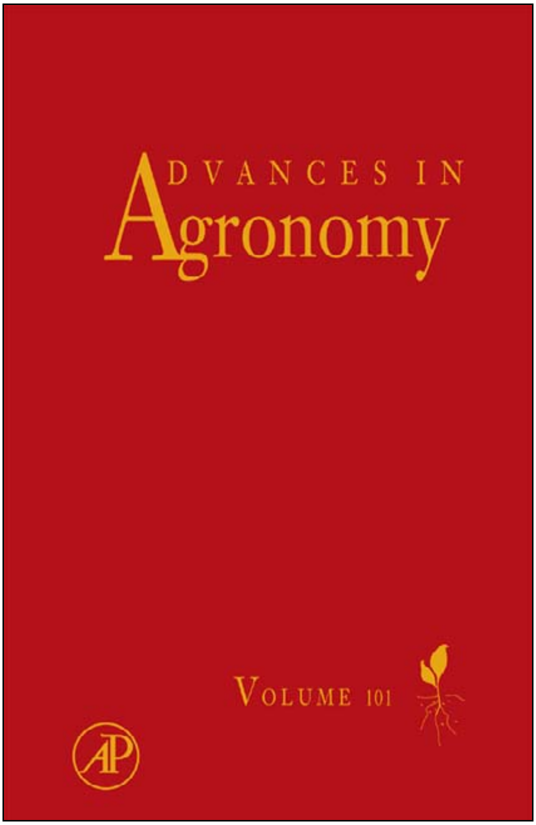

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CHAPTER ONE

SOIL ORGANIC MATTER: ITS IMPORTANCE IN SUSTAINABLE AGRICULTURE AND CARBON DIOXIDE FLUXES

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Contents

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Abstract

Soil organic matter is important in relation to soil fertility, sustainable agricultural systems, and crop productivity, and there is concern about the level of organic matter in many soils, particularly with respect to global warming. Long-term experiments since 1843 at Rothamsted provide the longest data sets on the effect of soil, crop, manuring, and management on changes in soil organic matter under temperate climatic conditions. The amount of organic matter in soil depends on the input of organic material, its rate of decomposition, the rate at which existing soil organic matter is mineralized, soil texture, and climate. All four factors interact so that the amount of soil organic matter changes, often slowly, toward an equilibrium value specific to the soil type and farming system. For any one cropping system, the equilibrium level of soil organic matter in a clay soil will be larger than that in a sandy soil, and for any one soil type the value will be larger with permanent grass than with continuous arable cropping. Trends in long-term crop yields show that as yield potential has increased, yields are often larger on soils with more organic matter compared to those on soils with less. The effects of nitrogen, improvements in soil phosphorus availability, and other factors are discussed. Benefits from building up soil organic matter are bought at a cost with large losses of both carbon and nitrogen from added organic material. Models for the buildup and decline of soil organic matter, the source and sink of carbon dioxide in soil, are presented.

1. INTRODUCTION

The following quotation taken from Sanskrit literature was written perhaps 3500 or 4000 years ago and yet it is as relevant today as it was then. Besides emphasizing the importance of the soil upon which food is grown, the phrase "surround us with beauty" brings to the fore issues about the environment:

> Upon this handful of soil our survival depends. Husband it and it will grow our food, our fuel and our shelter and surround us with beauty. Abuse it and the soil will collapse and die taking man with it

The decline and collapse of many ancient civilizations is clear evidence of the truth of these statements. In Mesopotamia, the Sumerian society, which started about 3000 BC, became the first literate society in the world, but then gradually perished as its agricultural base declined as the irrigated soils on which its food was produced became so saline that crops could no longer be grown. In Mesoamerica, the earliest settlements of the Mayan society date from about 2500 BC. Intellectually this society was remarkable, particularly in its study of astronomy, yet its decline started once internal and external factors led it to give too little attention to managing its intensive agriculture in terraced fields on the hillsides and raised fields in swampy areas.

Although soil cultivation and growing crops produce food for people and animals, the appreciation and understanding of the processes involved took many centuries. It was in 1840 that Liebig (1840) presented his report entitled "Organic Chemistry in its Application to Agriculture and Physiology" to the British Association for the Advancement of Science. In it he noted that: "The fertility of every soil is generally supposed by vegetable physiologists to depend on . . . humus. This substance (is) believed to be the principle nutriment of plants and to be extracted by them from the soil." The hypothesis was that plant roots have tiny mouths and ingest small fragments of humus directly. Liebig demolished this hypothesis and he expressed the view that humus provides a slow and lasting source of carbonic acid. This could be absorbed directly by the roots as a nutrient or it could release elements like potassium (K) and magnesium (Mg) from soil minerals.

The importance of soil organic matter (SOM) in soil fertility was questioned by the early results from the field experiments started by Lawes and Gilbert at Rothamsted between 1843 and 1856. The results showed that plant nutrients like nitrogen (N), phosphorus (P), and K, when added to soil in fertilizers and organic manures, like farmyard manure (FYM), were taken up by plant roots from the soil. As the annual applications of fertilizers and FYM continued, the level of SOM in FYM-treated soils increased relative to that in fertilizer-treated soils, but even into the 1970s, yields of cereals and root crops were very similar on both soils (see later). This gave rise to the belief that, provided plant nutrients were supplied as fertilizers, extra SOM was of little importance in producing the maximum yields of the crop cultivars then available. It should be noted, however, that Lawes and Gilbert never said that fertilizers were better than FYM. They realized that no farmer would ever have the amount of FYM they were using (35 t ha^{-1} annually on each FYM-treated plot) to apply to every field every year. However, what they appreciated was that by using fertilizers, there was the possibility that farmers could produce the increasing amounts of food that would be necessary to feed the rapidly increasing population of the UK at that time.

Very much more recently, Holmberg *et al.* (1991), like many others, have talked about the importance of agricultural sustainability:

> Sustainable agriculture is not a luxury . . . When an agricultural resource base erodes past a certain point, the civilisation it has supported collapses . . . There is no such thing as a post-agricultural society. (Holmberg *et al.*, 1991)

Any definition of sustainability related to the managed use of land must include physical, environmental, and socioeconomic aspects. No agricultural system will be sustainable if it is not economically viable both for the farmer and for the society of which he is a part. But, economic sustainability should not be bought at the cost of environmental damage, which is ecologically, socially, or legally unacceptable or physical damage that leads to irreversible soil degradation or uncontrollable outbreaks of pests, diseases, and weeds. Within these boundaries, food production requires fertile soils, the level of fertility needed depending on the farming system practiced in each agroecological zone. Irrespective of the level required, soil fertility depends on complex and often incompletely understood interactions between the biological, chemical, and physical properties of soil.

Of these various properties, the role of SOM has been frequently discussed. Russell (1977) noted that:

> It has long been suspected, ever since farmers started to think seriously about raising the fertility of their soils from the very low levels that characterised mediaeval agriculture, that there was a close relationship between the level of organic matter, or humus, in the soil and its fertility. In consequence good farmers have always had, as one of their goals of good management, the raising of the humus content of their soils.

Russell went on to point out that present-day economic factors have caused farmers to adopt practices which may cause the level of SOM to decline. Consequently, he stressed that the research community must seek to explain and quantify the effects of SOM in soil fertility and crop production to help farmers develop cropping systems that will prevent or minimize any adverse effect that a lowering of SOM levels may bring about. Thus, there are three important topics to which answers have to be sought, namely:

- Is SOM important in soil fertility?
- Over what time scales and with what farming practices do SOM contents change?
- Can the various soil factors that might/can contribute to the ‘‘organic matter effect’’ be identified, separated, and quantified?

Here, we attempt to provide answers to these questions by presenting data on the effects of fertilization and cropping systems on the level and rate of change of organic matter in soils of the long-term experiments at Rothamsted and Woburn. We show how SOM affects crop productivity in these experiments and discuss ways in which SOM has caused and/or affected these changes. Examples of the use of these long-term data sets to provide models for the turnover of SOM are given because of their use in discussions of carbon dioxide fluxes. The soil at Rothamsted is a well- to moderately well-drained silty clay loam classified as Batcombe Series (Soil Survey of England and Wales, SSEW), as an Aquic Paleudalf (USDA) and as a Chromic Luvisol (FAO). The soil at Woburn is a well-drained, sandy loam classified as Cottenham Series (SSEW), as a Quartzipsammetric Haplumbrept (USDA) and as a Cambric Arenosol (FAO).

2. SOME ASPECTS OF THE NATURE AND BEHAVIOR OF SOIL ORGANIC MATTER

2.1. The nature and determination of soil organic matter

Soil organic matter consists of organic compounds containing carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and phosphorus (P). Most agronomic studies of SOM are interested in it as a possible source of N, S, and P or in its contribution to the biological and physical properties of soil and these are discussed in this chapter. The constituents of SOM can range from undecomposed plant and animal tissues through ephemeral decay products to fairly stable brown and black material often called humus. The latter is usually the largest proportion and it contains no trace of the anatomical structure of the material from which it was derived. Percent SOM is measured by multiplying percent organic C (%C) by the factor 1.724, derived from the %C in peat. The determination of %C includes C in the soil microbial biomass, but this usually accounts for less than 5% of the total soil organic carbon so this does not greatly affect the estimate of SOM. Throughout this chapter %C is % total organic C.

The surface layer of many soils growing arable crops contains 1–3%C as SOM while grassland and forest soils usually contain somewhat more. The ratio (by weight) of organic C to organic N in SOM is relatively constant and ranges between about 9:1 and 14:1 for different soils under different management conditions, but excluding strongly acid and poorly drained soils. Why the ratio falls within such narrow limits is unclear. It may relate to the fact that SOM is largely a fairly uniform end product from the microbial decomposition of plant and animal residues together with material that is very resistant to such attack. The C:N ratio of material added to soil determines whether N will be released or fixed in SOM as the material decomposes. For example, the Market Garden experiment started in 1942 on the sandy loam at Woburn compared four organic manures. They and their C:N ratios were FYM, 13.0:1; vegetable compost, 13.8:1; sewage sludge (biosolids), 9.5:1; and a compost of biosolids and straw, 11.6:1. After 25 years, the C:N ratio of the differently treated soils ranged from only 10.0:1 to 11.1:1 (Johnston, 1975). All but the biosolids would have released some N as the result of their decomposition by microbial activity, but the biosolids would have fixed some mineral N. Similarly, straw with a C:N ratio of 100:1 requires mineral N from the soil for its decomposition but N-rich crop residues like those of lucerne (alfalfa) or clover with a C:N ratio less than 40:1 release N as they are decomposed.

2.2. Relationship between amount and C:N ratio of added plant material and organic matter in soil

In the Woburn Market Garden experiment mentioned earlier, the four organic manures were each applied at the same two amounts of the fresh material but because of differences in composition and percent dry matter, different amounts of organic matter were added between 1942 and 1967. These amounts (in t ha^{-1}) for the single and double application were, respectively, FYM, 138 and 276; biosolids, 165 and 330; vegetable compost, 118 and 236; and biosolids/straw compost, 118 and 236. There was a linear relationship between the amount of organic matter added and %C in soil (Fig. 1) that accounted for 82% of the variance (Johnston, 1975). However, much C and N was lost from the soil following the addition of these different manures. At the end of 25 years, 75% of the C added in FYM had been lost; similar losses from added FYM occurred in the Woburn Green Manuring experiment (Johnston, 1975 using data from Chater and Gasser, 1970). After 18 years, of the C added in biosolids, 64% had been lost and about 60% from the composts. Much the same proportions of added N were lost as for C, that is, the losses were appreciable. Thus, there is a major cost in terms of the losses of C and N from the soil, with associated environmental impacts, when building up SOM from additions of organic manures.

It has been noted that SOM is the end product of microbial decomposition of organic material added to soil which could explain its fairly constant

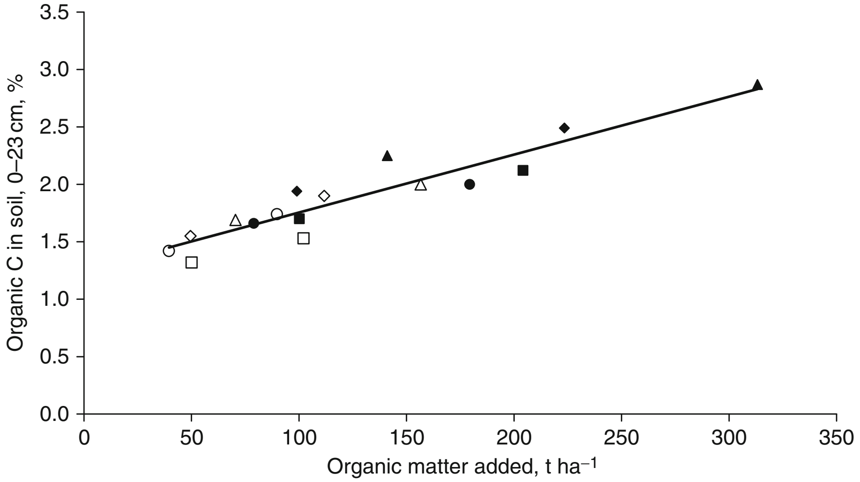

Figure 1 Relationship between organic matter added (t ha^{-1}) during 1942–1950 and 1942–1960 and percent organic carbon (%C) in the top 23 cm of a sandy loam soil in 1951 and 1960. Market Garden experiment, Woburn. FYM, single □, double ▪; biosolids, single △, double ▲; FYM compost, single ○, double •; biosolids compost, single ◇, double ◆. Manure applied as fresh material, single and double rate 37.5 and 75.0 t ha^{-1} each year. (Adapted from Johnston *et al.*, 1989.)

C:N ratio. The uniformity of composition is illustrated again by data from the Woburn Market Garden experiment discussed earlier. The treatment with biosolids and biosolids/straw compost ceased in 1961 because of concerns about heavy metal additions in these two materials, and no further organic manures were applied to these plots. The use of vegetable compost ended also in 1961 and was replaced by FYM, but both FYM treatments ceased in 1967. The different types and amounts of organic manures applied had increased SOM to different levels (Fig. 1) by the time the additions ceased; SOM then began to decline from these different levels starting in 1962 for the two biosolids treatments and in 1968 for the FYM treatments. The soil on each plot was sampled and %C determined for a number of years and an individual carbon decay curve was produced for each plot. Visual observation suggested that these individual decay curves were sections of a single decay curve and an exponential decay model was then fitted to each individual curve; by using horizontal shifts (in years) all eight decay curves were brought into coincidence (Fig. 2).

The shifts required to bring the curves into coincidence were related only to the different starting levels of SOM and not to the different organic manure added. Thus, the microbial decomposition of these different manures had produced SOM that decayed at the same rate suggesting a very uniform composition. The half-life of the SOM, relative to the asymptotic %C, was calculated to be 20.1 years from the fitted C decay curve (Fig. 2). The half-life for organic N (not shown) was calculated to be 12.4 years. The half-life for C and N was calculated relative to the equilibrium level of soil C

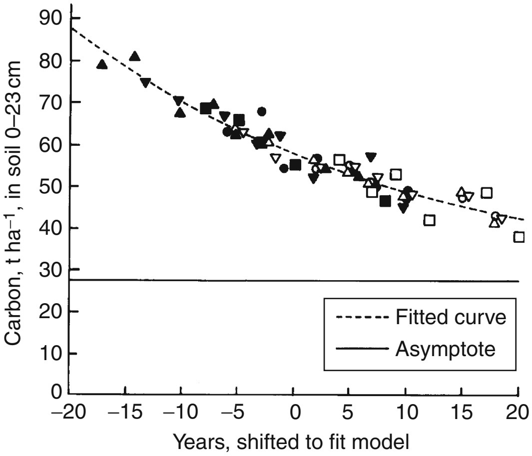

Figure 2 Decline in soil organic carbon (t ha^{-1}) in the top 23 cm of a sandy loam soil. Market Garden experiment, Woburn. Individual decline curves for each treatment shifted horizontally to fit model (see text). FYM, single □, double ▪; biosolids, single △, double ▲; FYM compost, single ○, double •; biosolids compost, single ◇, double ◆. (Adapted from Johnston *et al.*, 1989.)

and N that would be reached eventually. Thus, it would take 20.1 years for organic C to decline by half between any starting level and the equilibrium level for soil C on this soil type and with this cropping system. The shorter half-life for organic N suggests that N-rich constituents of SOM decompose more quickly than those with less N.

In another experiment on the sandy loam soil at Woburn, three amounts of peat were added for a number of years to build up different levels of SOM where horticultural crops were grown (Johnston and Brookes, 1979). Once peat applications ceased, the decline in %C was monitored during a number of years and again the three individual C decay curves could be brought into coincidence by horizontal shifts (Johnston *et al.*, 1989); the half-life of the peat-derived soil C was 12.4 years. The difference in the C half-lives in the two experiments is interesting. Possibly, it relates to the different C:N ratios of the organic materials (45:1 for peat and a range from 9.5 to 13.8:1 for the other organic manures) and this could lead to different equilibrium levels of SOM in the two experiments on the same soil type.

2.3. Equilibrium levels of soil organic matter

The concept of equilibrium levels of SOM, introduced in the paragraph above, is crucially important. It is not always appreciated that SOM changes toward an equilibrium level in any farming system and the level will vary with a number of factors. Supporting evidence for this statement is presented in this chapter. However, there is a paucity of appropriate data because in temperate climates SOM changes slowly and long-term experiments with unchanged cropping and management are required to monitor such changes and determine the appropriate equilibrium level. Existing evidence shows that the amount of organic matter in soils depends on:

- The input of organic material and its rate of oxidation
- The rate at which existing SOM decomposes
- Soil texture
- Climate

The first two factors depend on the farming system practiced. In addition to the aboveground crop residues that are ploughed-in, there will also be different amounts of root remaining in the soil. Root weights are difficult to determine but some indication of the differences can be seen in the different root length densities in the top 20 cm soil, which can vary from 0.8 to 12.2 cm cm^{-3} for broad beans and winter wheat, respectively (Johnston *et al.*, 1998; Table 8). Decomposition of added and existing organic matter in soil is by microbial activity and the extent and speed of decomposition depends on a carbon source for the microbes, temperature, and the availability of oxygen and water. Thus, activity in the northern hemisphere will be greater in autumn when C from crop residues is incorporated into warm soil and rainfall provides adequate moisture. In addition, the extent of soil cultivation affects oxygen availability and hence microbial activity. Consequently, SOM will decline more quickly when soil is cultivated too frequently and unnecessarily. Soil cultivation and a lack of organic inputs, for example, when soils are fallowed (i.e., grow no crop) to control weeds can lead to an appreciable loss of SOM. In the Broadbalk Winter Wheat experiment at Rothamsted, the plots were divided into five sections in 1925 so that weeds could be controlled by fallowing the individual sections in sequence. In 1968, the five sections were each divided into two to give ten sections, so that wheat continued to be grown each year on some sections while on others there were two rotations, one included a fallow year, the other potatoes. Between 1925 and 2000, the number of years that the different sections had been fallowed or grown potatoes ranged from 8 to 24 and by 2000, %C in the top 23 cm on fertilizer-treated plots was strongly linearly related ($R^2 = 0.9266$) to the number of fallow and potato years. From the linear relationship, soil with least fallowing contained 1.16%C and this declined to 0.91%C with most fallowing.

Soil texture, besides affecting some of these properties, is also important because clay helps to stabilize SOM and limit its decomposition. Besides rainfall, the other important climatic factor is temperature because it greatly affects the rate of organic matter decomposition. When Jenkinson and Ayanaba (1977) prepared a bulk sample of ^{14}C-labeled plant material and added part to similar textured soils, one in the UK and the other in Nigeria, the decomposition curve for the labeled material was the same in both soils. But the rate of decomposition was four times faster in Nigeria than in the UK due to the difference in temperature at the two sites. Excessive rainfall can create anaerobic conditions in soil and then, especially at low ambient temperature, plant material decomposes very slowly leading to the formation of peat.

The four factors listed above interact so that the equilibrium level of SOM is specific to the farming system, soil type, and climate. In general under similar climatic conditions, for any one cropping system, the equilibrium level of SOM in a clay soil will be larger than in a sandy soil, and for any one soil type the equilibrium level will be larger under permanent grassland than under continuous arable cropping. Examples are given later.

The fact that SOM changes toward an equilibrium value dependent on the interaction of the four factors listed above does not seem to have been appreciated and mentioned in two recent papers, one by Khan *et al.* (2007) and the other by Bellamy *et al.* (2005). Khan *et al.* (2007) discussing the effect of N fertilization on C sequestration in soil, support their contention that the application of N fertilizers causes a decrease in soil C by presenting, very briefly (Khan *et al.*, 2007; Table 4) results from two long-term Rothamsted experiments (Jenkinson, 1991; Jenkinson and Johnston, 1977) and one at Woburn (Christensen and Johnston, 1997). There was an initial decline in soil C in the first few years of the Rothamsted experiments where NPK fertilizers were applied but the decline was less than on plots with PK but no N. Khan *et al.* (2007) suggest that comparing %C on soils with NPK and PK only is unacceptable, but why? For any one comparison of a with and without N treatment, the result is ‘‘a snapshot in time’’ and a perfectly valid comparison can be made between soils with and without fertilizer N and the effect on %C in soil. For example, in the Broadbalk Winter Wheat experiment at Rothamsted, there are plots which, since 1852, have had PKMg either without or with 144 kg N ha^{-1} each year. Percent organic C in these soils without and with N has been at equilibrium, about 0.93 and 1.12%C, respectively, during the last 100 years. Additional N treatments testing 240 and 288 kg N ha^{-1} were started in 1985 on plots that had received smaller amounts of fertilizer N previously. Since 1985, %C has increased by about 16%, to 1.22 and 1.29% C on plots with 240 and 288 kg N ha^{-1}, respectively, concentrations larger than that in the soil getting 144 kg N ha^{-1}; adding more fertilizer N has increased %C. Similar data showing that SOM is increased where fertilizer N is applied comes from many long-term experiments (Glendining and Powlson, 1995). Applying N increases both crop yield and the return of plant residues to the soil and more carbon is retained in the soil. The initial decline in soil C in the Rothamsted and Woburn experiments noted by Khan *et al.* (2007) was not due to the use of N fertilizer; it was because there was a change in farming system. For many decades prior to the establishment of the experiments, the fields had grown arable crops in rotation: turnips (*Brassica napus*), spring barley, a forage or grain legume, and winter wheat. Besides crop residues, there were two additional inputs of organic matter, from occasional applications of FYM to the turnips and from weeds, which grew in all four crops, were difficult to control at that time, and often made considerable growth after harvest of the crop and before ploughing. It is most probable that the very small amount of SOM in the soils getting only fertilizers in the experiments on arable crops started by Lawes and Gilbert in the 1840s–1850s compared to the amount in other soils growing arable crops on the Rothamsted farm is largely due to the fact that weeds were controlled very efficiently in the experiments. Changes in the soil C status of the Morrow plots at Illinois presented by Khan *et al.* (2007; Fig. 2) could equally well be explained due to the changes in husbandry and cropping leading to different C inputs and SOM changing toward a new equilibrium level associated with the new system. This would be especially so for plots where organic manure inputs had ceased some years previously.

We agree with Khan *et al.* (2007) when they assert that when long-term sustainability of an agricultural system is discussed then changes in SOM over time are important. But the importance is related to the equilibrium level of SOM, the speed with which it is reached, and the productivity of the soil at the equilibrium level. For example, in the two Rothamsted experiments referred to above, there was a decline in SOM initially, more without than with applied N, but the new equilibrium level of SOM in these soils has been maintained for the last 100 years (see later), and, where NPK fertilizers are applied yields have increased over time as discussed later.

It seems to us that much of the current discussion about soil carbon sequestration is related to interest in carbon trading. Such discussion should be based on acknowledging that, for any farming system and its management, including fertilizer and manure inputs, there is an equilibrium level of SOM dependent on the interactions of the four factors listed above. In any soil, the level of SOM does not increase indefinitely. The experimental data presented here from experiments in a temperate climate show that in different farming systems with acceptable fertilizer inputs, increases and decreases in SOM are often small and in most cases the new SOM equilibrium level has been reached only after many years. Achieving significant increases in the equilibrium level of SOM in most farming systems requires very large inputs of organic matter and these have to be maintained if SOM is not to decline.

Similarly, in a recent paper discussing C losses from all soils across England and Wales during the period 1978–2003, Bellamy *et al.* (2005) make no mention of the fact that where C has been lost this is most probably because of changes in farming systems. Such changes have included the ploughing of grassland and growing arable crops with a decrease in annual C inputs and decline in SOM as it changes toward a new equilibrium value. The authors used data from the National Soil Inventory of England and Wales, which holds soil data for 5662 soils sampled 0–15 cm at the intersections of an orthogonal 5-km grid in 1978–1983. Sufficient subsets of the sites were resampled at intervals from 12 to 25 years after the original sampling to be able to detect changes in C content with 95% confidence (Bellamy *et al.*, 2005). While the authors highlight losses of soil carbon, they make little mention of the fact that for soils originally under arable cropping and maintained in mainly arable cropping, the C content of these soils remained largely unchanged or had increased slightly. These soils had reached the appropriate SOM equilibrium value when the initial sample was taken and have remained at this level subsequently. The loss of C from soils will only be halted if farming systems change and any change must be financially viable for the farmer and continue to provide food and feed in both amount and quality.

3. CHANGES IN THE ORGANIC CONTENT OF SOILS AND THEIR CAUSES

3.1. Effects of fertilizer and manure inputs on soils of different texture where cereals are grown each year

The effect of organic matter inputs and soil texture on the level of SOM and the rate of change as it moves toward the appropriate equilibrium level is well illustrated by changes in %C in the top 23 cm of soil during more than

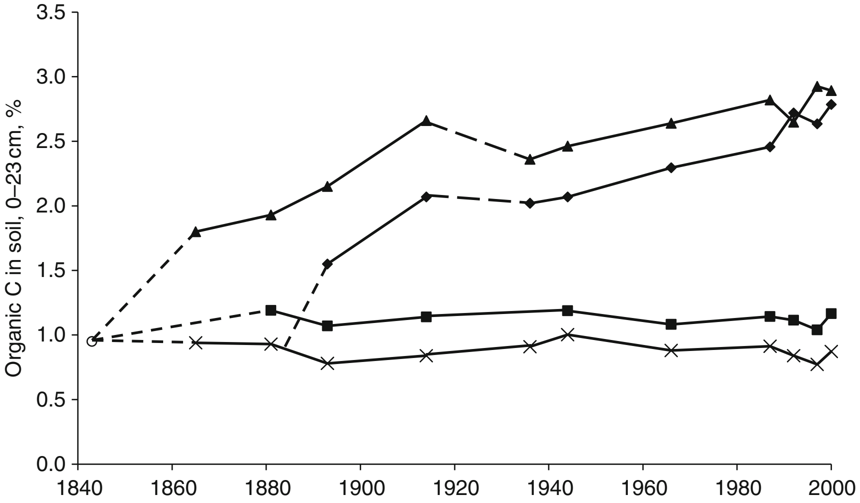

Figure 3 Changes in percent organic carbon (%C) in the top 23 cm of a silty clay loam soil, Broadbalk Winter Wheat experiment, Rothamsted. Annual treatments: unmanured since 1844, x; PKMg plus 144 kg N ha^{-1} since 1852, ▪; 35 t ha^{-1} FYM since 1844, ▲; 35 t ha^{-1} FYM since 1885 plus 96 kg N ha^{-1} since 1968, ◆.

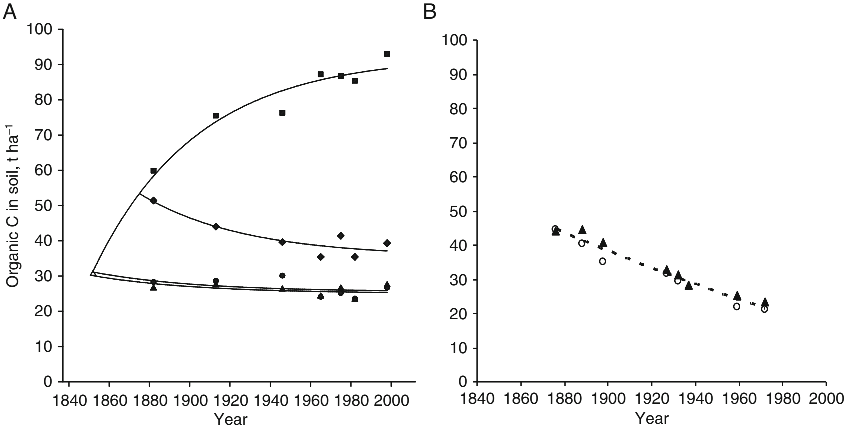

Figure 4 Changes in organic carbon (t ha^{-1}) in the top 23 cm of a silty clay loam soil. (A) Hoosfield Continuous Barley experiment, Rothamsted. Annual treatments since 1852: unmanured ▲; NPK fertilizers •; 35 t ha^{-1} FYM ▪; 35 t ha^{-1} FYM 1852–1871 none since ◆. (Adapted from Jenkinson and Johnston, 1977 with additional data). (B) Woburn; continuous cereals given inorganic fertilizers only ○; manured four-course rotation ▲. (Adapted from Mattingly *et al*., 1975.)

100 years of cropping, mainly with cereals, at Rothamsted and Woburn (Figs. 3 and 4). The Broadbalk Winter Wheat experiment was started in autumn 1843 on a field that had probably been in arable cropping for several

centuries; the soil is a silty clay loam. Winter wheat has been grown on all or most of the experiment each year since then. Changes in %C with four contrasted treatments are shown in Fig. 3. On the unfertilized plot, SOM probably declined a little initially and has then remained essentially constant at about 0.85%C, its equilibrium level, for about 150 years. Applying 144 kg N ha^{-1} together with P and K each year gave larger crops and organic matter returns in stubble and roots have been greater than on the unfertilized plot. In this soil, SOM has remained largely unchanged at its equilibrium level, about 1.12%C, for many years and it now contains about 25% more SOM than the unfertilized control. Where 35 t ha^{-1} FYM has been applied annually since autumn 1843, %C increased rapidly at first and then more slowly as SOM approached the equilibrium level for this treatment. This soil now contains about 2.82%C, some 2.5 times more than the unfertilized soil. A second FYM treatment (also 35 t ha^{-1}) was started in 1885 and the change in SOM on this plot closely mirrors that on the original FYM plot. Currently this soil contains about 2.65%C, some 2.4 times more than that in the control soil.

On the two FYM plots, %C declined between 1914 and 1936 (the data points for these 2 years are joined by dotted lines) because there were major changes in this period. FYM continued to be applied each year until 1925 so SOM was still increasing. Then in 1925, it was decided to take steps to control weds by occasional fallow years with frequent soil cultivation to kill germinating seedlings. The experiment was divided into five sections and from 1926 to 1929 each section was fallowed in 2 of the 4 years, the soil was cultivated intensively and no FYM was applied in the fallow year. From 1931, each section was fallowed and no FYM was applied 1 year in five. Thus, as a consequence of fallowing, intensive soil cultivation and not applying FYM, SOM had declined by 1936. Fallowing 1 year in five and not applying FYM continued until 1967. The less frequent fallowing with less soil cultivation allowed SOM to increase again after 1936. Not having soil samples in 1925 was unfortunate but it highlights the need to take samples before major changes in husbandry practices when monitoring changes in soil fertility. The apparent convergence in %C on the two FYM treatments in recent years may be due to the extra N fertilizer added, since 1968, to the treatment which had received FYM since 1885. This extra N has increased yields and hence the return of organic residues to the soil.

One aspect of change that can be followed occurred in 1968. The five sections were each halved so that a comparison could be made between wheat grown continuously on some half-sections and wheat grown in rotation on the others. The rotation included some fallow years and growing potatoes and field beans. The extra soil cultivations for these crops and fallowing caused SOM to decline by about 16% in the rotation soils between 1966 and 2000 compared with the SOM in soils continuously cropped with wheat. However, yields of the first and second wheat crops grown after a 2-year break always exceeded those of wheat grown continuously. Thus, any possible adverse effect of a small decrease in SOM due to rotational cropping was more than balanced by the beneficial effect of controlling soil pathogens, especially take-all.

Figure 4A shows data from the Hoosfield experiment where spring barley has been grown each year since 1852 (Warren and Johnston, 1967). Jenkinson and Johnston (1977) showed that on the unmanured and fertilizer-treated plots of this experiment, %C declined a little initially and has then remained constant for more than 100 years at the equilibrium value for this farming system on this soil type. In the fertilizer-treated soil, %C is about 10% larger than in the unfertilized soil and has been for more than 100 years because annually more organic matter is ploughed-in as stubble and root residues from the larger crops grown with N fertilizer. Annual applications of FYM (35 t ha^{-1}) increased %C rapidly at first and then more slowly as the equilibrium value for this input and cropping system was approached (Fig. 4A). The very slow decline in %C on the plot that received the same amount of FYM for the first 20 years and none since is very interesting. Even after 130 years, the level of SOM has not declined to that on the plot that receives fertilizers only (Fig. 4A). Presumably some SOM very resistant to microbial decomposition was accumulated from the applied FYM.

The buildup of SOM with the FYM treatment in the long-term Rothamsted experiments accounts for only a fraction of the applied C and N, much of both has been lost, and the annual losses have increased as the SOM level approached the equilibrium level. Evidence for this comes from the Broadbalk experiment at Rothamsted where winter wheat has been grown each year since 1843 (Johnston and Garner, 1969). The amount of FYM applied annually was 35 t ha^{-1} and the buildup of SOM is shown in Fig. 3. An estimated N balance and the average annual accumulation of soil N can be calculated for four periods using the N added in FYM and by aerial deposition and that removed in grain plus straw (Table 1). Nitrogen inputs increased in periods 3 and 4, and the N offtake increased as yield increased on the FYM plot until the 1980s. However, gradually less N has been retained as SOM approached the equilibrium level. Over the whole period of the experiment, although more N has been removed in the increasing yields of grain plus straw, this has not compensated for the declining retention of N in SOM. Consequently, the amount of N not accounted for has increased gradually from about 110 to 170 kg N ha^{-1} (Table 1; Johnston *et al.*, 1989 with additional data). Rosenani *et al.* (1995) considered leaching of nitrate to be the dominant process causing these losses. On this experimental site leaching usually ceases in spring, however, even small anaerobic sites would lead to denitrification provided there was a C source for the denitrifying bacteria and Rosenani *et al.* (1995) did observe more denitrification on the FYM-treated soil rather than fertilizer-treated soil.

Table 1 Nitrogen balance and increase in soil nitrogen at various periods in the FYM-treated plot on the Broadbalk Winter Wheat experiment, Rothamsted[a]

	N input in[b]		N in crop kg ha^{-1} each year	Increase in soil N	N not accounted for
Period	FYM	Atmosphere			
1852–1861	225	20	65	70	110
1892–1901	225	20	90	30	125
1970–1978	250	45	125	5	165
1996–2006	230	30	86	5	169

[a] Adapted from Johnston *et al.* (1989) with later additions.

[b] Atmospheric N inputs specific to Rothamsted: pre-1901 are estimates; 1970–1978 from Powlson *et al.* (1986) and 1996–2006 from Jenkinson *et al.* (2004).

Adding organic manures to soil can lead to large losses of C and N when the SOM level is near the equilibrium level.

The effect of soil texture on SOM is illustrated by comparing changes in SOM in long-term experiments growing arable crops at Rothamsted with those at Woburn (Fig. 4). The sandy loam soil at Woburn contained more SOM at the start of the experiments there in 1876 than did the silty clay loam at Rothamsted in 1852 (cf. Fig. 4A and B) but with all-arable cropping at Woburn, SOM declined more quickly than it did at Rothamsted to approach an equilibrium level lower than that in the heavier textured soil at Rothamsted. At Woburn, even with a well-manured four-course rotation with good yields for the period (Fig. 4B, triangles), the decline in SOM was very similar to that where cereals were grown continuously (Fig. 4B, open circles).

The difference in %C at the start of the long-term experiments at Rothamsted and Woburn relates to the previous cropping and manuring histories of the fields on which the experiments were established. The fields at Rothamsted had a long history of arable cropping with occasional applications of small amounts of FYM and ploughed-in weeds. The field at Woburn had been in grass before it was ploughed some years before the experiments started but it is probable that large amounts of FYM were added for the arable crops grown after ploughing the grass. The effects of growing grass for long and short periods on SOM are discussed in the following sections.

3.2. Effects of short-term leys interspersed with arable crops

Traditional farming practice in the UK was to have some fields on the farm growing arable crops continuously whilst others were in permanent grass. This, in part, was probably because of the difficulty of quickly establishing productive grass swards on arable fields. From the 1930s, high-yielding cultivars of grasses and clovers that established well given good soil conditions were being introduced. This allowed the development of Ley–arable farming systems in which 3- or 4-year leys (grass or clover or mixtures of both) were interspersed with a few years of arable crops, that is, a cycle of ley, arable, ley, arable cropping. The perceived benefit was that the "restorative ley" would increase SOM and increase yields of arable crops that followed. Experiments testing this concept were started at Woburn in 1938 (Boyd, 1968; Mann and Boyd, 1958), then at Rothamsted in 1949 (Boyd, 1968). Similar experiments were started in the early 1950s on six of the Experimental Husbandry Farms belonging to the UK's National Agricultural Advisory Service (Harvey, 1959); regrettably with the current interest in SOM these were not continued.

At Woburn, four different "treatment" cropping systems, each lasting 3 years, were compared and their effects were measured on the yields of two "test" crops that followed (Johnston, 1973). Each phase of the treatment and test cropping was present each year; there was no permanent grass treatment. Initially the treatment cropping had two arable rotations and two ley treatments, and all were followed by two arable test crops, which changed during the course of the experiment. The arable rotations differed only in the crop grown in the third year; in one it was a 1-year grass ley (Ah), the grass seed being undersown in the preceding cereal; in the other it was a root crop (Ar) usually carrots. The two leys were lucerne (alfalfa) harvested for hay (Lu) and grass–clover grazed by sheep (L). There was a half-plot test of FYM (38 t ha^{-1}) applied only to the first test crop, that is, every fifth year. Each treatment sequence and the half-plot test of FYM continued on the same plots ("Continuous Rotations"). The soil, 0–25 cm, was sampled at the end of the third treatment year to determine %C (Table 2). Initially the soil had 0.98%C. After 33 years there was 1.04%C in the soil of the Ah rotation, that is, SOM had increased slightly. Replacing the 1-year grass ley with a root crop resulted in a small loss of SOM, %C declined to 0.90%, presumably due to a smaller input of C from the root crop compared to the 1-year grass ley, and autumn ploughing and spring soil cultivation before sowing the carrots and cultivations to control weeds. After 33 years with the grazed ley in 3 years of the 5-year cycle, %C increased to 1.26%C but there was very little increase in %C where lucerne was grown as the ley. The very small effect of lucerne in increasing SOM was also found in the Rothamsted Ley–arable experiment. We can offer no reason except to note that the lucerne was grown in rows 25 cm apart and the plant has little fibrous root compared to grass. For all these treatment sequences, the increase in %C from applying FYM (38 t ha^{-1}) ranged from 6% to 14%, the larger values being on the plots with leys (Table 2).

In the early 1970s, it was decided to simplify the experiment while providing additional information and changes were phased in over a period

Table 2 Effect of cropping sequences on percent organic carbon (%C) in the 0–25 cm plough layer of a sandy loam soil, Ley–arable experiment, Woburn

	Period[a]							
	1955–1959		1960–1964		1965–1969		1970–1974	
Crop rotation	No FYM	FYM[b]	No FYM	FYM[b]	No FYM	FYM[b]	No FYM	FYM[b]
Arable with roots	0.91	0.99	0.90	0.97	0.88	0.98	0.90	0.99
Arable with hay	0.98	1.07	0.94	1.07	0.95	1.04	1.04	1.10
Grass ley grazed	1.10	1.21	1.09	1.28	1.13	1.32	1.26	1.44
Lucerne for hay	1.00	1.14	0.96	1.11	0.95	1.13	1.03	1.20

[a] Soil sampled at the end of the third treatment year, mean of five plots, one sampled each year.

[b] FYM, 38 t ha^{-1} applied once in 5 years to the first test crop.

of 5 years. The arable rotations became barley, barley, beans (AB, after Ah) and fallow, fallow, beans (AF, after Ar); the ley rotations became grass with N fertilizer (Ln3, after L) and grass–clover (Lc3, after Lu). The test of FYM was stopped. A test of 8-year leys (Ln8 and Lc8) was introduced to compare the benefit, if any, of having longer leys.

Changes in %C for four main treatments during the 60 years since the start of the experiment are in Fig. 5. Three treatments have remained relatively unchanged, AB, AF, and Ln3 while one, Lc3 followed the lucerne ley. On this plot there was no increase in SOM during the period when lucerne was grown and it is only since the early 1970s under the 3-year grass/clover (Lc) ley that SOM has increased (Fig. 5). On this sandy loam soil, changes in SOM due to differences in cropping have been relatively small over many years as the level of SOM in each system has changed toward its equilibrium value. An overall summary of the changes in %C during almost 60 years is in Table 3 . From a starting level of 0.98%C, most SOM was lost (~25%) in an all-arable cropping rotation which initially had cereals and root crops and then after 35 years had 2 year fallow in each 5-year cycle. Arable cropping with mainly cereals and initially a grass crop for 1 year in five has resulted in a smaller decline in SOM. Growing grass or clover for 3 years followed by two arable crops in a 5-year cycle, increased %C but only by 10–15% after 60 years. The more recent introduction of an

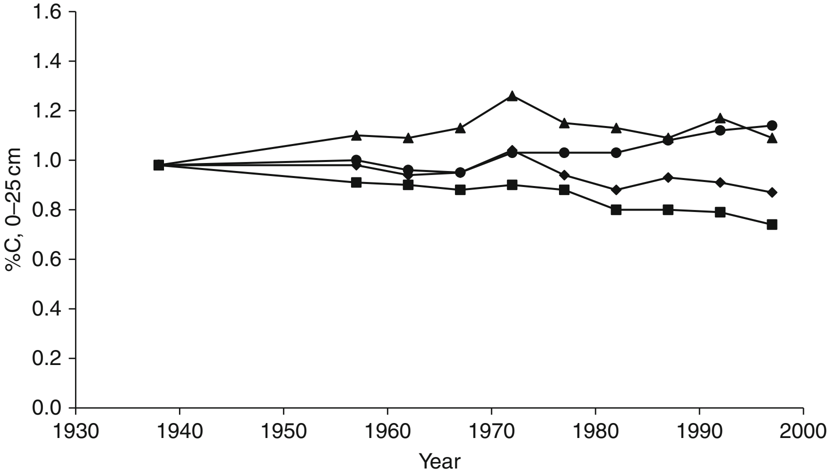

Figure 5 Changes in percent organic carbon (%C) in the top 25 cm of a sandy loam soil under continuous arable and Ley–arable cropping, Ley–arable experiment, Woburn. Continuous arable, AB ◆; Continuous arable, AF ▪; 3-year all-grass ley, Ln ▲; 3-year grass/clover ley, Lc •. For treatment details see text. (Adapted from Johnston, 1973 with recent data added.)

Table 3 Percent organic carbon (%C) in 0–25 cm soil after 58 years of different cropping sequences, Ley–arable experiment, Woburn

Cropping sequence[a]	FYM treatment[b]	%C in 1995–1999	Change from initial value[c]
Ar that became AF after 35 years	No	0.74	−0.24
	Yes	0.76	−0.22
Ah that became AB after 35 years	No	0.87	−0.11
	Yes	0.92	−0.06
L that became Ln3 after 35 years	No	1.09	+0.11
	Yes	1.17	+0.19
Lu that became Lc3 after 35 years	No	1.14	+0.16
	Yes	1.18	+0.20
L that became Ln8 after 35 years	No	1.22	+0.24
	Yes	1.30	+0.32
Lu that became Lc8 after 35 years	No	1.16	+0.18
	Yes	1.27	+0.29

[a] For treatment symbols, see text.
[b] FYM at 38 t ha^{-1} to the first test crop, only five applications in the first 25 years.
[c] Initial value 0.98%C.

8-year ley followed by two arable crops further increased SOM, but by only a small amount (Table 3).

Today, when much is said about the importance of SOM in soil fertility it is not always appreciated that changes in SOM over time are small unless there are major modifications in cropping practice to achieve a large change (see later). These comparatively small changes in acceptable farming systems over many years are very similar to those in long-term experiments on a similar sandy loam soil at Askov in Denmark (Christensen and Johnston, 1997).

At Rothamsted, there are two Ley–arable experiments in which the treatment cropping lasts for 3 years followed by three test crops (Johnston, 1973). One experiment (Highfield) was sited on what had been an old arable field that was sown to grass in 1838, so that by 1949 SOM would be reaching the equilibrium value for less-intensively managed grassland; the soil (0–23 cm) contained about 2.75%C. The other experiment (Fosters) was sited on a field that had been in permanent arable cropping for many decades and the soil contained about 1.65%C. On Highfield some plots were left in the original permanent grass sward (Permanent Grass). In both experiments some plots were sown to grass that was to remain unploughed (Reseeded Grass), on Highfield this treatment was established on plots where the original sward was ploughed-in autumn 1948 and the same grass mixture as used on Fosters was sown in spring 1949. Common to both experiments were three types of ley and one arable treatment. Initially the 3-year leys were lucerne, grass–clover grazed by sheep and grass given N fertilizer and cut for conservation. The arable treatment rotation was sugar beet, oats and 1-year grass undersown in the oats and cut for hay. The test crops grown in rotation were winter wheat, potatoes, and spring barley. In these experiments each phase of the 6-year cycle was present in duplicate each year and the soil, 0–23 cm, was sampled at the end of each third treatment year. Figure 6 shows the changes in t organic C ha^{-1} for two treatments on each field, permanent grass and permanent arable on Highfield and permanent arable and reseeded grass on Fosters for a period of some 50 years. Changes in total organic C are used in Fig. 6 rather than changes in %C because this allows for the differences and changes in bulk density in the differently treated soils (see later for an explanation).

Under arable cropping, the amount of organic C remained essentially constant on the old arable field (Fosters) but declined steadily where the old grassland soil was ploughed (Highfield) and the amounts of organic C in these two soils are now similar but the soil weight on Highfield is slightly

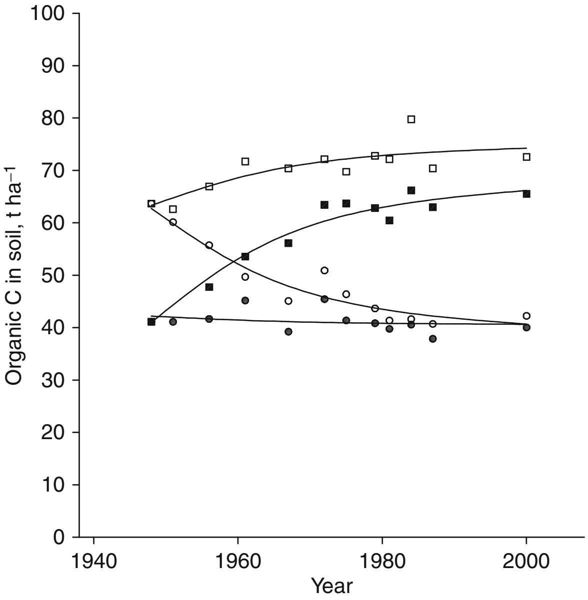

Figure 6 Changes in organic carbon (t ha^{-1}) in the top 23 cm of a silty clay loam soil, Ley–arable experiment, Rothamsted, 1949–2002. Highfield old grassland soil: kept in grass □; ploughed and kept in arable cropping ○. Fosters old arable soil: kept in arable •; sown to grass and kept in grass ▪. (Adapted from Johnston, 1973 with recent data added.)

less than on Fosters. Where the permanent grass was left undisturbed on Highfield, organic C slowly increased toward a new equilibrium level as a result of more intensive management and increased N applications that increased aboveground yields and consequently greater root growth and decay that increased organic matter inputs. Where the old arable soil was sown to grass on Fosters, the amount of C increased slowly but after about 50 years it was still much less than in the permanent grass plots on Highfield.

The effect of the different 3-year leys that were compared at the start of the experiment on %C after 36 years was remarkably small (Table 4). After this long period and compared to the all-arable soil in each experiment, %C was increased by about 18% under the two grass leys but by only 6% under the lucerne. The cumulative buildup of SOM was small because most of the organic matter accumulated during the 3 years of ley was decomposed during the following 3 years of arable cropping.

The important effect of soil texture on SOM is seen again in these data sets from the Ley–arable experiments at Rothamsted and Woburn when the cropping and management of the experiments were very similar. The lowest level of SOM in the continuous arable plots on the silty clay loam (25% clay) at Rothamsted (Fig. 6) is still larger than the highest level of SOM achieved on the sandy loam (12% clay) at Woburn with the largest input of organic matter from an 8-year ley followed by two arable crops (Table 3).

Table 4 Effect of 3-year leys compared to all-arable cropping on percent organic carbon (%C) in the 0–23 cm depth of a silty clay loam after 36 years, Ley–arable experiments, Rothamsted

	Cropping sequence			
	Continuous arable	3 years arable preceded by 3 years		
		Lucerne	Grass/ Clover	Grass + N
Old grassland soil				
% organic carbon in soil[a]	1.70	1.80	2.06	1.99
Increase in %C due to ley		+0.10	+0.36	+0.29
Old arable soil				
% organic carbon in soil[a]	1.43	1.52	1.66	1.66
Increase in %C due to ley		+0.09	+0.23	+0.23

[a] Soil sampled in the third year of the ley before ploughing, for initial values see text. %C measured at the end of the sixth 3-year period in ley in the ley and arable cropping sequence.

3.3. Effect of different types of organic inputs to soils growing arable crops

In 1964 the Organic Manuring experiment was started on the sandy loam at Woburn to test the effects of different types of organic matter inputs on SOM and crop yields (Mattingly, 1974). Six organic treatments were compared with two fertilizer-only treatments. For the first 6 years, the two fertilizer treatments and four of the organic treatments had arable crops grown in rotation: spring barley, potatoes, winter wheat, sugar beet, field beans (*Vicia faba*), and winter rye. Three of the organic treatments applied annually during the first 6 years were FYM (about 50 t ha^{-1}) and straw and peat (both at 7.5 t ha^{-1} dry matter). The fourth organic treatment was ''green manures''; these were undersown in the three cereal crops and allowed to grow until the soil was ploughed for the next spring-sown crop. Four rates of N were also tested on the arable crops. In addition there were two ley treatments, one grass–clover and the other grass with fertilizer N and these were not ploughed in the first 6 years. The amounts of organic matter added during the first 6-year treatment phase and their effect on %C in soil are in Table 5 . In 1971, the two fertilizer-treated soils contained, on average, 0.69%C. The largest increase in %C was with peat; the next largest was with the FYM treatment. The leys and straw increased %C by the same amount but there was only a very small increase where green manures were incorporated. Although SOM accumulated with these treatments, there were varying and often large losses of C and N. About 50% of the C added in FYM was lost and the loss was even larger with straw and green manures (Table 5). Much of the C added in peat was retained, presumably because most of the readily decomposable organic matter had already gone, so that the C:N ratio of the peat was about 10:1. Estimating the amount of the organic matter accumulated under the leys was difficult but Mattingly *et al.* (1974) considered that in 1971 much of the C accumulated under the leys had been retained in the soil.

Arable crops were grown in rotation with an eight-level N test (see page 31) during the next 8 years (1973–1980) to assess the effects of the increased levels of SOM achieved by the organic amendments. During this period the only organic inputs were ploughed-in roots and cereal stubble and the level of SOM declined on all plots, more where there had been organic amendments than on fertilizer-treated plots. This period was followed by another treatment phase from 1981 to 1986, but with some modifications. The fertilizer, FYM, straw, and grass/clover ley treatments were continued but the green manure, peat, and grass ley with N treatments were all replaced with a grass/clover ley, that is, half the plots were in grass/clover ley, half in arable crops and of the latter, two had organic matter additions, FYM and straw. Again, SOM increased with the organic treatments and leys but continued to decline slowly where only fertilizers were applied.

Table 5 Changes in percent organic carbon (%C) in the top 23 cm of a sandy loam after applying different organic matter amendments for 6 years and percent retention of applied carbon, Organic Manuring experiment, Woburn (adapted from Mattingly *et al.*, 1974)

		Organic treatment 1965–1971					
	Fertilizer	Straw	FYM	Grass/clover	Grass + N	Green manure	Peat
%C in top 23 cm in 1971	0.69	0.92	1.04	0.92	0.92	0.79	1.33
Increase in %C compared to fertilizer		0.23	0.35	0.23	0.23	0.10	0.64
Amount of organic matter added (t ha^{-1})		43.4	41.8	9.0	10.5	6.1	36.2
% organic matter retained in topsoil		13	50	100	120	35	90

This treatment phase from 1981 to 1986 was followed by another 8-year test phase in 1987–1994 when six rates of N were tested on the arable crops. Then from 1995 to 2002, arable test cropping continued but with only two rates of N being tested. In 2002 all the plots were sampled before another treatment phase started. The effects of the different treatments on SOM during the period 1965–2002 are shown in Fig. 7. At the last sampling in 2002, %C had apparently increased on all plots by much the same amount; we cannot offer an explanation for this apparent increase, it may be due to sampling or analysis. Soil sampling should always be as consistent as possible following agreed protocols for an experiment. Changing analytical techniques poses a problem; much of the earlier C data presented here were determined using a wet digestion technique that was later replaced by an automated combustion technique. Archived soil samples have been used for cross checking but to reanalyze all samples would be a major undertaking.

During the 38-year period, SOM declined slowly for the first 20 years to reach an equilibrium value about 0.65%C where arable crops were grown only with fertilizers. All the organic treatments increased SOM initially by varying amounts (Table 5), but SOM then declined once the input of organic matter, over and above that is ploughed-in as crop residues, ceased. During the second 6-year organic treatment phase, SOM increased again, more with the FYM treatment than any other, and then declined again when the extra organic inputs ceased. Interestingly, although the initial

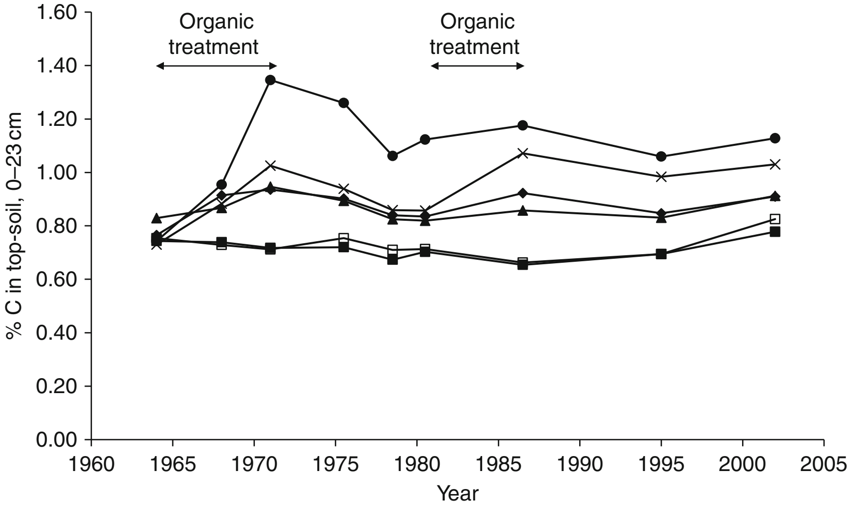

Figure 7 Changes in percent organic carbon (%C) in the top 23 cm of a sandy loam soil, Organic Manuring experiment, Woburn, 1965–2002. Fertilizers only □, ▪; Straw dry matter 7.5 t ha^{-1}, ▲; Grass/clover ley, ◆; FYM 50 t ha^{-1}, x; Peat dry matter 7.5 t ha^{-1}, •.

large increase in SOM from applying peat was not maintained once the peat applications ceased, there was nevertheless a residue of very resistant organic matter that has maintained a higher level of SOM on this treatment than on any other even though peat was not applied after autumn 1970. Although there was an appreciable increase in SOM from applying FYM, the amount applied annually was far larger than that which would be available in many farming systems unless very large numbers of animals are kept. As in the Ley–arable experiments described above, interspersing leys with arable crops in this experiment increased SOM by about 30%, a worthwhile increase, but the adoption of such a farming system requires that it is financially viable.

3.4. Effects of straw incorporation

Incorporating plant residues from grain crops, like cereal straw and maize stover, is one means by which farmers can add organic matter to soil. Experiments to test the effects of straw incorporation compared to its removal by burning were started at Rothamsted and Woburn in 1985. Chopped straw was incorporated either by ploughing to 20 cm (inversion tillage) or by tine cultivator (noninversion tillage) to 10 or 20 cm. About 4 t ha^{-1} of straw was incorporated each year for 17 years before the 0–10 and 10–20 cm soil depths were sampled in 2001 (Table 6). There was no measurable increase in %C where straw was incorporated by ploughing at Rothamsted but at Woburn there was a small increase in both soil horizons. Where straw was incorporated by tine cultivator to 10 cm, there was a small increase in %C at both depths at Rothamsted but no effect at Woburn. Such differences in the change in %C between sites and methods of incorporation are difficult to explain.

The effects of straw incorporation on %N were more consistent (Table 6). The difference between C and N is because during the microbial decomposition of straw, with its wide C:N ratio, there is a greater loss of C than of N to reach the C:N ratio of about 10:1 for SOM. Thus, while only about 10% of the added C was retained in the soil, 70–100% of the added N could be accounted for at both Rothamsted and Woburn.

These straw incorporation experiments were stopped in 2001. However, to assess any long-term effect of straw incorporation on SOM, it was decided in 1986 to plough-in the straw produced each year on the plots of Section O of the Broadbalk Winter Wheat experiment. After 14 years, changes in %C and %N have been small but mainly positive where straw has been incorporated on plots getting fertilizer N each year. In both these experiments, it is difficult to explain why so little C has been retained in the soil after 14–17 years of straw addition on plots that have received sufficient N fertilizer to grow acceptable yields of grain crops. However, anecdotal evidence from farmers who have been incorporating straw for some years

Table 6 Effect of straw incorporation for 17 years (1985–2001) on percent soil organic carbon (%C) and total N (%N) on two contrasted soil types

		Rothamsted silty clay loam, 20% clay		Woburn sandy loam, 13% clay	
		Straw		Straw	
Treatment[a]	Depth sampled[b] (cm)	Burnt	Incorporated	Burnt	Incorporated
		Organic C (%)		Organic C (%)	
Ploughed	0–10	1.84	1.87	1.08	1.28
	10–20	1.86	1.85	1.14	1.26
Tined	0–10	2.28	2.40	1.54	1.58
	10–20	1.86	2.02	1.23	1.18
		Total N (%)		Total N (%)	
Ploughed	0–10	0.150	0.160	0.093	0.108
	10–20	0.152	0.161	0.096	0.104
Tined	0–10	0.179	0.201	0.117	0.134
	10–20	0.160	0.173	0.098	0.106

[a] Straw was either burnt or chopped and incorporated by ploughing to a depth of 20 cm or by tine cultivation to a depth of 10 cm.

[b] Soils sampled in autumn 2001.

invariably suggests that there has been a benefit in terms of ease of ploughing. Possibly incorporation of crop residues by inversion or noninversion tillage prevents the soil becoming seriously compacted.

3.5. Effect of different arable crop rotations on the loss of soil organic matter

Different arable crop rotations can have different effects on SOM. At Rothamsted two different arable rotations followed the ploughing of old grassland soil that contained 3.0%C. One rotation had four root crops and two cereals in 6 years; the other had three cereals, two root crops, and a 1-year grass ley in the 6 years. In both rotations crop residues like straw and sugar beet tops were removed after each harvest, and no organic manures were applied. Changes in SOM with these two rotations were compared with those where no crop was grown after ploughing the grass and weeds were controlled by soil cultivation, the fallow treatment. All soils were sampled periodically to 23 cm and %C determined. Where the soil was continuously fallowed, the decline in %C was exponential, about 50% of the original SOM was lost in the first 20 years and about 60% had been lost after 40 years. While such losses were expected there were also large losses on the soils growing the arable crop rotations. During the first 20 years after ploughing the grass, SOM declined by 40% in the rotation with most root crops and by 30% in the rotation with more cereal crops (Johnston, 1986). Presumably the extra soil cultivations to prepare for sowing root crops and to control weeds caused the larger decline in SOM.

3.6. Increases in soil organic matter when soils are sown to permanent grass

Comment has been made about the difficulty of increasing SOM but appreciable increases are possible when permanent grass is established and maintained on soils with little SOM as a consequence of growing arable crops for very many years. At various times in the 1870s–1880s, a number of fields on the Rothamsted farm were sown to grass and periodically the soils were sampled 0–23 cm and the total N determined by Lawes and Gilbert. Their data in the Rothamsted archive were published by Richardson (1938). In the 1960s a few of these fields were still in grass and they were sampled again and the soil analyzed for total N. Lawes and Gilbert's and our data for the 1960s were combined to show the buildup of soil N over time (Johnston and Poulton, 2005; Fig. 5). Subsequently more data related to the buildup of N in soil with time have been collected and are shown in Fig. 8. The approximately 220- and 350-year values in Fig. 8 are from soils from the Park Grass experiment at Rothamsted (Warren and Johnston, 1964). This experiment was started in 1856 on a site that had been in grass for at least 200 years so the "220 year" %N was for soil sampled in 1876 and the "350 year" %N was that in 2002, 150 years after the start. Adding in more

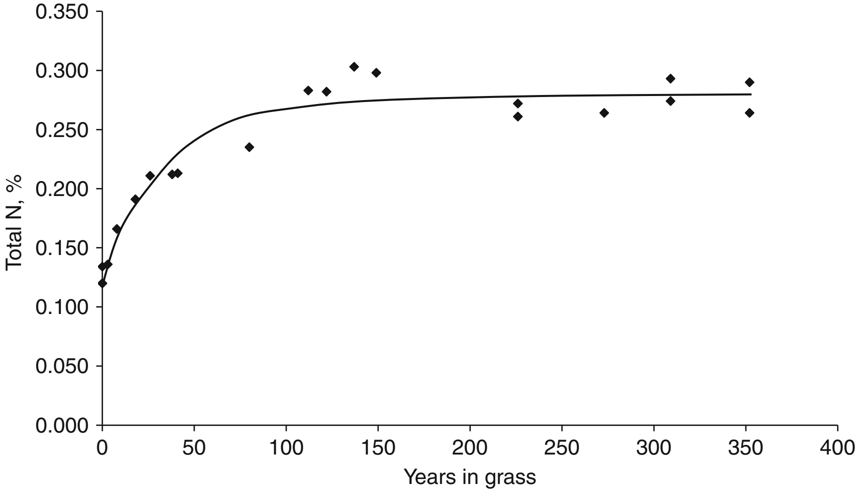

Figure 8 Buildup of organic nitrogen (%N) in the top 23 cm of a number of silty clay loam soils that had been in arable cropping and were then sown to grass at various times and for various periods at Rothamsted.

data has inevitably increased the scatter shown in Fig. 8. The scatter in percent N appears to be related to management; grassland that is intensively managed, harvested more frequently and given more N seems to accumulate more N than extensively managed grassland. However, the underlying principle is unaltered, namely for the silty clay loam at Rothamsted it takes about 100 years for the equilibrium %N content, typical of an old arable soil to increase to the equilibrium %N of a soil under permanent grass. However, Fig. 8 also shows that on this soil type under the prevailing climatic conditions, it takes about 25 years to increase SOM to a level half-way between that of an old arable soil and a permanent grassland soil. Even under this ideal condition for SOM accumulation, SOM increases only slowly.

4. SOIL ORGANIC MATTER AND CROP YIELDS

4.1. Arable crops grown continuously and in rotation

4.1.1. Experiments before the 1970s

Comment has already been made that in the early years of the Rothamsted experiments Lawes and Gilbert showed that it was possible to get the same yields of winter wheat, spring barley, and mangels (*Beta vulgaris* var. *esculenta*) with fertilizers, providing the right amounts of N, P, and K were applied, as with FYM applied at 35 t ha^{-1} annually. As these experiments continued the annual applications of FYM gradually increased SOM so that these soils contained 2.5–3.0 times more SOM in the 1970s than soils getting fertilizers only. Yet throughout the period from the 1850s to the mid-1970s, yields were the same with the two contrasted treatments (Table 7) leading to an oft repeated comment that SOM was unimportant provided sufficient nutrients were applied as fertilizers.

The wheat and barley experiments did not, at that time, include a treatment with FYM plus N, but this was a treatment on Barnfield where root crops were grown each year. Applying 96 kg ha^{-1} fertilizer N with FYM appreciably increased yields of both mangels and sugar beet (Table 8). Presumably N mineralized from the large annual application of FYM and any N mineralized each year from SOM were not sufficient to meet the N requirements of these root crops. This result led subsequently to a test of FYM plus additional amounts of fertilizer N in many experiments at Rothamsted.

Until the 1970s, other results from long-term experiments confirmed the lack of benefit from the extra SOM shown in Table 7, for example, those in the Rothamsted Ley–arable experiments (Johnston and Poulton, 2005; Fig. 6). Where N fertilizer was not applied, yields of potatoes, winter wheat, and spring barley were larger following ploughing a 3-year grass/clover than those following arable crops. However, where fertilizer N at 100 and 90 kg ha^{-1} was given to the wheat and barley, respectively,

Table 7 Yields of winter wheat and spring barley grain and roots of mangels and sugar beet at Rothamsted (adapted from Johnston and Mattingly, 1976)

			Yield (t ha^{-1}) with	
Experiment	Crop	Period	FYM[a]	NPK fertilizers[a]
Broadbalk	Winter wheat	1852–1861	2.41	2.52
		1902–1911	2.62	2.76
		1970–1975	5.80	5.47
Hoosfield	Spring barley	1852–1861	2.85	2.91
		1902–1911	2.96	2.52
		1964–1967	5.00	5.00
Barnfield	Mangels	1876–1894	42.2	46.0
		1941–1959	22.3	36.2
	Sugar beet	1946–1959	15.6	20.1

[a] FYM, 35 t ha^{-1}; N to wheat, 144 kg ha^{-1}; to barley, 48 kg ha^{-1} but 96 kg ha^{-1} in 1964–1967; to mangels and sugar beet, 96 kg ha^{-1}.

Table 8 Yields (t ha^{-1}), roots of mangels, 1941–1959, and sugar beet, 1946–1959, Barnfield, Rothamsted (adapted from Johnston, 1986)

	Mangels		Sugar beet	
Treatment	No N	+N[a]	No N	+N[a]
PK	6.8	36.2	4.5	20.1
FYM[b]	22.3	50.2	15.6	27.9

[a] 96 kg N ha^{-1} as sodium nitrate.
[b] 35 t ha^{-1}.

the yields of both cereals were the same following the ley and arable cropping. Also, when comparing yields in both experiments, although the soil on Highfield contained 2.1%C compared to 1.6%C on Fosters, the larger amount of SOM in Highfield soils did not affect the yields of the cereals provided sufficient fertilizer N was applied. However, the yields of potatoes were always larger on Highfield with more SOM than Fosters. There was a "crop effect" in the response to SOM.

4.1.2. Experiments after the 1970s

Having shown that one amount of fertilizer N applied with FYM increased the yields of mangels and sugar beet in the Barnfield experiment (Table 8), this experiment was modified in 1968, to test four amounts of N on potatoes, sugar beet, spring barley, and spring wheat grown three times in rotation on all plots between 1968 and 1973. Irrespective of the amount of N applied, the largest yields of the root crops were always on FYM-treated soils that contained more SOM and the benefit of the extra SOM was smaller for spring barley and spring wheat. However, for all four crops less fertilizer N was needed to achieve the optimum or near optimum yield when the crops were grown on the plots with more SOM (Table 9).

Similar benefits on crop yields from extra SOM were evident on the sandy loam at Woburn from the early 1970s. Yields of red beet in the Market Garden experiment were larger on soils with more SOM even though as much as 450 kg N ha^{-1} was applied to fertilizer-only plots (Johnston and Wedderburn, 1975). In the Ley–arable experiment sugar yields were about 0.6 t ha^{-1} larger when the beet followed a 3-year lucerne ley than in an all-arable rotation even though 220 kg N ha^{-1} was applied (Johnston, 1986). Cereals and potatoes were both grown between 1973 and 1980 in an experiment where two levels of SOM were established by adding peat (Johnston and Brookes, 1979). Peat was chosen as the source of organic matter because it would add little or no mineral nutrients. Four amounts of N appropriate to the crop were tested and yields of the spring crops, potatoes, and barley were always larger on the soil with more organic matter irrespective of the amount of N applied, but yields of winter-sown cereals were independent of SOM (Table 10). Spring-sown crops have to

Table 9 Yields of potatoes and sugar beet, spring barley, and spring wheat in 1968–1973 on soils treated with PK fertilizers or FYM since 1843[a], Barnfield, Rothamsted (adapted from Johnston and Mattingly, 1976)

		Fertilizer N applied[b]			
		N0	N1	N2	N3
Crop	Treatment	Yields (t ha^{-1})			
Potatoes, tubers	FYM[c]	24.2	38.4	44.0	44.0
	PK	11.6	21.5	29.9	36.2
Sugar beet, roots	FYM	27.4	43.5	48.6	49.6
	PK	15.8	27.0	39.0	45.6
Spring barley, grain	FYM	4.18	5.40	5.16	5.08
	PK	1.85	3.74	4.83	4.92
Spring wheat, grain	FYM	2.44	3.73	3.92	3.79
	PK	1.46	2.97	3.53	4.12

[a] PK- and FYM-treated soils contained 0.10 and 0.25%N, respectively.
[b] N applied: N0, N1, N2, N3: 0, 48, 96, 144 kg ha^{-1} to cereals; 0, 72, 144, 216 kg ha^{-1} to root crops.
[c] FYM, 35 t ha^{-1} annually.

Table 10 Yields of potatoes, spring barley, winter wheat, and winter barley, 1973–1980, Peat experiment, Woburn (adapted from Johnston and Brookes, 1979 and Johnston and Poulton, 1980)

		Fertilizer N applied[a]			
		N0	N1	N2	N3
Crop	%C in soil	Yields (t ha^{-1})			
Potatoes, tubers, 1973 and 1975	0.76	25.7	35.6	41.7	43.2
	2.03	27.1	40.6	50.7	59.0
Spring barley grain, 1978	0.76	2.19	5.00	6.73	7.05
	1.95	2.58	5.12	6.85	7.81
Winter wheat grain, 1979	0.76	3.54	7.32	8.05	7.82
	1.95	4.81	7.21	8.09	8.08
Winter barley grain, 1980	0.76	3.05	6.01	7.32	7.83
	1.95	3.57	5.92	7.00	7.98

[a] N applied: N0, N1, N2, N3: 0, 100, 200, 300 kg N ha^{-1} for potatoes; 0, 50, 100, 150 kg N ha^{-1} for cereals.

develop a sufficiently large root system quickly to acquire nutrients and water and for this a good soil structure, which is related to SOM, is required. Autumn-sown crops have a long period to develop an adequate root system. In this experiment all operations were done by hand so there was no effect of SOM on soil compaction.

The effect of management and a range of organic inputs on SOM in the Woburn Organic Manuring are described on page 22. In the first test cropping phase potatoes, winter wheat, sugar beet, and spring barley were grown in rotation and on each crop eight amounts of N were tested. The two fertilizer treatments had received different amounts of P, K, and Mg to allow for the very different amounts applied in FYM and the other organic amendments, and this resulted in differences in readily plant-available P, K, and Mg in the two soils. However, crop yields were almost identical on these treatments and as the upper and lower values spanned the range in plots testing the organic inputs this suggests that yields on the latter were not limited by these nutrients. Yields of all four crops, averaged over the four lowest and four largest amounts of N fertilizer, were always larger on soils with more organic matter (Johnston, 1986). After the first test phase there was another treatment phase (see page 24) followed by another test phase in which only potatoes and wheat were grown in rotation and six amounts of N were tested. The response of wheat and potatoes to N on the four treatment sequences common to both treatment phases is shown in Fig. 9. Yields were always smallest on soil with least SOM and generally largest on soils ploughed out from a grass/clover ley. Some of the benefit from N-rich

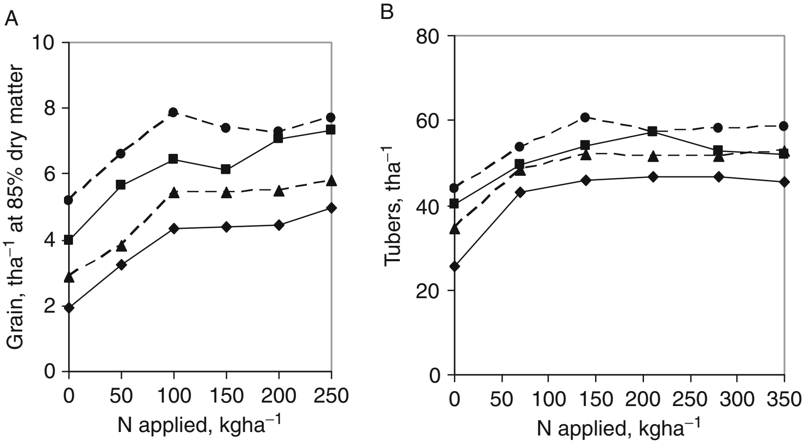

Figure 9 Yields (t ha^{-1}) of test crops in the Organic Manuring experiment, Woburn. Annual organic treatment from 1965 to 1971 and again in 1981–1986: fertilizers only, ◆; 7.5 t ha^{-1} straw, ▲; 50 t ha^{-1} FYM, ▪; grass/clover ley, •. (A) Winter wheat in 1987 and 1988; (B) potatoes in 1988 and 1989.

clover ley residues ploughed-in the previous autumn could derive from the availability of N, by mineralization of the residues, late in the growing season and at positions in the soil profile difficult to mimic with applications of fertilizer N. Good yields were given by 50 t ha^{-1} FYM but very few farms have such quantities available for application every year to build up SOM to the levels in this experiment. For both wheat and potatoes in the second test phase, yields following grass/clover leys exceeded those given by fertilizers with the largest amount of N, in most other cases less N was required to achieve maximum yield on the soils with organic amendments compared to those on fertilizer-only plots. Of considerable interest is the benefit from ploughing in straw each year at a rate that a good crop of cereals should produce. That yield benefits continue to be measured with this treatment suggests that on soils with little SOM, straw incorporation will increase SOM sufficiently to have beneficial effects. Straw incorporation is one method readily available to farmers for increasing or maintaining SOM, or perhaps preventing it declining to very low levels where there could be adverse effects on crop yields.

4.1.3. Recent data from long-term experiments

In 1968 a number of major changes were made to the experiment on winter wheat on Broadbalk and that on spring barley on Hoosfield. Besides growing wheat or barley continuously, a three-course rotation of potatoes, field beans, and wheat or barley was started to estimate the effects of soil borne pathogens on the yields of the cereal crop. Modern, short-strawed cultivars of either wheat or barley were also introduced.

On Hoosfield, where spring barley has been grown in all but 4 years since 1852, all plots were divided into four subplots to test four rates of fertilizer N on all treatments including the FYM- and fertilizer-treated plots. By the 1960s the FYM-treated soil contained 2.5 times more SOM than did the fertilizer-treated plot but in 1964–1967 this extra SOM did not increase yield provided the optimum amount of fertilizer N was applied, see Table 7. The first of the modern cultivars, Julia, was introduced in 1968 together with the increased rates of N. Grain yield was larger when 48 kg N ha^{-1} was applied in spring to the FYM-treated soil than with the largest amount of N on the fertilizer-treated soil (Fig. 10A). Yields were the

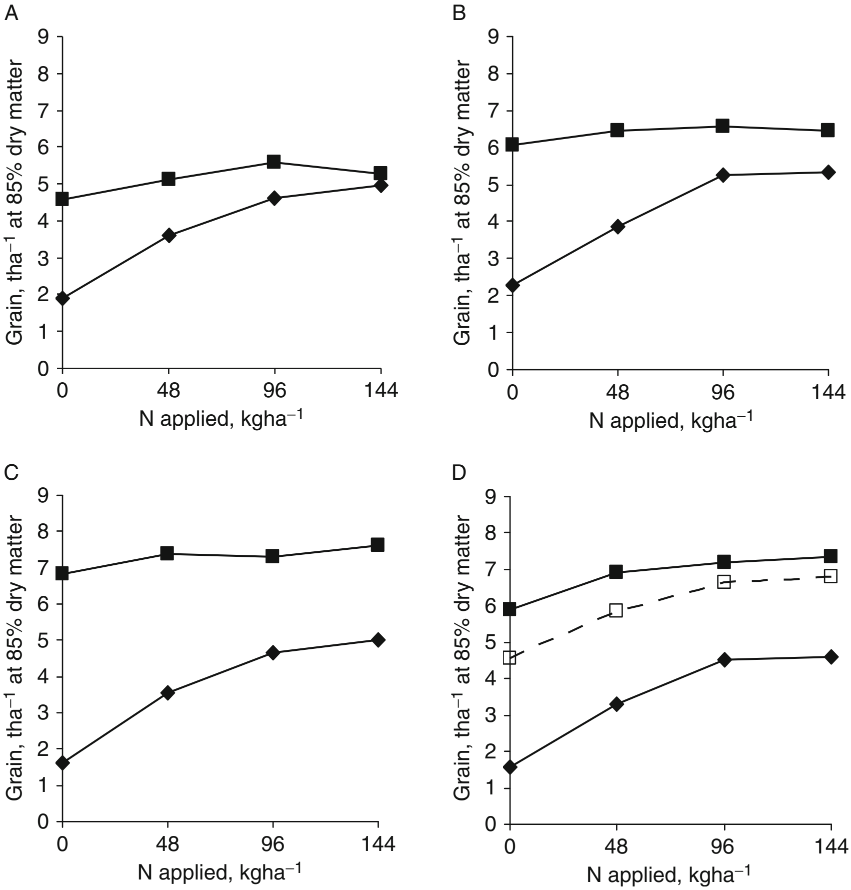

Figure 10 Yields of spring barley grain (t ha^{-1}) Hoosfield Continuous Barley, Rothamsted. Annual treatment 1852–2006: PK fertilizers, ◆; 35 t ha^{-1} FYM, ▪; annual treatment only from 2001 to 2006: 35 t ha^{-1} FYM, □. (A) *cv.* Julia, 1976–1979, (B) *cv.* Triumph, 1988–1991, (C) *cv.* Cooper, 1996–1999, and (D) *cv.* Optic 2004–2007.

same on both treatments when 144 kg N ha^{-1} was given. In the following years cultivars with a larger yield potential were grown and the difference in yield between the FYM- and fertilizer-treated soils increased. In 1996–1999, *cv.* Cooper yielded as much as 2.5 t ha^{-1} more grain on the soil with more organic matter (Fig. 10C). Interestingly, the maximum yield of each cultivar grown on the fertilizer-treated soil has not declined since the mid-1970s, it has remained largely unchanged. Rather it is the yields on the soil with more SOM that have been larger as the yield potential of the cultivar grown has increased. We believe that much of the difference in yield between these soils with different levels of SOM is because the extra SOM improves soil structure, although additional N, mineralized late in the growing season and deeper in the soil profile, may have contributed to the larger yield. A better soil structure allows a spring-sown crop to quickly develop an adequate root system for maximum water and nutrient uptake. The shape of the N response curve on the soil with less SOM does not indicate that applying more N would increase yield to that on the FYM-treated soil.

In 2001 a new FYM-treated plot was started within the Hoosfield experiment with annual applications of 35 t ha^{-1}. Yields on this plot, which also tests four rates of N, have increased very rapidly to be intermediate between those on the long-continued fertilizer- and FYM-treated soils (Fig. 10D). This shows that even a small increase in SOM together with N from the current application of FYM and fertilizer N has improved yield on a soil that had been in cereal cropping for 150 years and contained little SOM.

On Broadbalk, where a range of fertilizer N rates was already being tested, changes in 1968 included testing extra fertilizer N, 96 kg ha^{-1}, on one of the FYM plots, and a comparison of wheat grown each year (continuous wheat) with wheat grown in a rotation designed to minimize any adverse effect of the soil borne pathogen *Gaeumannomyces graminis*, which causes take-all in wheat. As on Hoosfield, modern, short-strawed cultivars, with an improved grain: straw ratio, were also introduced. Now the cultivar grown is reviewed periodically and a new one introduced when appropriate. The yields of the different cultivars of wheat grown continuously and in rotation with fertilizers, FYM and FYM + 96N since 1968 are in Fig. 11. The yields of continuous wheat with either PK + 144 kg N ha^{-1} or 35 t ha^{-1} FYM have remained closely similar as they have from the beginning of the experiment in 1843 (Fig. 11A). However, as the yield potential of the cultivar grown has increased, and, since 1979, where that yield potential has been protected by the use of fungicides, grain yield has increased where more N has been applied. Consequently, the maximum yield with both "PK + best N" and FYM + 96N is now about 2 t ha^{-1} larger than with PK + 144 kg N and FYM alone, respectively (Fig. 11A). (The yield with the "PK + best N" treatment is the largest yield given by

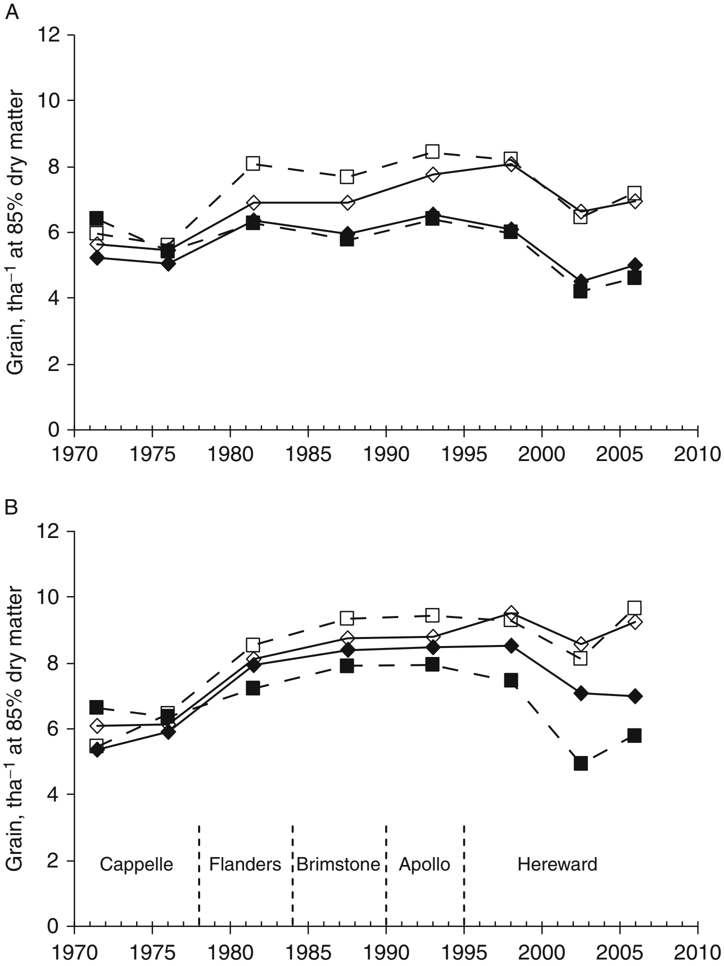

Figure 11 Average yields of winter wheat grain (t ha^{-1}) with different cultivars on the Broadbalk Winter Wheat experiment, 1970–2006. Annual treatment: PK + 144 kg N ha^{-1}, ◆; FYM 35 t ha^{-1}, ▪; "Best" NPK, ◇; FYM 35 t ha^{-1} plus 96 kg N ha^{-1}, □. (A) Wheat grown year after year; (B) wheat grown after a 2-year break.

either 192, 240, or 288 kg N ha^{-1} each year; this yield has been averaged for each group of years.)

For each of the cultivars shown in Fig. 11, the effect of growing "a first" wheat after a 2-year break has been to increase comparable treatment yields by about 2 t ha^{-1}. Thus, there is a large benefit from minimizing the adverse effects of take-all. In many cases, the yield of *cv.* Hereward grown between 1996 and 2007 has declined both when grown continuously and in rotation. In part, this can be explained by some poor growing seasons in this period and also it appears that this cultivar has a high demand for N. For example, in 1996–2000, both when grown continuously and in rotation, the yield with the "PK + best N" and FYM + 96N treatments were similar to those of cultivars Brimstone and Apollo. Then, with all treatments, there was a serious decline in yield in 2001–2004 with very poor growing seasons. Yields improved somewhat in 2005–2007, more so with wheat grown in rotation than continuously, where the best yields with "PK + best N" and FYM + 144 kg N ha^{-1} were closely similar; adding 144 kg fertilizer N with FYM was first introduced in 2005. It is difficult to see why the N available from the mineralization of the extra SOM in the FYM-treated plot plus that from a fresh application of 35 t ha^{-1} FYM requires an extra 144 kg ha^{-1} fertilizer N to meet the N requirement of Hereward.

The yields of the three cultivars grown between 1979 and 1995 with FYM + 96N were always larger than those with the "PK + best N" treatment, especially when the wheat was grown in rotation. This suggested that there was a benefit from the extra SOM, probably through an improvement in soil structure. However, with the increased amounts of fertilizer N applied to *cv*. Hereward these two treatments have given very similar yields suggesting no benefit from the extra SOM accumulated from FYM. This change is difficult to explain.

A number of changes have been made in the test and treatment crops in the Woburn Ley–arable experiment over the period of the experiment. In 1981–1991, winter wheat and spring barley, each testing four amounts of N, were grown as first and second test crops following the 3-year treatment cropping. Wheat yields following ploughed-in leys were always larger than those following arable crops at all levels of N except the largest (Fig. 12).

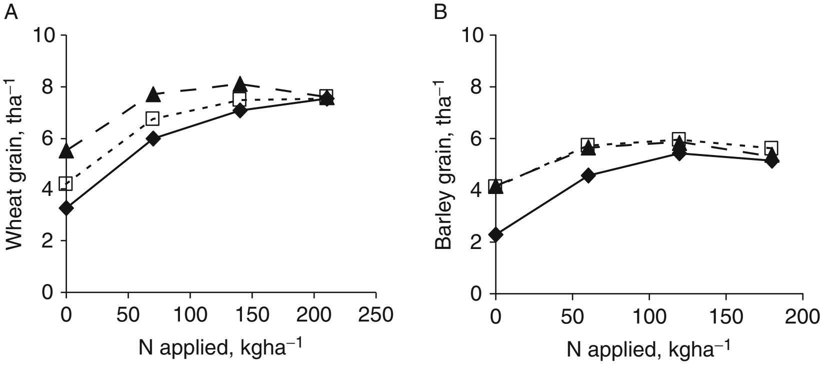

Figure 12 Yields (t ha^{-1} grain) of test crops in the Ley–arable experiment, Woburn. Three-year treatment cropping: arable crops, ◆; grass ley + N, □; grass/clover ley, ▲. (A) Winter wheat, 1981–1990; (B) spring barley, 1982–1991. (Adapted from Poulton and Johnston, 1996.)

However, less fertilizer was needed to get maximum yield following the leys and more N was mineralized from the grass/clover ley than the all-grass ley to give a larger increase in yield of wheat but not of barley. In terms of N fertilizer use there is a benefit for arable crops that follow ploughed-in leys but within a farming enterprise the use of the leys has to be financially viable.

5. EXPLAINING THE BENEFITS OF SOIL ORGANIC MATTER

As mentioned in Section 1, Russell (1977) noted that ‘‘the major problem facing the agricultural research community is to quantify the effects of soil organic matter on the complex of properties subsumed under the phrase soil fertility. . .’’ Soil organic matter can/may contribute to soil fertility in a number of ways, namely:

- During its microbial decomposition it may release N, P, and S and some trace elements at times during the growing season and positions within the soil profile when it is difficult to mimic the effect with a fertilizer application.
- Stabilize soil structure especially in poorly structured soils.
- Increase cation and anion exchange capacity especially in light textured soils.
- Increase water-holding capacity, especially that of available water.

It is difficult to identify and quantify the interrelationships of these factors with the biological, chemical, and physical properties of soil especially when there are few appropriate techniques to use in the laboratory and setting-up field experiments with plots with different levels of SOM on the same soil type takes many years and can be very expensive. Here, results from some long- and short-term experiments at Rothamsted are used to try to tease out some of these effects and interactions.

5.1. Organic matter, soil structure, and sandy loam soils

Soil organic matter could improve soil structure through a range of mechanisms like bonding mineral particles into crumbs or peds and then stabilizing them, so that the formation of large pores would increase the rate of water infiltration and speed the exchange of gases. However, these mechanisms do not seem to work on sandy loam soils and the following results from field experiments suggest that generalizing about short-term effects of SOM is not easy.

Observations on the behavior of the sandy loam soil at Woburn suggest that the buildup of SOM from long-continued applications of FYM does not seem to create more stable crumbs than those on fertilizer-treated soils. With both treatments soil aggregates can be created during seedbed preparation, but the impact of heavy rain disintegrates them and small amounts of silt and clay particles fill the voids between the sand-sized particles. As the surface soil dries a "crust" is formed through which young seedlings have to emerge. On fertilizer-treated soils the crust is "hard" and seedlings emerge with difficulty resulting in less than optimum plant populations. On FYM-treated soil the extra SOM appears to form a thin film around sand grains decreasing friction between them, so that emerging seedlings can more easily push them apart to establish a plant population giving acceptable yields. When peat was incorporated into the soil surface to minimize the formation of a crust and compared with peat dug into the top 25 cm soil, the yields of globe beet but not carrots were increased by the surface application while the dug-in peat increased yields of carrots but not globe beet (Johnston *et al.*, 1997).

Attempts to simulate the effects of the extra root mass when grass leys are ploughed-in was tried by incorporating coir fiber that looks like fine roots. The intimate distribution of fine roots within the soil mass was difficult to mimic with the coir fiber and the seedbed remained very "open," dried very quickly and lack of moisture decreased seedling emergence. Consequently the yields of sugar from beet and of globe (red) beet were smaller than those on the control plot (Johnston *et al.*, 1997).

After producing a range of crumb sizes by cultivation during seedbed preparation, these were stabilized by coating them with a (hydrolyzed poly (acrylonitrile)) that was available as "Krilium," produced by Monsanto Chemicals. It stabilized the soil crumbs against rain but not against mechanical impact. Effects on yields were variable, compared to the untreated soil, those of globe beet were increased, sugar yields were the same but lettuce yields were decreased, the latter probably because the surface soil remained "too open" and rapid drying adversely affected germination of the small-seeded lettuce (Johnston *et al.*, 1997).

5.2. Separating nitrogen and other possible effects of soil organic matter

5.2.1. Nitrogen, crop rotation, and soil organic matter effects

In Tables 9 and 10 and Figs. 9 and 10, the yields in the absence of applied fertilizer N are all larger on soils with more SOM. This could be due solely to N released by the mineralization of the organic matter but a component of this benefit could also have been due to an improvement in soil structure or some other factor affecting yield. Following the changes to the Broadbalk experiment in 1968 wheat was grown, either continuously, or as fallow,

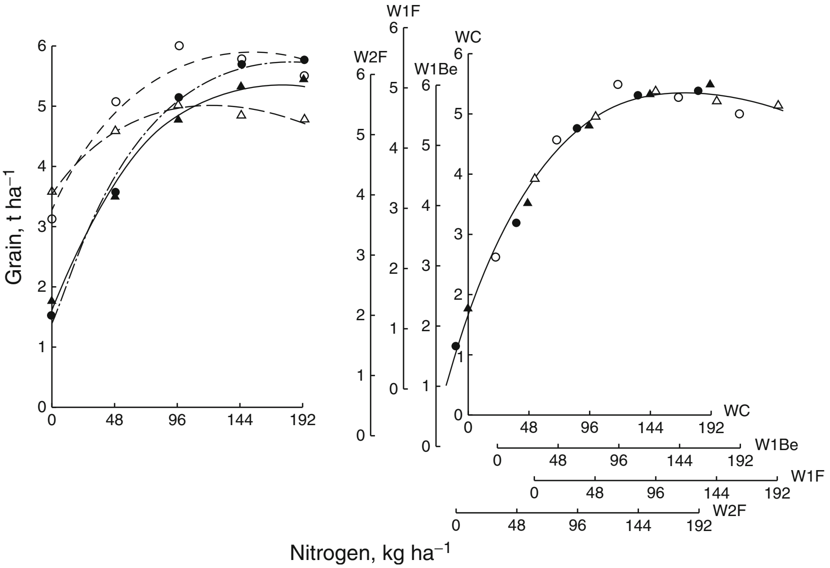

Figure 13 Broadbalk Winter Wheat experiment 1970–1978. Relationship between nitrogen applied and mean yield of grain (t ha^{-1}) when wheat was grown either: continuously, ▲; after a 2-year break, ○; after a 1-year fallow, △; or as a second wheat after a 1-year fallow, •. (A) Individual fitted N response curves; (B) fitted N response curves brought into coincidence by vertical and horizontal shifts.

wheat, wheat or potatoes, beans, wheat; N was tested on each wheat crop at 0, 48, 96, 144, and 192 kg ha^{-1} (Dyke *et al.*, 1983). Thus, there were four grain yield/N response curves (Fig. 13A) on soils with similar levels of SOM in the 8 years, 1970–1978. However, visual inspection of these curves suggested that each curve could be a segment of a single N response curve, which would be expected in terms of the biochemistry and physiology of the N nutrition of the plant. Fitting an exponential plus linear model as the response function produced a maximum yield for each response curve and these maximum yields could be brought into coincidence by appropriate horizontal and vertical shifts to produce a single N response curve (Fig. 13B). Horizontal shifts were interpreted as differences in available N, vertical shifts as differences in potential yield. Relative to continuous wheat, the first wheat after field beans (the second crop in the 2-year break) benefited by 23 kg ha^{-1} available N and produced 0.51 t ha^{-1} more wheat, probably because the adverse effect of take-all was decreased after a 2-year break. The first wheat after a 1-year fallow benefited by 53 kg ha^{-1} available N but produced 0.36 t ha^{-1} less grain because the adverse effects of take-all is more severe immediately following a 1-year break than in continuous wheat (Dyke *et al.*, 1983).

A similar exercise was done on the fertilizer- and FYM-treated plots, with their different levels of SOM, and the N response curves were brought into coincidence. The average horizontal shift, 69.2 kg N ha^{-1} represents the fertilizer N equivalent of the extra SOM while the average vertical shift, 1.39 t ha^{-1} grain, represents a unique benefit of extra SOM that did not equate to an application of N fertilizer in spring (Johnston, 1987).

5.2.2. Nitrogen and organic matter effects from short-term leys

A similar approach to that above was taken to try to separate the N effects from other factors affecting yield in an experiment on the sandy loam soil at Woburn. Following the ploughing of 1–6-year old grass/clover leys, the yields and N response of the four following arable crops were measured (Johnston *et al.*, 1994). The four crops, grown in rotation, were winter wheat, potatoes, a second winter wheat, and finally field beans and on each crop, except the beans, there was a test of nil and five amounts of fertilizer N applied in spring. For each of the four test crops a linear plus exponential N response model was fitted to the yields given by each ley treatment. The six N response curves were then brought into coincidence by vertical and horizontal shifts with that for the 1-year ley (Fig. 14). For the first test crop winter wheat, most of the shift was horizontal, suggesting that the differences between the preceding ley treatments was largely due to the N released from the ploughed-in crop residues. The available N after the 4- and 5-year leys was equivalent to about 85 kg N ha^{-1} applied as one application in spring, while for the 6-year old ley it was about 126 kg N ha^{-1}. The vertical shift represents some unique, but undefined effect of ploughing in the 2–5-year old leys was just less than 1.0 t ha^{-1} grain.

For the second test crop potatoes, little horizontal shift was required, the range was 2–6 kg N ha^{-1}, suggesting that there was much less mineral N available from the mineralization of the ploughed-in ley residues. The vertical shift, range 6–10 t ha^{-1} tubers, suggested an appreciable organic matter effect, which has not been defined. Yields of winter wheat grown in the third year after ploughing the leys (not shown) showed little residual N effect.

5.3. Soil organic matter and soil structure

In an experiment on a silty clay loam soil at Rothamsted, plots were established over a 12-year period with two levels of SOM and at each level of SOM, 24 levels of Olsen P. After 12 years both the SOM and the Olsen P were well incorporated into the 23 cm plough layer. Potatoes, spring barley, and sugar beet were then each grown twice in rotation. The yields of tubers, grain, and sugar were plotted against Olsen P at each level of SOM and from the fitted response curve the yield at 95% of the asymptote and the Olsen P associated with this yield was estimated (Table 11). The soil

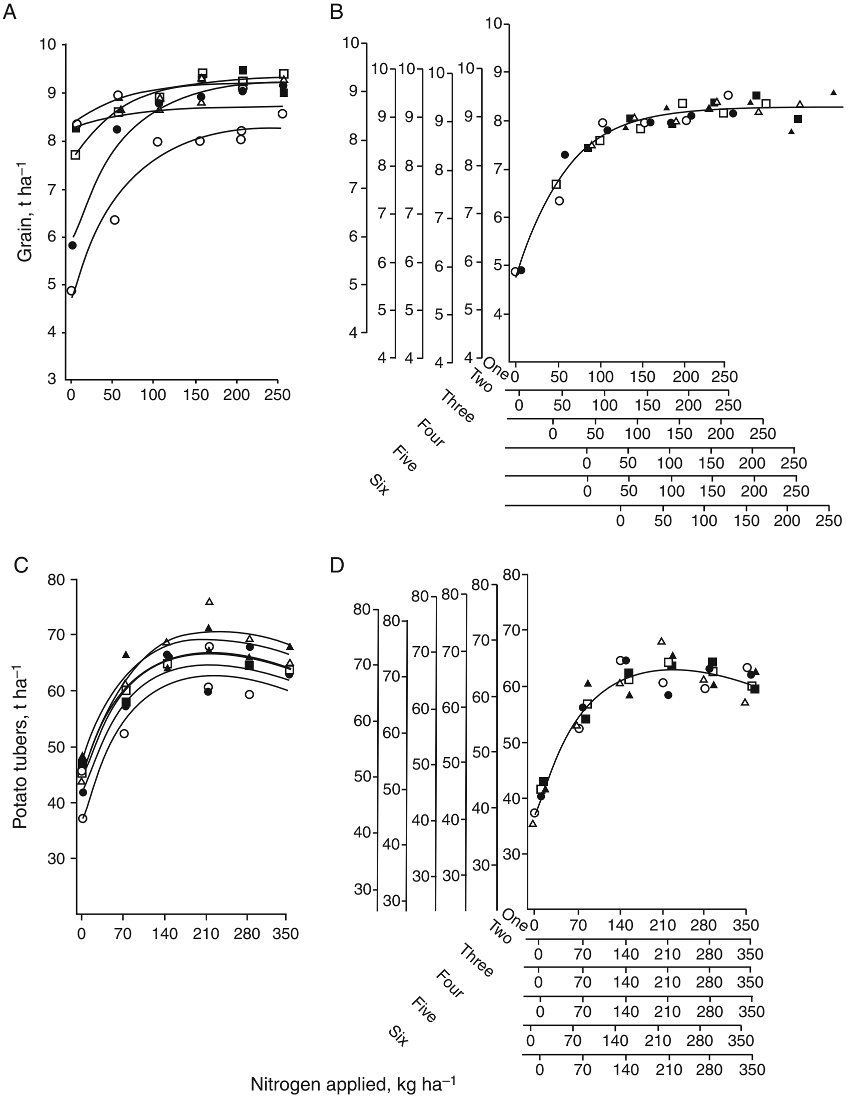

Figure 14 Effect of age of a grass/clover ley ploughed-in before growing winter wheat and potatoes in succession on their response to nitrogen fertilizer. Ley age in years: one, ○; two, •; three, □; four, ▪; five, △; six, ▲. (A) and (C) Individual N response curves for wheat (A) and potatoes (C); (B) and (D) individual N response curves brought into coincidence by appropriate horizontal and vertical shifts for wheat (B) and potatoes (D).

on which this experiment was made is one of the most difficult to cultivate on the Rothamsted farm, particularly for early spring drilling of cereals. The yield of spring barley at 95% of the asymptote was appreciably smaller

Table 11 The effect of soil organic matter on yield responses to Olsen P, Agdell, Rothamsted

Crop	Organic C (%)	Yield at 95% of the asymptote (t ha^{-1})	Olsen P associated with 95% yield (mg kg^{-1})	Variance accounted for (%)
		Field experiments		
Spring barley grain (t ha^{-1})	1.40	5.00	16	83
	0.87	4.45	45	46
Potatoes tubers (t ha^{-1})	1.40	44.7	17	89
	0.87	44.1	61	72
Sugar beet sugar (t ha^{-1})	1.40	6.58	18	87
	0.87	6.56	32	61
		Pot experiment		
Ryegrass dry matter (g pot^{-1})	1.40	6.46[a]	23	96
	0.87	6.51	25	82

[a] The response curves at the two levels of SOM were not visually different.

on the soil with less SOM compared to that where there was more SOM. For the potatoes and sugar, the 95% yields were very similar because there was time in spring to produce good seedbeds for both crops. Of great importance, however, the level of Olsen P associated with the 95% yield was very much lower on the soil with more SOM compared to the Olsen P on the soil with less SOM and the percentage variance accounted for in the yield/Olsen P relationship was very much larger where there was more SOM. These differences were most probably due to the effects of SOM on soil structure, which was improved where there was more SOM so that roots grew more freely and more thoroughly explored the soil to find nutrients, especially P. Hence less Olsen P was required to achieve the optimum yield. To test this, soil samples from all 48 plots (2 levels SOM × 24 levels Olsen P) were brought to the laboratory, air-dried, and ground to pass a 2 mm sieve before being put in pots and cropped with ryegrass given adequate N, K, and Mg. The grass was harvested four times and the total yield of dry matter plotted against Olsen P. The response curves at the two levels of SOM were not visually different and the Olsen P associated with the 95% yield was essentially the same at both levels of SOM (Table 11). Because any soil structure effects were minimized under the conditions of the pot experiment, we consider that the differences in the critical Olsen P values seen in the field experiment were due to differences in soil structure under the field conditions.

The experiments discussed here have also been used to measure the effects of SOM on other aspects of soil structure. For example, the draught required for inversion ploughing to 23 cm was assessed on Broadbalk. Although the largest differences were related to clay content, the small (∼10%) increase in SOM on plots that had received more than 96 kg N ha^{-1} decreased draught appreciably (Watts *et al.*, 2006). Other examples include effects on soil friability (Watts and Dexter, 1998), soil aggregation (Watts and Dexter, 1997; Watts *et al.*, 2001), aggregate stability (Williams, 1978), and water infiltration (Blair *et al.*, 2006).

5.4. Soil organic matter and soil phosphorus and potassium availability

5.4.1. Availability of soil phosphorus

Soil organic matter contains both anion and cation exchange sites able to hold readily plant-available P and K. Comparing the retention of P in soils with different levels of SOM in the Rothamsted long-term experiments shows some interesting differences. Soil samples taken in the 1950s and 1970s from the 0–23 cm soil horizon of the unmanured, fertilizer- and FYM-treated soils were analyzed for total P, Olsen P, and P soluble in 0.01 M $CaCl_2$. The latter solution has about the same ionic strength as the soil solution in neutral and slightly calcareous soils like those at Rothamsted, so that the P in the extract would be similar to that in the soil solution. Much more P was extracted by all three reagents from the fertilizer- and FYM-treated soils than from the control (Table 12) and the amounts of total P and Olsen P in the two P-treated soils were similar. However, there was appreciably more $CaCl_2$ P extracted from the FYM-treated soils than from those given superphosphate. Only on the Barnfield experiment was superphosphate and FYM applied on the same plot. With this treatment the increase in both total and Olsen P was equal to the sum of the increases on plots getting only superphosphate or FYM, but the increase in $CaCl_2$ P was larger than the sum of the increase on plots getting either superphosphate or FYM (Table 12). This suggests that the extra SOM on the FYM-treated soils was providing a larger number of low energy bonding sites holding P and where superphosphate was added with FYM some of the P from the superphosphate was also held on these low energy bonding sites.

The importance of SOM in retaining readily plant-available P is seen in the data from the Exhaustion Land experiment (Table 12). Some plots had superphosphate from 1856 to 1901, others FYM from 1876 to 1901, and there was a control (no P) treatment. All plots were sampled in 1903 and the increase in total P, Olsen P, and $CaCl_2$ P followed the same pattern as in the other experiments (Table 12). No more superphosphate or FYM was applied after 1901 and SOM gradually declined in the previously FYM-treated plots (Johnston and Poulton, 1977). When the plots were sampled

Table 12 Total, Olsen, and $CaCl_2$-soluble P in 0–23 cm topsoil from three long-term experiments at Rothamsted (adapted from Johnston and Poulton, 1993)

Experiment and year started	Soil sampled	Treatment[a]	Total P (mg kg^{-1})	Olsen P (mg kg^{-1})	$CaCl_2$ P ($\mu g\ l^{-1}$)
Barnfield, 1843	1958	Control	670	18	15
		P	1215 (545)[b]	69 (51)	93 (78)
		FYM	1265 (595)	86 (68)	396 (381)
		FYM + P	1875 (1205)	145 (127)	691 (676)
Hoosfield, 1852	1966	Control	630	6	9
		P	1175 (545)	103 (97)	446 (437)
		FYM	1340 (710)	102 (96)	787 (778)
Exhaustion Land, 1856	1903	Control	530	8	6
		P	885 (355)	65 (57)	173 (167)
		FYM	860 (330)	66 (58)	297 (291)
Exhaustion Land, 1856	1974[c]	Control	480	2	3
		P residues	595 (115)	10 (8)	6 (3)
		FYM residues	630 (150)	12 (10)	9 (6)

[a] P single superphosphate at 33 kg P ha^{-1}; FYM, 35 t ha^{-1}.
[b] Figure in parenthesis is the difference from the control.
[c] No superphosphate or FYM applied after 1901.

again in 1974, the total P and Olsen P had both declined but were still very much the same in both soils, but interestingly, there was now little difference in $CaCl_2$ P. The decline in SOM had depleted the number of low energy bonding sites on which $CaCl_2$ P was held. Other examples of SOM holding more $CaCl_2$ P were given by Johnston and Poulton (1993).

5.4.2. Availability of soil potassium

Soil organic matter has cation exchange sites that hold exchangeable K, thus extra SOM can increase the plant-available K in soil. As in many field experiments in temperate climates, Addiscott and Johnston (1971) showed a very strong linear relationship between exchangeable K and K balance (K applied *minus* K removed in the harvested product) in many long-term Rothamsted experiments. Interestingly they showed that K retention in soil as exchangeable K by SOM appeared to be related to differences in the selectivity of clay and organic matter for K relative to calcium (Ca). Where K was applied in FYM, the K was already held on exchange sites. Where K was applied in fertilizer to a permanent grass sward on a slightly calcareous soil, there was competition between K and Ca for exchange sites on SOM as it was produced in the soil. In consequence, the ratio of K:Ca was larger in SOM derived from FYM than in SOM derived from grass roots in a slightly calcareous soil.

5.5. Soil organic matter and water availability

The effect of SOM on increasing the available water capacity (AWC) in the top 30 cm of soil has been assessed in a number of experiments at Rothamsted and the increases, ranging from 4 to 10 mm, are very small (Salter and Williams, 1969). These authors compared the AWC in soils of fertilizer- and FYM-treated plots from two of the long-term experiments at Rothamsted where there was a well-established difference in SOM. The AWC in the silty clay loam of fertilizer- and FYM-treated plots was, respectively, 49 and 58 mm on Broadbalk and 44 and 48 mm on Barnfield. On the sandy loam soil at Woburn the comparison was between a soil growing cereals continuously and one just ploughed from a 3-year grass/clover ley, the AWC was 45 and 55 mm, respectively.

Later, D. Hall (personal communication) measured the AWC in the 10–15 cm layer of the fertilizer- and FYM-treated plots, which are ploughed annually to 23 cm, in the Broadbalk and Barnfield experiments where there is 2.5 times more SOM where FYM is applied compared to where fertilizers are used. Hall found that for the fertilizer- and FYM-treated soils, the AWC was 32 and 44 mm, respectively, that is, an increase of 12 mm, in soils with extra SOM from long-continued applications of FYM. He also found that the easily available water was only increased by 8 mm, from 17 to 25 mm. Such small differences might be sufficient to mitigate against the adverse effect of short-term drought on young plants until they develop a root system capable of finding water in the deeper soil horizons.

6. MODELING CHANGES IN SOIL ORGANIC MATTER

The soil is a major sink for carbon dioxide (CO_2) in the form of SOM. Thus, there is considerable interest in modeling changes in SOM because, as the amount increases or decreases, CO_2 will be either retained in or lost from the soil. The large amount of data on changes in SOM in Rothamsted experiments has made it possible for Jenkinson and his coresearchers to develop models to describe such changes, and some examples are given here. The current Rothamsted model (ROTHC-26.3; Jenkinson, 1990; Jenkinson *et al*., 1994) is a five compartment model. Added plant material is initially divided between two input compartments: decomposable plant material (DPM) and resistant plant material (RPM). Both DPM and RPM are retained in the soil and gradually decompose by first-order processes, which have characteristic (and different) rates, to CO_2 (lost from the system), and to microbial biomass (BIO) and humified organic matter (HUM), which are also retained in the soil. Both microbial biomass and humified organic matter decompose at their characteristic rates by first-order processes to give more CO_2, biomass, and humified matter. The soil is also assumed to contain a small organic compartment (IOM) that is inert to biological attack. Decomposition processes in the model work in monthly intervals and allow for the effects of temperature (mean monthly air temperature), soil moisture content (calculated from rainfall and evaporation), plant cover (decomposition being faster in bare soil than under vegetation; Jenkinson, 1977), and soil clay content (from which is calculated the moisture held in a soil layer between field capacity and wilting point and the proportion of CO_2 that is evolved).

Data on both sequestering C and its release from soil are calculated in t organic C ha^{-1}, and this can be done for the top 23 cm of soil in the long-term experiments at Rothamsted. Lawes and Gilbert originally sampled the top 23 cm of soil although initially perhaps only the top 12.5 cm was ploughed; perhaps they thought roots took up nutrients from this deeper layer of soil. Sampling to this depth has continued so it is now possible to make direct comparisons for total element content of the soil from any plot throughout the period of the experiment. However, there is a complicating factor. Where SOM is increasing, soil bulk density is decreasing and, conversely, where SOM is deceasing bulk density is increasing. The first situation arises where large amounts of FYM have been added each year, and the second where permanent grass has been ploughed. Where SOM has increased, then at each sampling occasion the top 23 cm of soil did not include some of the mineral soil that was part of the top 23 cm soil at the start of the experiment. So, to estimate the total C content in the same weight of mineral soil on each sampling occasion, it is necessary to add an amount of C in the appropriate weight of ''unsampled original 23 cm soil.'' It is possible to do this for these experiments because soil weights and %C and %N in the 0–23 and 23–46 cm depths were determined on a number of occasions. This ''correction'' only applies to the FYM-treated plots and those sown to and kept in grass for many years or old arable sites which have been abandoned and have since reverted to woodland and it has been made to the data given here. Soil weights on fertilizer-treated plots have changed very little, but often %C has also changed very little also.

A similar allowance for change in bulk density has been made where permanent grass was ploughed for continuous arable cropping. Here, the increasing bulk density as a result of loss of SOM has been used because SOM in the soil layer below 23 cm at the start of the experiment has been incorporated into the 23 cm plough layer over time and the organic matter it contained has been subject to microbial decomposition. Thus, it is necessary to add, for the earlier samplings, an amount of C in the appropriate weight of ''unsampled original 23 cm soil.''

The fit of the model to the observed changes in SOM for three treatments in the Hoosfield Barley experiment is good (Fig. 15), with the exception of the first few years where SOM was declining after the addition of FYM for 20 years. Jenkinson *et al.* (1987, 1994) give other examples. It should be emphasized that Fig. 15 is a true test of the model because no data from the Hoosfield experiment were used to set the model parameters and no adjustments were made to improve the fit.

Figure 16 shows the fit of the model to changes in SOM in two contrasted situations, namely increasing and decreasing SOM, on closely similar soils less than 500 m apart. In 1847, Lawes and Gilbert started a field experiment in Geescroft in which field beans (*V. faba*) were grown year after year with three fertilizer treatments. Over time, yields declined and in many years the crop failed; the experiment was stopped in 1878. After 4 years bare fallow followed by 3 years when clover was grown, part of the experimental site was fenced off and allowed to revert to natural vegetation. The sequence of vegetation has been herbaceous plants followed by shrubs and now semimature oaks with an understorey of holly (Harmer *et al.*, 2001; Poulton *et al.*, 2003). The first soil sample, 0–23 cm, taken in 1883 had 1.07%C and $\mathrm{pH_{water}}$ 7.1; with natural acidifying inputs the pH had fallen to 4.4 in 1999. Estimated changes in C inputs throughout the period from 1883 have been used to model the accumulation of soil C and the fit of the model to the measured data is good (Fig. 16).

In 1949, an area of permanent grass near to Geescroft and adjacent to the Highfield Ley–arable experiment was ploughed, has not grown a crop since,

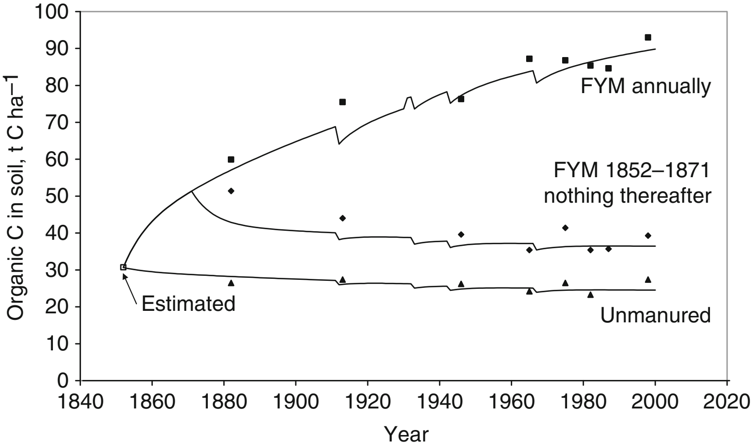

Figure 15 Organic carbon (t ha^{-1}) in the top 23 cm from three plots growing spring barley on the Hoosfield Barley experiment, Rothamsted. Treatments are unmanured, ▲; FYM, 35 t ha^{-1} annually, ▪; FYM 35 t ha^{-1} annually 1852–1871, none since, ◆. The data points are adjusted for changes in soil bulk density (see text) and the solid lines are the model output. The FYM, ploughed-in in February 1852–1930 and in late autumn after 1932, was assumed to contain no biomass but DPM, RPM, and HUM in the proportions 0.49, 0.49, and 0.02, respectively. The incoming plant residues were assumed to have DPM and RPM in the proportion 0.59 and 0.41, respectively. The IOM for these treatments contained 2.7 t C ha^{-1}. See text for explanation of DPM, etc. To obtain a (modeled) value for the amount of carbon in the soil at the start of the experiment, a plant debris input of 1.69 t C ha^{-1} was used. Thereafter, the annual C inputs (t ha^{-1}) were unmanured plot, 1.28 (from plant debris); FYM plot, 2.8 (from plant debris) plus 3.0 (from FYM); FYM residues plot as FYM plot 1852–1871 then 2.0 (from plant debris) after 1872.

and has been kept weed free by soil cultivation—Highfield Bare Fallow. In this case without having to estimate any C inputs the model describes the decline in soil carbon very well (Fig. 16). The results from these two experiments contrast sharply. Under a bare fallow system, more SOM has been lost in 50 years from the top 23 cm soil than has been built up in the same depth of soil under regenerating natural woodland in 120 years. Under regenerating woodland there has been some accumulation of soil C below 23 cm and in 1999, the total C in the top 69 cm soil was 105 t ha^{-1}. This amount of C in the top 69 cm soil is only about half of that (~200 t ha^{-1} C) which has accumulated in the trees during the 120 years (Poulton *et al.*, 2003). This is a significant amount if one is looking to sequester C and mitigate against the effects of global warming, but the aboveground biomass will not accumulate C indefinitely and at some time a new equilibrium value for C in the soil will be reached and further accumulation of C will cease.

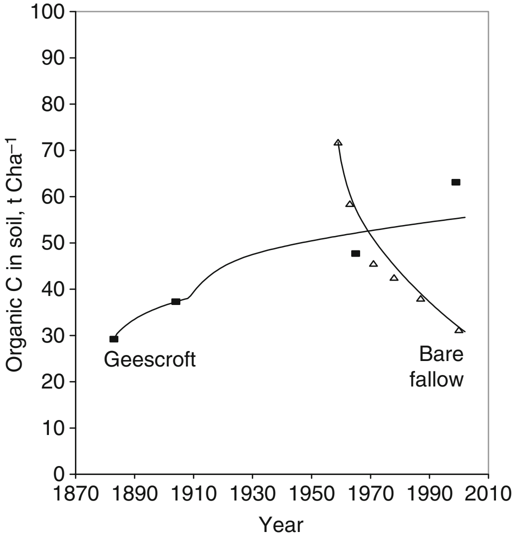

Figure 16 Organic carbon (t ha^{-1}) in the top 23 cm on Geescroft Wilderness and Highfield Bare Fallow, Rothamsted. The data points are adjusted for changes in soil bulk density (see text) and the solid lines are the model output. The incoming plant residues were assumed to have DPM and RPM in the proportion 0.59 and 0.41, respectively. The IOM for these sites contained 2.5 and 3.0 t C ha^{-1} on Geescroft and Highfield, respectively. See text for explanation of DPM, etc. To obtain a (modeled) value for the amount of carbon in the soil at the start of the experiment, a plant debris input of 1.48 and 3.0 t C ha^{-1} for Geescroft and Highfield, respectively, was used. Thereafter, the annual C inputs (t ha^{-1}) were Geescroft, ▪, 2.5 (from plant debris); Bare Fallow, △, zero.

The fit of the model to the observed changes in SOM for two contrasted treatments in the Rothamsted Ley–arable experiments on Highfield and Fosters (see also Fig. 6) is shown in Fig. 17. Figure 17A shows, for the experiment on Highfield, the changes in SOM on the permanent grass plots and the continuous arable plots after ploughing out the grass. For the first 12 years, the grass was grazed by sheep before the treatment changed to a grass/clover sward harvested three or four times per year for conservation. Different annual C inputs were estimated for the two periods and the fit of the model to the observed amounts of soil C is good. The fit is not so good where the grassland soil was ploughed to grow a rotation of arable crops. An average annual C input of 1.4 t C ha^{-1} has been assumed and the model predicts a slower rate of decline in SOM than that observed. The fit of the model to the data is good if the input was 0.6 t C ha^{-1}, but this is probably too small.

The fit of the model to the observed data for the Fosters experiment (Fig. 17B) is good, the change from grazing to harvesting herbage for

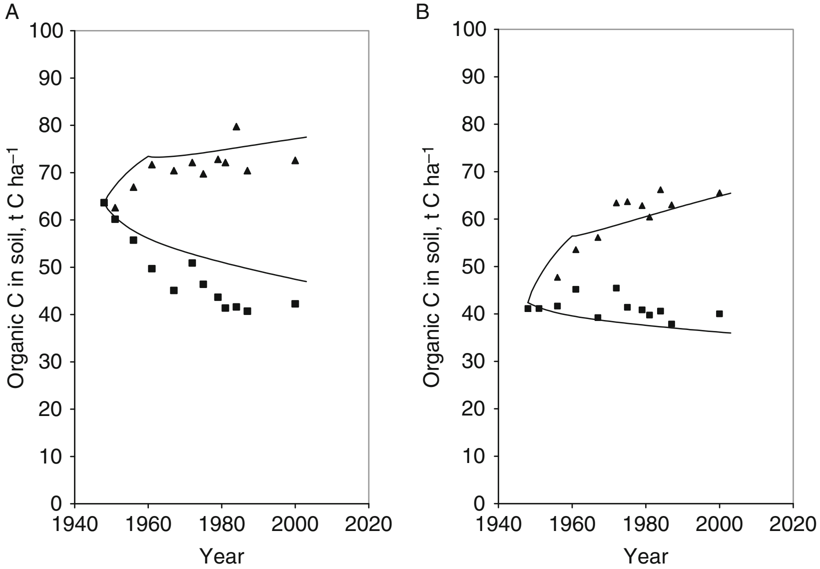

Figure 17 Organic carbon (t ha^{-1}) in the top 23 cm on Highfield and Fosters Ley–arable, Rothamsted. The data points are adjusted (for each site) for changes in soil bulk density (see text) and the solid lines are the model output. The incoming plant residues were assumed to have DPM and RPM in the proportion 0.59 and 0.41, respectively. The IOM for these experiments was 3.0 t C ha^{-1}. See text for explanation of DPM, etc. To obtain a (modeled) value for the amount of carbon in the soil at the start of the experiments, a plant debris input of 2.7 and 2.1 t C ha^{-1} for Highfield and Fosters, respectively, was used. Thereafter, the annual C inputs (t ha^{-1}) from plant debris were (A) Highfield grass, ▲, 5.0 for 12 years then 4.0; Highfield arable, ▪, 1.4; and (B) Fosters grass, ▲, 5.0 for 12 years then 4.0; Fosters arable, ▪, 1.4.

conservation being well modeled. On the plots that remained in continuous arable the fit of the model to the observed data was good. The same annual input of C was used for plots growing arable crops on both Highfield and Fosters because the yields were very similar on both experiments. Further work is needed to see whether altering the parameters for the rate of decline of SOM will give a better fit to the observed decline in SOM on Highfield. It should be noted that all the model parameters in Figs. 16 and 17 were exactly the same as those used in the initial model developed by Jenkinson, which gave the fit to the data shown in Fig. 15; the only driving variable was the annual input of organic carbon. Many of the aberrant observed points in all four relationships are probably, in part, due to soil sampling issues.

This approach to modeling, which can be perceived as "bottom-up," that is, a single site studied in great detail, has the benefit that the parameters in the model can be determined on the basis of well-estimated data and then, as other data sets become available, the parameters can be adjusted so that the model adequately describes changes in a wider range of soils, farming systems and climates. Climate change will influence the stock of SOM in two ways: by altering plant production, thus altering the annual return of plant debris to the soil, and by changing the rate at which this input decays in or on the soil. Global warming will increase decomposition rates and if inputs remain unchanged the world stock of SOM will decline releasing CO_2 to the atmosphere. A similar positive feedback will be caused by an increase in rainfall (except for wetlands) in those situations where decomposition is currently restricted by drought. In reality, however, inputs of organic matter may increase, sequestering CO_2 in SOM. Models describing change based on past well-known events can be good as shown here, predicting change when there is doubt about the magnitude of change in any one compartment of a model and its possible interaction with other compartments is much more difficult.

The model described earlier, as with most other models for SOM turnover, was designed for use in topsoils. However, if half of the world's organic C held in the top meter of soil (estimated at 1600 Gt by Prentice, 2001) is in the 25–100 cm layer (Jobbágy and Jackson, 2000) then any effect of global warming on this subsoil C could be important. Thus, realistic models dealing with the turnover of subsoil C need to be developed. This has been done for sites from four contrasted systems of land management at Rothamsted, namely continuous arable, permanent grassland, and regenerating woodland on both calcareous and acidic soils. Crucially these soils had been sampled in the 1870s by 9 in. (23 cm) depths to 36 in. and were sampled again by these depths recently; in presenting the C data here the metric equivalent for sampling depth is used. All these samples were analyzed for organic C and ^{14}C to develop a C turnover model for the top 91 cm soil. This model, Roth PC-1, is based on the earlier model, ROTHC-26.3, originally developed to model C turnover in topsoil and used to provide the data presented above. Two extra parameters have been added to the original model; one allows for movement of C down the profile by advection, the other slows decomposition of that C with depth.

Jenkinson and Coleman (2008) describe in detail Roth PC-1 while the data used to develop and test it are given by Jenkinson *et al.* (2008). Jenkinson and Coleman (2008) also compared the new multilayer model and the single layer version to see how they respond to a possible increase in global warming of 0.25 °C per decade over the next 100 years. The model runs strongly suggest that treating the top meter of soil as a single homogeneous layer overestimates the decomposition of the SOM it contains due to global warming. More realistic estimates of SOM decomposition, and hence the release of CO_2, will be obtained from multilayer models such as Roth PC-1.

7. DISADVANTAGES FROM INCREASING SOIL ORGANIC MATTER

The benefits of increasing the amount of SOM are bought at a cost and this should be realized. Data given here show how much C and N is lost during the microbial decomposition of added organic matter and, that, at the equilibrium level of SOM for any soil, climate, and farming system, all the C and N in further additions of organic matter will be lost. There are some further problems too.

The loss of nitrate from soil in autumn is an issue that has attracted much attention because of possible environmental risks, but there is also a financial cost to the farmer if N fertilizers are not used efficiently. Fertilizer- and FYM-treated soils on the Hoosfield Barley experiment were sampled to 110 cm on eight occasions between September 1986 and early May 1987 and the total mineral N content determined. Throughout the period, FYM-treated soil contained much more mineral N than did fertilizer-treated soil (Powlson *et al.*, 1989) due to the mineralization of existing SOM and there was little contribution to the mineral N pool from the FYM ploughed-in in autumn until March (Fig. 18). The large amounts of mineral N in the FYM-treated soil were at risk to loss by leaching whenever excess rainfall caused through drainage. Goulding *et al.* (2000) also showed that, on the Broadbalk

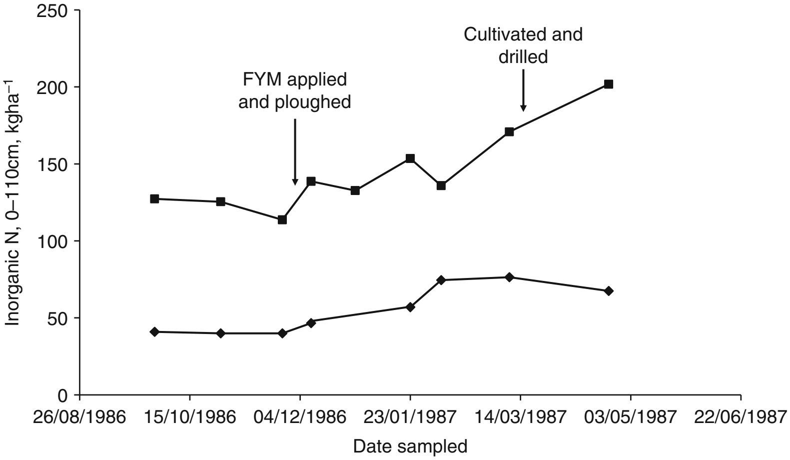

Figure 18 Inorganic N (kg ha^{-1}) in the soil to 110 cm in autumn/winter 1986/1987, Hoosfield Continuous Barley experiment, Rothamsted. Annual treatment since 1852: NPK fertilizers, ◆; FYM 35 t ha^{-1}, ▪. Both soils had received 96 kg N ha^{-1} in spring 1986. (Adapted from Powlson *et al.*, 1989.)

Wheat experiment, more inorganic N was at risk of loss by leaching under soils with a history of FYM addition.

Many field experiments with cereals have shown that when fertilizer N is applied to achieve the economic optimum grain yield the amount of mineral N remaining in the soil at harvest is often only a little larger than that in soil to which no fertilizer N was applied (Glendining and Powlson, 1995). To assess the relative efficiency of added fertilizer N and fertilizer N added to soil with extra SOM, some ^{15}N experiments have been done on long-term experiments at Rothamsted. In the Hoosfield experiment, labeled fertilizer N was applied to spring barley grown on both fertilizer- and FYM-treated soil. The labeled N was taken up with similar efficiency on both soils and at harvest less than 4% of the added fertilizer N was present in inorganic form in either soil (Glendining *et al.*, 1997). Thus, it appeared that fertilizer N was taken up preferentially to soil N even though there was more soil N in FYM-treated soil. A similar result was found where winter wheat was grown after ploughing in leys in the Woburn Ley–arable experiment (Fig. 19). Wheat given 140 kg ha^{-1} labeled fertilizer N gave good yields and at harvest only about 3 kg ha^{-1} of the labeled N was present as inorganic N in the top 50 cm of soil. However, while the total mineral N in this depth of soil was about 16 kg ha^{-1} following all-arable cropping, the unlabeled mineral N following ploughed-in leys was much larger, up to about 60 kg ha^{-1}. Thus, the overwhelming majority of the mineral N in soil at harvest was not the residue of the fertilizer N applied in spring but came from the mineralization of SOM (Macdonald *et al.*, 1989).

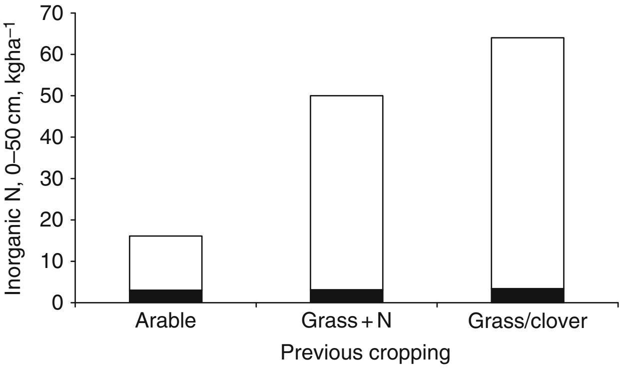

Figure 19 Inorganic N (kg ha^{-1}) in the soil to 50 cm after wheat following different rotations, Ley–arable experiment, Woburn. Total inorganic N, unfilled + filled bars; inorganic N derived from spring-applied ^{15}N-labeled fertilizer, filled bars. (Adapted from Macdonald *et al.*, 1989.)

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