	SOC, total N, P, Ca, Mg, pH, bulk density
Ismail et al., 1994		20		pH, bulk density
Edwards et al., 1992	AL, USA	10	No-tillage, moldboard plow	SOM, pH, P, K, Ca, Mn, Zn, Cu, bulk density
Wood and Edwards, 1992				SOC, N, C and N mineralization potential
Wood et al., 1991				SOC, N
Bakermans and de Wit, 1970	Netherlands	7	No-tillage, plowed (undefined)	Soil P, K, Mg, pH, SOM
Pidgeon and Soane, 1977	Scotland	7	Moldboard plow, chisel plow, no-tillage	Bulk density, cone resistance, soil water, air-filled porosity
Ball et al., 1989		16–19	No-tillage, moldboard plow	SOM, pore continuity, porosity, cone resistance, bulk density, Mn
Douglas et al., 1986	England	10	Shallow-tine cultivation, no-tillage, moldboard plow	Porosity, bulk density, air permeability, soil strength, water retention, aggregate stability, SOM, microbial biomass, earthworms

Horne et al., 1992	New Zealand	10	No-tillage, moldboard plow, disk and tine harrow, sod	SOC, total N, aggregate stability, cone resistance, K_{sat}, porosity, infiltration, CEC, P, K, pH
Francis and Knight, 1993	New Zealand	9	No-tillage, moldboard plow	SOC, total N, bulk density, macroporosity, earthworm population, N mineralization, available water holding capacity
Francis et al., 1992				SOC, total N, N mineralization, earthworm population, macroporosity, aggregate stability
Chan et al., 1992	Australia	10	No-tillage, reduced tillage (1 pass, disk harrow), conventional tillage (3 passes disk harrow), stubble burning	SOC, total N, substrate-induced soil respiration, water stable aggregates, bulk density, Ca, Mg, Al, CEC, pH
Dick et al., 1991	OH, USA	> 18	Varied by site, includes no-tillage, paraplow, chisel plow, moldboard plow	SOC, P, soil enzymes, erosion
Dick, 1984			Varied by site, includes no-tillage, paraplow, chisel plow, moldboard plow	soil enzymes
Dick, 1983	OH, USA	18–19	No-tillage, minimum tillage, moldboard plow	SOC, total N, P, pH
Rasmussen, 1991	Denmark	18	Moldboard plow, rotavator (2 depths), stubble cultivate	SOC, bulk density, pH, P, K
Lal et al., 1990	OH, USA	12	Tillage rotation of no-tillage and moldboard plow	SOC, pH, CEC, P, Ca, K, Mg, saturation
Lal et al., 1989a				Bulk density, penetration resistance, aggregation and aggregate stability, infiltration
Lal et al., 1989b				Infiltration, sediment loss
Mahler and Harder, 1984	ID, USA	8	No-tillage, minimum tillage, conventional tillage	pH
Ehlers et al., 1983	Germany	6–11	No-tillage, moldboard plow	Bulk density, soil water content, penetration resistance, biopores
Kladviko et al., 1986	IN, USA	7	No-tillage, moldboard plow, chisel plow, disk, ridge-tillage	SOC, aggregate stability, soil water, soil temperature

Table 4 (*continued*)

Reference	Location	Experiment duration at report (yr)	Tillage variables	Soil properties measured
Mielke et al., 1986		6–13		SOC, bulk density, soil water content, porosity, air permeability, K_{sat}, microbial activity
Bruce et al., 1990	GA, USA	8	No-tillage, strip tillage (in-row chisel), conventional tillage (disk harrow)	SOC, aggregate stability, bulk density, air-filled pore space, particle size distribution, infiltration
Langdale et al., 1990				SOC, N, Ca, Mg, K, pH
Chang and Lindwall, 1992	Alberta, Canada	8	No-tillage, minimum tillage (sweep cultivator), conventional tillage (disk harrow, sweep cultivator)	K_{sat}, bulk density
Carter and Steed, 1992	Australia	7–10	No-tillage, rotavator, stubble burning, spring-tine cultivator	SOC, infiltration, bulk density
Heard et al., 1988	IN, USA	5,10	No-tillage, ridge tillage, moldboard plow, chisel plow	K_{sat}, macroporosity, air permeability, bulk density
Lal and Van Doren, 1990	OH, USA	25	No-tillage, chisel plow, moldboard plow	infiltration
Lindstrom et al., 1984	MN, USA	10	No-tillage, chisel plow, moldboard plow	infiltration
Chang and Lindwall, 1989	Alberta, Canada	20	No-tillage, minimum tillage (sweep tillage), conventional tillage (heavy cultivator)	K_{sat}, macroporosity, bulk density, infiltration
Smika, 1990	CO, USA	12	Stubble mulch (sweep tillage)–rod weeder combinations, no-tillage	Soil water storage, nitrate-N, aggregate size distribution
Brandt, 1992	Saskatchewan, Canada	12	No-tillage, conventional tillage (sweep tillage, harrow cultivation, rod weeder)	Soil water, nitrate-N, P
Lafond et al., 1992	Saskatchewan, Canada		No-tillage, spring chisel plow, spring–fall chisel, disk	Soil water
Schjonning and Rasmussen, 1989	Denmark	18	Shallow disking, rotatill, moldboard plow	Aggregate stability, soil compressibility, penetration resistance
Schjonning and Rasmussen, 1989				Soil water retention, air diffusivity, air permeability
Pikul et al., 1993	OR, USA	19	Moldboard plow, rotatill (sweep), no-tillage (sweep)	SOC, pH, bulk density, penetration resistance, K_{sat}

4. Long-term tillage studies

Data from long-term cropping systems experiments have repeatedly shown that continuous cultivation depleted SOC and reduced soil quality compared to native vegetation, regardless of cropping system (Webb et al., 1980; Odell et al., 1982; Bowman et al., 1990; Bremer et al., 1994; Darmody and Norton, 1994; Kay et al., 1994; Riffaldi et al., 1994; Robinson et al., 1996). In these studies, the impact of tillage per se on soil quality under continuous cropping systems was usually not a concern, and if it was, it could only be inferred from comparisons with continuous sod or ley rotations. In such comparisons, however, tillage effects were confounded with cropping system effects. It has only been in the last 30 to 35 yrs that the role of tillage, or the lack of it, in maintaining SOC and soil quality has been evaluated. The feasibility of planting and growing food and fiber crops without tillage, and consequently of evaluating tillage effects on soil quality with a proper control, was ushered in by advances in herbicide developments (Baeumer and Bakermans, 1970; Cannell and Hawes, 1994) during the 1960s. Consequently, the longest running tillage studies are generally less than 30 yrs old. Because of the high level of technology, i.e., herbicides and specialized equipment, required for managing conservation tillage systems, the longest-term studies are located in developed countries with temperate climates.

Cannell and Hawes (1994) recently reviewed the impact of tillage on soil quality as reported from many of these long-term studies in North America, Europe, Australia, and New Zealand. In their excellent review, special attention was given to the impact of tillage systems on SOC, nutrient availability, CEC, pH, bulk density, hydraulic conductivity, plant available water, and aggregate stability. To avoid redundancy, I will not review the topics covered by Cannell and Hawes. The reader is referred to their review or to the papers in Table 4 which lists reports from tillage experiments of 7 or more years duration (my arbitrary value for qualifying an experiment as long-term) which were either included in their review or are companion papers to reports included in their review. Other qualifying experiments (> 7-yr duration) dealing with the topic but not discussed by Cannell and Hawes (1994) are listed in Table 5. The recognition of the importance of SOC in maintaining soil quality is illustrated by the fact that this indicator is the single soil attribute determined most frequently in research studies (Tables 4 and 5). Arguably, SOC is also often reported because it is a standard measurement in soil surveys and is routinely measured in many experiments. But the relationship between other soil quality indicators and SOC has been pointed out previously in this paper and the critical role of tillage–residue management on this relationship is well documented in extensive reviews (Kladivko, 1994; Shomberg et al., 1994); Cannell and Hawes, 1994).

5. Sustaining soil C

Maintenance of SOC is paramount to sustaining soil quality. Tillage-induced losses of SOC occur rapidly. In Texas, USA, researchers found the loss of SOC from a field taken out of native sod production and tilled for 7 yrs equivalent to that from a field

Table 5
Additional long-term tillage experiments (> 7-yr duration) not reviewed by Cannell and Hawes (1994)

Reference	Location	Experiment duration at report (yr)	Tillage variables	Soil properties measured
Dalal et al., 1994	Australia	7	No-tillage, conventional tillage (shallow tine)	SOC, microbial biomass, N, mineralizable N
Dalal et al., 1995			No-tillage, conventional tillage (shallow tine)	SOC, N
Franzluebbers et al., 1994	TX, USA	9	No-tillage, disk harrow	SOC, mineralizable C and N, microbial biomass
Pikul and Aase, 1995	MT, USA	9	No-tillage, sweep-disk, disk	SOC, pH, bulk density, penetration resistance, water infiltration, particle size distribution
Dickey et al., 1994	NE, USA	10	No-tillage, no-tillage + cultivation, disk, chisel plow, moldboard plow	SOC, penetration resistance
Arshad et al., 1990	Alberta, Canada	10	No-tillage, chisel-disk harrow	SOC, N, pH, SOC quality
Hermawan and Cameron, 1993	New Zealand	10	Conventional (plow grubbing), disk harrow (rolling), minimum tillage (previous operations minus plow)	SOC, aggregate stability and size, porosity, bulk density, penetration resistance, infiltration
Aase and Pikul, 1995	MT, USA	10	No-tillage, conventional tillage (sweep-disk), minimum tillage (sweep)	SOC, P, nitrate-N, pH, bulk density
Hammel, 1989	ID, USA	10	Moldboard plow, chisel plow, no-tillage	Bulk density, penetration resistance
Hammel, 1995				Soil water content, N
Raimbault and Vyn, 1991	Ontario, Canada	10	Moldboard plow, chisel plow	Aggregate size distribution, aggregate stability
Havlin et al., 1990	KS, USA	6–12	No-tillage, conventional tillage (chisel–disk)	SOC, organic N
Hill and Meza-Montalvo, 1990	MD, USA	11–12	No-tillage, moldboard plow	Bulk density, pore size distribution, particle size distribution, soil strength, water retention
Campbell et al., 1995	Saskatchewan, Canada	13	No-tillage, conventional tillage (sweep cultivator, rod weeder, harrow)	SOC, N

Campbell et al., 1996a	Saskatchewan, Canada	11	-tillage, conventional tillage (sweep cultivator, rod weeder, harrow), minimum tillage	SOC, N, bulk density
Campbell et al., 1996b	Saskatchewan, Canada	11	No-tillage, conventional tillage (sweep cultivator, rod weeder, harrow), minimum tillage	SOC, N, bulk density
Heenan et al., 1995	Australia	14	No-tillage, conventional tillage (disk harrow), stubble burn	SOC, N, bulk density
Chan and Heenan, 1996		10	No-tillage, conventional tillage (disk harrow)	SOC, N, earthworm populations, macroporosity, soil water, pH, Mg, Al, P, Ca, K, rooting depth
Hunt et al., 1996	SC, USA	14	Strip tillage (no-tillage + in-row subsoiling)	SOC
Vyn and Raimbault, 1993	Ontario, Canada	15	No-tillage, moldboard plow, chisel plow, disk harrow	Bulk density, penetration resistance, aggregate size distribution
Thompson, 1992	Australia	8–15	No-tillage, tine harrow, stubble burn	SOC, N, N mineralization, soil respiration, microbial biomass C and N, nematode population, earthworm population, nitrate-N
Fettell and Gill, 1995	Australia	14–15	No-tillage, scarifier, cultivator, disk plow, chisel plow with sweeps, stubble burn	SOC, N, pH
Chagas et al., 1995	Argentina	15	No-tillage, moldboard plow, chisel plow	SOC, aggregate stability and size distribution, soil respiration, microbial biomass, pH, CEC, exchangeable bases
Balesdent et al., 1990	France	17	No-tillage, superficial tillage (shallow cultivation with rotavator, cultivator), conventional tillage (moldboard plow, cultivator)	SOC (^{13}C–^{12}C ratios), C mineralization
Dalal et al., 1991	Australia	20	No-tillage, conventional tillage (chisel plow), stubble burn	SOC, N, N mineralization, microbial biomass, pH
Lal et al., 1994	OH, USA	28	No-tillage, chisel plow, moldboard plow	SOC, aggregate stability, bulk density, porosity, penetration resistance, pH, CEC, K, Ca, Mg
Pikul and Zuzel, 1994	OR, USA	48–57	moldboard plow, disk, sweep, stubble burn	SOC, infiltration, aggregate size distribution, bulk density, porosity (Hg intrusion), water release

cultivated for 70 yrs (Zobeck et al., 1995). In Georgia, USA, soil organic matter decreased about 2.3 Mg ha^{-1} (to 80 mm depth) within 1 yr after shallow tillage following 4 yrs of a no-tillage grain sorghum–crimson clover cover crop system (Bruce et al., 1995; Reicosky et al., 1995). Reicosky and Lindstrom (1993, 1995) measured short-term CO_2 (19 d) flux from an Aeric Calciaquoll in Minnesota, USA immediately following various methods of tillage, including no-tillage. The C released during the 19 d period following moldboard plowing, plowing + two diskings, disk-harrowing, chisel plowing, and no-tillage was 134, 70, 58, 54, and 27% of that estimated in residue from the wheat crop of the immediate past season. This research suggests that tillage induced losses of soil C may occur even more rapidly than previously thought.

The effectiveness of soil management practices (rotations, crop residue inputs, manures, conservation tillage) to sustain or increase SOC is climate dependent. Tillage-based agricultural systems occur in areas with relatively high potential evapotranspiration (PET) and moderate precipitation (sub-humid to semi-arid climates) (Spedding, 1988 in Carter, 1994). Sustainability of agricultural systems is easiest to achieve in cooler wetter climates (Stewart et al., 1991). The need for crop residue inputs and conservation tillage is reduced in cooler wetter regions and in fact this type of climate imposes constraints and special needs for handling crop residues and adopting conservation tillage practices (Carter, 1994). Conversely, the need for crop residues–manures and conservation tillage practices to sustain SOC and consequently effect changes in soil quality is greater for warmer more humid climates.

In Iowa, USA, Larson et al. (1972) reported that 6 Mg ha^{-1} yr^{-1} corn residue incorporated with a moldboard plow prevented decline of SOC from a Typic Hapludult. Determination of this rate was based on maintenance of an initial value of 18.1 g kg^{-1} SOC. Thus, the 'maintenance' of SOC was based on a near equilibrium value attained after years of continuous corn cultivation and SOC decline. By comparison, SOC concentrations for similar prairie soils in Iowa maintained in native sod ranged from 35.6 to 46.1 g kg^{-1} (Robinson et al., 1996). In a warmer more humid environment in the southern Appalachian region of Georgia, USA, 12 Mg ha^{-1} yr^{-1} crop residues left to decompose on the soil surface as a result of a no-tillage cropping system were required to sustain soil quality commensurate with the inherent soil and climatic resources (Bruce et al., 1995). Under the heavy degradative pressures for this soil, one cropping season with conventionally tilled soybean destroyed the benefits achieved after 4 yrs of the sustainable no-till cropping system.

5.1. Crop rotation, soil C and tillage

Without significant inputs of C from crop residues and/or manures, conservation tillage alone can only slow the loss of SOC, not halt or reverse it. Across a wide range of climatic conditions, research has shown SOC increases with increased cropping intensities in conservation tillage systems.

In a 14-yr study comparing soil management factors of stubble mulching or burning; rotations of lupin (*Lupinus angustofolius* L.)–wheat, continuous wheat, and subterranean clover (*Trifolium subterraneum* L.)-wheat; and no-tillage and cultivation intensity; Heenan et al. (1995), reported the greatest rate of SOC loss with continuous wheat

managed with stubble burning and intensive cultivation. Chan and Heenan (1996) sampled a more comprehensive set of soil quality parameters from selected treatments in the same study after 10 yrs. Significant differences in SOC between the wheat–lupin (2.74 g kg^{-1}) and wheat–clover (3.56 g kg^{-1}) rotations in the top 0.05 m depth were only found under no-tillage. However, earthworm populations and macroporosity were similar in both tillage systems. Inclusion of the deep-rooted lupin in rotation with wheat increased the effective rooting depth and subsoil water storage following summer fallow compared to the more shallow-rooted clover. Like SOC, these differences were only found under no-tillage.

In a 13-yr study on a silt loam soil (Orthic Brown Chernozem) in semi-arid Saskatchewan, Canada, SOC increased with continuous spring wheat vs. the standard fallow–wheat cropping system (Campbell et al., 1995). No-tillage provided no increase in SOC in the fallow–wheat system but did result in a moderate increase in SOC in the more intensive continuous wheat system. Results reported from a similar study after 11 yrs on a Sceptre clay soil (Red Brown Chernozem) (Campbell et al., 1996a) were more definite. Both SOC and N concentrations were increased to the 15 cm depth under no-tillage, regardless of fallow frequency. Soils managed with a minimum tillage (1–3 cultivations during summer fallow) wheat–fallow system gained no additional C during the 11-yr study. Continuous wheat under conventional tillage (sweep cultivator with a rod weeder) gained 2 Mg C ha^{-1} and both wheat–fallow and continuous wheat gained 5 Mg C ha^{-1} under no-tillage. Increases in SOC and N were greatest during the last 4 yrs of the experiment when crop residue production was the greatest. On a fine sandy loam soil (Orthic Brown Chernozem or Typic Haploboroll) with the same cropping system and tillage treatments, no-tillage increased SOC and N concentrations to the 7.5 cm depth after 11 yrs (Campbell et al., 1996b). Unlike the clay soil studied (Campbell et al., 1996a), SOC and N concentrations were not increased in the 7.5 to 15 cm depth, nor were the mass of C and N increased at either depth. Similar to the clay soil, however, cropping system had no effect on SOC or N and differences in SOC and N occurred during the last 4 yrs of the 11-yr study, due to increased production of crop residues under favorable environmental conditions. The lack of response by SOC and N to cropping system was attributed to the fact that fallow frequency had no effect on crop residue production during the period studied.

Differences in C sequestration response to cropping and tillage systems among the three soils were attributed to differences in environmental effects (hail and rainfall amounts) on crop residue production as well as soil texture. Gains in mass C were linearly positively correlated to per cent clay (Campbell et al., 1996a). The authors speculated that several proposed mechanisms for stabilization and protection of SOC by clay (van Veen and Paul, 1981; Parton et al., 1987; Hassink and Whitmore, 1995 in Campbell et al., 1996a) might offer an explanation for the increased C sequestration with increasing clay content.

In south–central Texas, with a thermic temperature regime and average annual rainfall of 978 mm, cropping intensity increased SOC under no-tillage but not under conventional tillage (Franzluebbers et al., 1994). Cropping intensity was defined as the year-fraction a crop was grown (0.5 for continuous wheat, 0.65 for wheat–soybean doublecrop, and 0.88 for a wheat–soybean–sorghum rotation). After 9 yrs, cropping

intensity increased SOC 9%, 22%, and 30%, respectively, under no-tillage but SOC did not increase in conventional tillage, regardless of cropping intensity.

The benefits of intensive cropping and rotations to produce copious amounts of residue, coupled with conservation tillage systems, on sustaining or increasing SOC have also been reported in semi-arid Kansas, USA (Havlin et al., 1990) and Montana, USA (Aase and Pikul, 1995), as well as in thermic udic regimes in Georgia (Bruce et al., 1990) and Alabama (Wood et al., 1991; Reeves and Wood, 1994).

5.2. Tillage-rotation interactions and agronomic sustainability

Advantages of crop rotation are illustrated by studies reviewed here and elsewhere (Dick, 1992; Caporali and Onnis, 1992; Reeves, 1994). Crop rotations not only sustain soil quality by providing increased above-and below-ground residues for soil C input but are also critical for maintaining economic sustainability. Sustainable soil management practices will not be adopted unless economically viable. With few exceptions, (e.g., Vyn et al., 1991; Wagger and Denton, 1992) the need for crop rotation becomes more critical with conservation tillage than with conventional tillage.

In the Midwestern USA, corn–soybean rotation, compared to continuous corn, has proven to ameliorate yield reductions of corn grown with no-tillage on poorly drained soils (Dick and Van Doren Jr., 1985; Kladviko et al., 1986; Griffith et al., 1988; Dick et al., 1991). In the Palouse region of northern Idaho, USA, winter wheat grown with chisel plowing and no-tillage yielded 92% and 78%, respectively, of that grown with moldboard plowing (Hammel, 1995). However, in both the chisel plow and no-tillage systems, wheat yields were greater with a 3-yr wheat–barley–pea (*Pisum sativum* L.) rotation than with a 2-yr wheat–pea rotation. On the same soil type, an Ultic Haploxeroll in Washington, USA, winter wheat yield increased compared to continuous wheat with a 3-yr wheat–barley–pea rotation, but the response was greatest in a conservation tillage system (chisel plow–no-tillage rotation) (Young et al., 1994).

In humid regions, the ability of rotation to ameliorate limitations to productivity or to increase crop yield potential in conservation tillage systems, compared to conventional tillage systems, is usually associated with reductions in disease (Dick and Van Doren Jr., 1985; Edwards et al., 1988; von Qualen et al., 1989; Dick et al., 1991; Reeves, 1994; Hammel, 1995) or weed pressures (Buhler et al., 1994; Moyer et al., 1994; Young et al., 1994). In semi-arid regions, tillage system interactions with rotations on productivity are often the result of improved harmonies or synergisms in water use efficiency. In Texas, USA, soil water storage generally increased with decreasing tillage intensity (tillage intensity in the order: No-tillage < sweep < disk < moldboard < rotavator) in a wheat–sorghum–sunflower (*Helianthus annuus* L.) rotation (Unger, 1984). Grain sorghum yield was commensurate with stored water and inclusion of sunflower in the rotation allowed extraction of water deeper in the profile, increasing the total amount of water available for production in the cropping system. Similarly, researchers in the Southern High Plains of Texas found that cotton lint yield increases were reflective of improved water relations in a comparison of no-tillage vs. conventional (bedding and cultivations) and continuous cotton vs. a cotton–wheat–fallow cropping systems using LEPA (low energy precision application) irrigation (Bordovsky et al., 1994). Maximum yields were

obtained with the cotton–wheat rotation in the no-tillage system. In Kansas, USA, the standard wheat–fallow cropping system was compared to a wheat–sorghum–fallow rotation, continuous sorghum, and sorghum–fallow with conventional (sweep tillage and rod weeder) and no-tillage (Norwood, 1994). During the 6-yr study, no-tillage increased wheat yield 1 crop in 6 with wheat–fallow but 2 crops of 6 with wheat–sorghum–fallow; sorghum yields in the wheat–sorghum–fallow rotation were increased 60% of the time (3 of 5 yrs measured). More efficient soil water storage, especially at deeper depths, favored the wheat–sorghum–fallow system grown with no-tillage.

Productivity interactions from crop rotation-tillage systems may also result from improvements in soil physical properties. In a 10-yr study in Ontario, Canada, corn yields increased 3.9% with rotation (2 yrs sequences of red clover–barley, soybean, alfalfa, soybean–wheat–red clover) in conventional tillage but 7.9% in minimum tillage (chisel plow) compared to continuous corn (Raimbault and Vyn, 1991). The legume-based rotations resulted in improved aggregate stability compared to continuous corn. In an 8-yr study in northern Georgia, USA, soybean and sorghum were doublecropped with wheat in various sequences under no-tillage, strip-tillage (in-row chisel and no-tillage), and conventional tillage (disk harrow) (Langdale et al., 1990). During the second 4-yr cropping cycle of the rotations, sorghum yields declined with increasing tillage intensity. Soybean yield responded favorably to increasing frequency of sorghum in the rotation and rotation with sorghum was more critical to maintain soybean yield in the conservation tillage systems. For example, soybean yields declined 15% with conventional tillage, 23% with minimum tillage and 32% in no-tillage when soybean were grown continuously as compared to a 1:1 rotation with sorghum. Further research (Bruce et al., 1990) found aggregate stability, air-filled pore space and bulk density were improved after two or more sequences of sorghum as compared to soybean. Infiltration was greater following 2 yrs sorghum in the no-tillage system, but rotation had no effect on infiltration under conventional tillage. This study illustrates the fact that tillage can negate or mask crop rotation effects on soil physical properties. Changes in surface soil properties, e.g., aggregation, resulting from differences in residue quantity–quality between crop species in a rotation could largely be eliminated by tillage-induced oxidation of residues. Tillage would also tend to eliminate variations in soil structure resulting from differences in rooting patterns and other biological activity associated with different crops in a rotation. This was the explanation offered by Chan and Heenan (1996) to account for increased soil water extraction by wheat following lupin rather than subterranean clover, which only occurred under no-tillage in their study. They noted that conventional tillage obliterated a rotation-induced difference in soil water extraction by wheat which was attributed to greater biopore formation from lupin compared to the more shallow-rooted clover.

6. Conclusions

Soil organic carbon is the most consistently reported soil attribute from long-term studies and is a keystone soil quality indicator, being inextricably linked to other

physical, chemical, and biological soil quality indicators. Long-term studies have shown that continuous cropping results in decline of SOC, although the rate and magnitude of the decline is climate and soil dependent and can be ameliorated by wise soil management practices. These include manure additions, adequate fertilization, return of crop residues to the soil, and most importantly, conservation tillage coupled with intensive cropping systems, and rotations which include pasture or ley periods. These lessons are not new but short-term economic pressures of highly capitalized and mechanized agriculture often result in our not practicing what we preach. Long-term conservation tillage studies have shown that, within climatic limits; conservation tillage can sustain or increase SOC when coupled with intensive cropping systems. However, the need for sound rotation practices in order to maintain agronomic productivity and economic sustainability is even more critical in conservation tillage systems than conventional tillage systems. Long-term tillage studies are in their infancy. Preserving and improving these valuable resources is critical if we are to develop soil management practices that maintain or improve soil quality in continuous cropping systems.

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