Figure 8 Influence of residue quality on soil C, showing net increment in soil C over the duration of the experiment, where constant amounts of residues were added each year. Data from Sowden and Atkinson\(^{38}\) for a 20-year experiment with addition of \(~500\) g C m\(^{-2}\) yr\(^{-1}\) to a sandy soil in Canada and from Paustian et al.\(^{38}\) for a 31-year experiment with \(~250\) g C m\(^{-2}\) yr\(^{-1}\) added to a sandy clay loam in Sweden. (From Paustian, K., Robertson, G.P., and Elliott, E.T., *Soil Management and Greenhouse Effect*, Lal, R., Kimble, J., Levine, E., and Stewart, B.A., Eds., *Advances in Soil Science*, Lewis Publishers, Boca Raton, FL, 1995. With permission.)
decomposition.\textsuperscript{53,64} Numerous field studies show increases in macroaggregate stability with reduced tillage, with no-till generally showing the highest degree of aggregate stability compared with conventional tillage employing moldboard plowing.\textsuperscript{118–122} While differences between various forms of intermediate tillage are less clear, aggregate stability tends to decrease with increasing tillage intensity.\textsuperscript{123}

Tillage practices which promote the greatest degree of soil disturbance also tend to be the most effective at burying crop residues. Estimates of residue burial rates for a variety of primary and secondary tillage implements are given in Table 3. The degree of residue incorporation has a major effect on the initial rate of decomposition. In temperate environments, decomposition rates of residues are generally slower when left on the surface than when buried in soil.\textsuperscript{124–127} Drier conditions and reduced mineral nutrient availability are probably the main reasons for reduced microbial activity in surface residues. Under some conditions, temperature extremes in surface residues may also be detrimental to microbial activity. For example, temperatures as high as 60°C have been recorded in unshaded residues under wind-still conditions in Australia\textsuperscript{128} and the western U.S.\textsuperscript{129}

Table 3  Percent of Crop Residue Remaining on Soil Surface Following Tillage Operations

<table>
<thead>
<tr>
<th>Tillage Implement</th>
<th>Good and Smika</th>
<th>Tindall and Crabtree</th>
<th>Stott</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moldboard plow</td>
<td>NI</td>
<td>0–5</td>
<td>2–4</td>
</tr>
<tr>
<td>Tandem disk</td>
<td>25</td>
<td>50</td>
<td>30–60</td>
</tr>
<tr>
<td>One-way disk</td>
<td>50</td>
<td>50–60</td>
<td>NI</td>
</tr>
<tr>
<td>Chisel plow</td>
<td>90</td>
<td>75</td>
<td>50–75\textsuperscript{a}</td>
</tr>
<tr>
<td>Sweep plow</td>
<td>90</td>
<td>85</td>
<td>85–90</td>
</tr>
<tr>
<td>Rod weeder</td>
<td>85</td>
<td>85–95</td>
<td>80–85</td>
</tr>
<tr>
<td>No-till drill</td>
<td>NI</td>
<td>NI</td>
<td>90–95\textsuperscript{b}</td>
</tr>
</tbody>
</table>

\textit{Note:} Values by Good and Smika\textsuperscript{130} and Tindall and Crabtree\textsuperscript{131} are for wheat residues. Ranges reported by Stott\textsuperscript{132} are from calculations using a general model for residue management which is parameterized for 21 major crop species. NI denotes not included in the cited reports.

\textsuperscript{a} Chisel with straight shank.

\textsuperscript{b} No-till drill with smooth coulters.

The combination of reduced litter decomposition rates and less soil disturbance usually results in greater amounts of soil C in no-till vs. conventionally tilled systems. Differences in C content between no-till and conventional till are most extreme near the surface, primarily due to differences in the distribution of C inputs.\textsuperscript{133} Consequently, comparisons of tillage effects based on sampling only the top few centimeters of soil can give a misleading and overly positive impression of the C buildup under no-till. However, comparisons based on deeper sampling where C levels are summed to below depth of plowing usually show higher overall levels in no-till (Figure 9). These data are from a number of long-term field studies, with paired conventional and no-till treatments. Carbon content and bulk density data were used to calculate C on a square-meter basis to below depth of plowing (generally 30 cm) and expressed on an equivalent soil mass basis to correct for differences in bulk density due to tillage.\textsuperscript{124} A number of other studies,\textsuperscript{135–141} most of which report increased C concentrations under no-till, were not included because of a shallower sampling depth or a lack of information on bulk density.

The average increase in soil C under NT was about 300 g m\textsuperscript{-2} with a few site/treatments showing increases as high as 1 kg C m\textsuperscript{2} (Figure 9a). On a relative basis, most sites showed 5 to 20% increases in soil C under NT vs. CT (Figure 9b). The range in absolute differences in C varied little as a function of total soil C (as measured under CT) and thus the relative difference tended to decrease with increasing soil C. It should be noted that the surface mulch which builds up on many NT soils may not be fully accounted for in comparisons of plowed and NT systems, if sampling has been restricted to the mineral soil. In such cases the effect of NT on total C storage would be underestimated.

There is no apparent pattern related to soil texture, with the exception of two instances showing substantially lower C under NT (e.g., Figure 9a). Both of these comparisons are for poorly drained clay soils with cropping systems producing lower residue yields (i.e., continuous soybeans\textsuperscript{148} and corn-soybean\textsuperscript{149}). The negative results may be associated with reduced yields and residue inputs with NT on
the wet clay soils and perhaps less moisture limitation on the decomposition of surface residues compared with better-drained soils. Overall, fine-textured soils tended to have the highest organic matter contents and hence show smaller relative differences between NT and CT.

There was no clear trend in tillage-induced changes as a function of time under no-till (Figure 9cd). There appears to be an early rapid gain in C following conversion to NT followed by a stabilization or much slower rate of C increase. However, site-specific and other management differences likely confound the interpretation so that generalizations regarding temporal dynamics cannot be made on the basis of cross-site comparisons. Unfortunately, relatively few studies of NT have been in existence for sufficient time to generate reliable time-series from repeated measurements. Plots at Lexington, Kentucky, and at Hoytville and Wooster, Ohio (see Chapter 12) have been sampled repeatedly over a 20- to 30-year period. At Lexington, there was an increase in C with time under NT, such that, after 20 years, C contents exceed that of the original bluegrass sod. However, there was a similar although lower increase under CT, reflecting the influence of the high residue inputs under both tillage treatments. In 25-year-old tillage experiments, Dick et al. reported that the most rapid changes in C levels under NT occurred during the first 10 years. Repeated sampling of NT plots in Saskatchewan over a 13-year period showed an increase of 15% in soil C (for 0- to 15-cm depth) after 6 years, whereas C increased by only an additional 4% during the subsequent 7 years (Campbell, C.A., unpublished data). In a study of a NT chronosequence at Coshocton, Ohio, Staley et al. found that total C was positively correlated to years under NT and that microbial biomass-C responded quickly to NT management and reached a new equilibrium value after about 10 years.
One reason that soil C responses to tillage are difficult to generalize is that tillage practices can have indirect effects by influencing crop productivity and thereby crop residue inputs. Lower soil temperatures under NT may delay germination and early plant development in regions with short growing seasons. Lower yields with NT under such conditions has been cited as limiting its applicability in cool regions. However, major yield reductions in cool climates are not universal. Riley et al., in summarizing field experiments for Denmark, Norway, and Sweden, found that NT yields averaged between 91 and 99% of yields obtained with plow tillage. Interestingly, Knight and Lewis reported higher spring soil temperatures and comparable yields in NT vs. CT in central Alaska; this was attributed to the insulating effect of greater snow retention due to more residue coverage under NT.

No-till often gives lower yields in poorly drained soils, which are subject to compaction in the absence of tillage, causing restricted root growth and greater susceptibility to disease than under CT. The retention of surface residues and lack of soil disturbance associated with NT have been found to increase the severity of a variety of wheat diseases, resulting in reduced yields. However, crop rotation and use of disease-resistant cultivars can reduce disease-induced yield declines in NT. In Indiana, yields under NT were lower for poorly drained soils with high organic matter contents, but yields were greater with NT on low organic matter soils with either poor or good drainage. Reduced tillage systems (chisel plow, ridge tillage) showed yield responses intermediate to plow tillage and NT.

Many other studies have shown no or variable differences in crop yield response to tillage and higher production under no-till has been shown for well-drained soils, particularly where water use efficiency is improved. Prasad and Power summarized the expected differences in yield between no-till and conventional till as follows: (1) little difference under conditions of adequate soil water, good drainage, and adequate available N; (2) increased yields under no-till where there is limited precipitation and soil water and adequate weed control and fertilization; and (3) reduced yields under no-till in areas with excessive precipitation, low temperatures, poor drainage, poor weed control, or low fertility levels.

Effects of tillage on soil physical parameters such as bulk density, porosity, pore size distribution, and pore continuity provide additional indirect controls on decomposition and soil C levels. Increased bulk density and reduced porosity in upper soil layers can occur under NT accompanied by a reduction in the number of large pores. For the root zone as a whole, however, the effect of surface compaction under no-till may be compensated for by lower bulk densities and increased porosity deeper in the profile. Plow pans, which can impede water movement and root penetration, may not form so readily with reduced tillage. In other cases, NT or other reduced tillage practices have had no effect on or have decreased bulk density. In most cases, irrespective of changes in overall porosity, no-till soils have equal or increased water infiltration rates probably due to greater continuity of macropores, such as earthworm burrows and root channels. The net effect of tillage-induced differences on soil water will vary for individual soils. However, the greater water capture and lower evapotranspiration of reduced tillage systems will generally increase soil moisture which may favor higher decomposition rates of root residues within the soil, in contrast to the lower decomposition rates of residues on the soil surface, as discussed earlier.

To summarize, it seems clear that reduced tillage, and especially no-till, is generally effective in increasing soil C, provided that yields and residue production are not adversely affected. Whether increases in soil C continue over long periods of time and how closely no-till soils can be made to mimic the characteristics and C levels of soils under native perennial vegetation remains to be seen. Because of the greater below-ground allocation in native perennial systems and the removal of a substantial portion of the net primary productivity in agricultural systems, it is unlikely that use of no-till practices alone can achieve the soil C levels of native ecosystems. However, if C inputs to soil can be increased to a similar magnitude as in native systems, by increasing nutrient and water supply and using highly productive crop species, then a restoration of soil C to precultivation levels (or higher) may be possible under no-till management.

**D. CROP ROTATION**

The selection of crops to be grown is the most basic management decision faced by the farmer and, as discussed in the earlier section on land resource areas, this decision is constrained by both climatic and economic factors as well as land suitability. It is recognized that the selection of crops grown may be closely linked to other management factors such as tillage (e.g., annual vs. perennial crops) and fertility (e.g., legumes vs. non-N-fixing crops). However, in this instance we focus mainly on how crop type, residue yield, and fallow frequency influence C inputs and the decomposition environment.
Overall comparisons of soil C contents under rotational systems vs. continuous corn, or continuous wheat, reveal some general patterns (Figure 10). Where corn is the dominant annual crop, only rotations which contain grass or forage crops show consistently higher C levels compared to continuous corn. For the most part, corn-soybean rotations show lower values, with the notable exception being the Morrow plot corn/soybean (earlier corn/oats) rotation (far right, Figure 10). The Morrow plot results, however, are atypical, as discussed below. In the wheat-dominated systems, there are few examples of rotations which yield higher C levels than continuous wheat except for a few treatments including green manures or legume crops. Rotations including 1 or 2 years of hay as well as rotations including other cereal crops show little effect on C content compared with continuous wheat. Wheat-fallow systems, however, show as much as 40% lower C compared to continuous wheat (Figure 10).

Figure 10 Summary of rotation influence on soil C levels, shown as percent of soil C under continuous corn or continuous wheat treatments in the same experiment, plotted as a function of experiment duration. Symbols depict different classes of rotations for corn- and wheat-based cropping systems. Data from Haas et al., Anderson and Peterson, Barber, Hooker et al., Odell et al., Upchurch et al., Dick et al., Soon and Broersma, Insam et al., Rasmussen et al., Campbell et al., and Monreal and Janzen.
1. Rotations with Annual Crops

The effect of rotations of annual crops on SOM may be attributable mainly to the amount of residues produced and returned to the soil. Representative yields of major field crops and estimates of associated above-ground crop residues for different regions in the United States are summarized in Table 4. Typically, highest residue levels for row crops are produced by C₄ feed grains such as corn and sorghum. Soybeans, mostly grown in rotation with corn, produce less than half as much residue. Residue production from most small-grain cereals is intermediate. It is more difficult to generalize about below-ground residue production, due to the limited number of measurements and differences in methodologies to determine below-ground productivity. However, for most annual crops, C inputs from root production usually account for 20 to 40% of total dry matter production.²⁷⁻²⁹

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield (bushels/ha)</th>
<th>Yield (kg/ha)</th>
<th>Harvest Index (%)</th>
<th>Crop Residue (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean</td>
<td>34</td>
<td>2000</td>
<td>50–60</td>
<td>1300–2000</td>
</tr>
<tr>
<td>Oats</td>
<td>51</td>
<td>1800</td>
<td>40–50</td>
<td>1800–2700</td>
</tr>
<tr>
<td>Wheat</td>
<td>34</td>
<td>2300</td>
<td>35–45</td>
<td>2800–4300</td>
</tr>
<tr>
<td>Barley</td>
<td>55</td>
<td>3000</td>
<td>45–50</td>
<td>3000–3700</td>
</tr>
<tr>
<td>Sorghum</td>
<td>59</td>
<td>3300</td>
<td>35</td>
<td>6100</td>
</tr>
<tr>
<td>Corn</td>
<td>108</td>
<td>6800</td>
<td>40–50</td>
<td>6800–10200</td>
</tr>
<tr>
<td>Sorghum (silage)</td>
<td>na</td>
<td>9070</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Corn (silage)</td>
<td>na</td>
<td>11,790</td>
<td>na</td>
<td>na</td>
</tr>
</tbody>
</table>

Note: Estimates of harvest index values of most crops based on Anderson and Vasilius,²¹ Brinkman and Rho,²² Cox et al.,²³ Donald and Hamblin,²⁴ Meyers et al.,²⁵ Russell,²⁶ and Walker and Fiorito.²⁷ Harvest index for sorghum based on silage yields as an estimate of total above-ground dry matter production.

Other species characteristics, such as residue quality, are also important factors affecting rotation responses. Cereals such as wheat and barley appear to have somewhat higher lignin contents (e.g., 16 to 24%) compared to corn (11 to 16%)²⁸,²⁹ which can retard decomposition rates and increase C stabilization efficiency as discussed previously.

The influence of crop rotation on residue production and soil C changes has been demonstrated in several long-term field experiments. Zielke and Christensen²⁰ found that changes in soil C for six rotations including corn, sugar beet, navy bean, oats, and alfalfa were closely correlated with the amount of residue returned. Carbon levels increased with the frequency of corn in the rotation. Similarly, Havlin et al.²⁸ reported that rotation effects on soil C were directly related to the amount of residues produced, where continuous sorghum > sorghum-soybean > continuous soybean at two sites and continuous corn > corn-soybean > continuous soybean at another site. Campbell and Zenner²¹ found that changes in SOM reflected the residue production of each rotation and its susceptibility to erosion. Organic matter in several rotations increased during a 15-year period of high crop yields and then decreased with lower production during a subsequent dry period.

At first glance, results from the Morrow plots (Figure 10, far right for “corn”) appear to contradict this pattern with the corn-oat (later corn-soybean) rotation having higher values than continuous corn, despite the lower residue yields expected from oats and soybean. However, as Guernsey et al.²² report, corn yields in the corn-oat rotation were nearly twice as high as in continuous corn through the first 80 years of the experiment. Moreover, the corn-oat rotation included a legume catch crop following oats, which provided additional organic matter and probably accounted for some of the higher productivity in the following corn crop. Based on yield information it appears likely that past residue inputs in the corn-oat rotation exceeded that in continuous corn. At two sites in Minnesota, Crookston et al.²³ reported an average of 10% higher corn yields in rotation with soybean as compared to continuous corn. Thus, if corn production is increased by rotation this can help offset lower residue inputs from other crops in the rotation.

In semiarid agricultural systems, where summer fallowing is routinely practiced, decreases in SOM with increasing fallow frequency have been well documented.⁴⁵,¹¹⁰,¹⁹¹,¹⁹⁴–¹⁹⁷ Data from three Canadian sites show a roughly linear decrease in soil C with increasing proportion of fallow in the rotation.
Summer fallowing is conducive to increased rates of organic matter decomposition for several reasons, including increased soil moisture, increased soil temperatures, increased soil disturbance associated with mechanical weed control during the fallow period, and greater susceptibility to erosion.

![Graph showing the relationship between fallow frequency and % Relative to continuous wheat for Lethbridge, Swift Current, and Indian Head.]

**Figure 11** Soil C response to fallow frequency, as a percentage of C content under continuous cropping, for three long-term experiments with fallow-wheat, fallow-wheat-wheat, and continuous wheat rotations in Saskatchewan. Data from Campbell et al. and Janzen. Rotations at Indian Head and Swift Current were N+P fertilized and those at Lethbridge were unfertilized.

Summer fallowing also affects total C inputs over the course of the rotation. In unfertilized systems, wheat yields following fallow may be nearly double those with continuous wheat and if residues are assumed to be proportional to yields then average C inputs might not be greatly different. However, moisture stress often results in a higher proportion of C allocation to crop roots so that the ratio between total residue production (including roots) and yield could be greater in continuous wheat compared to wheat-fallow systems. The impact of fallow frequency on average residue return rates can also vary with N availability. Where N fertilizer was applied, Horner et al. found that annual wheat yields with continuous cropping were about 70% of those in wheat-fallow, which would give greater residue inputs with continuous cropping over the course of the rotation.

### 2. Rotations with Perennial Crops

Inclusion of perennial crops into the rotation has long been recognized as an effective means of increasing SOM. Interestingly, Johnston attributes the relatively high organic matter content of many English arable soils, which have been under cultivation for several hundred years, to periodic reversions to pasture during times of economic depression. As discussed in the first part of this paper, the development of ley cropping played an important role in the increased productivity and soil fertility of late pre-industrial agriculture.

The efficiency of rotations that include hay crops (i.e., leys) in maintaining or increasing soil C tends to be greater in more humid regions. Clement and Williams reported an average increase of 15% in total soil C after 4 years of pasture whereas C decreased in annually cropped treatments. Grazed pastures had greater increases than where hay was mowed and removed. Long-term rotations at Woburn (U.K.) had approximately 25% greater C levels in 5-year rotations with 3 years of ley compared with 5 years of only annual crops. In experiments on both old grassland soil and old arable soil at Rothamsted, 6-year rotations with 3 years of fertilized grass or grass-clover ley increased soil C by 10 to 15% compared with rotations with annual crops only. In contrast, where alfalfa was used as the hay crop, C levels were no higher than in the annual crop rotation. Increases in total C levels under ley cropping have been reported in a number of other European studies. In Indiana, 7 years of continuous alfalfa or bromegrass yielded up to 25% more soil C than continuous corn. However, 4 years of pasture crops followed by 3 years of corn resulted in similar C levels as found in continuous corn. In a study comparing continuous cotton with lespeceza, a perennial forage crop, Davidson et al. found dramatic increases in soil C under lespeceza (to 30-cm depth), with C levels nearly double that in cotton in the top 10 cm.
Use of perennial crops in rotation in dry climates is constrained by moisture limitations and cereal crop harvests following perennial crops are often reduced. In summarizing results from 17 long-term sites in the Great Plains, Haas et al. concluded that biennials and perennials (e.g., sweet clover, ryegrass) grown for 1 year as green manure crops were not effective at reducing soil C declines in 2-, 3- and 4-year cereal-based rotations. However, other studies under semiarid conditions in the U.S. have shown less decline in soil C using hay crops in rotation with cereals compared to cereal-only rotations. In several studies for the subhumid regions of the Canadian prairies, summarized by Campbell et al., rotations with forage crops gave roughly similar C levels to those in continuous wheat. In Australia, use of forage crops in wheat rotations has become an important management practice for dryland agriculture. As an example, Drover reported that fallow-wheat-lupin-lupin rotations increased C levels by 12% compared to continuous wheat, in a sandy loam brown soil, and 33% in a lateritic sand. On these nutrient-poor soils, productivity and residue production of the wheat crop was greatly enhanced by the increased N supplied by the legume. Grace et al. cite several other examples of soil C enhancement of dryland wheat systems in Australia by the incorporation of 1- or 2-year legume pastures into the rotation.

Changes in the distribution and amount of C inputs and the absence of tillage are key components of the ability of perennial crops to sequester C. Rapid increases in total C following initiation of ley cropping are largely due to increases in particulate organic matter (POM), comprised of partially decomposed root and leaf material. Garwood et al. reported that POM (>0.25 mm) was twice as high under grass-legume leys as in arable soils and that about half of the increase in total carbon during a 4-year ley cycle was in this fraction. Comparing soils under pasture (2.7% C) and wheat-fallow (1% C), Oades and Turchenek reported that the pasture soil was enriched mainly in the POM fraction and in silt-sized fractions which were thought to represent microbial debris. Tyson et al. found that POM in a 30-year-old ley was four times that in the annually cropped treatment and POM comprised 15 to 20% of the total C in the pasture. Similarly, budgets of continuous barley, grass, and alfalfa leys reported by Paustian et al. showed a total C increase of ~1.5% in the two leys the 2nd year after ley establishment, due to increases in POM and litter and standing root biomass.

Table 5 Influence of Previous Cropping History on Aggregate Stability, Expressed as Mean Weight Diameter (MWD, i.e., aggregate stability increases with increasing MWD) and Organic Carbon in a Lismore Silt Loam in New Zealand

<table>
<thead>
<tr>
<th>Cropping History</th>
<th>Aggregate Stability (MWD)</th>
<th>Organic C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 year arable</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>4 year arable</td>
<td>1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>1 year arable</td>
<td>1.3</td>
<td>2.4</td>
</tr>
<tr>
<td>1 year pasture</td>
<td>2.0</td>
<td>2.4</td>
</tr>
<tr>
<td>4 year pasture</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>10 year pasture</td>
<td>2.7</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Note: Cropping histories for arable systems indicate years under annual cropping after coming out of pasture and conversely, for pastures, years in pasture after coming out of annual cropping.


Thus, the maintenance of higher soil C under perennial crops will be associated with a relative increase in POM and an increase in the physical protection of SOM. Aggregate stability increases rapidly after perennials are established (Table 5), both due to a lack of tillage disturbance and the characteristics of the below-ground system of most perennial grasses. These characteristics include a dense, fibrous root system, which helps to form and bind soil aggregates, and the large production of fungal hyphae and microbially derived polysaccharides and gums, which are effective in binding mineral and organic matter particles. Over extended time periods, POM under perennial crops can be maintained at higher levels and gradually more resistant humic substances are formed. However, the potential for long-term C
stabilization may not be realized until after several cycles of aggregate dissolution and reformation have led to the encapsulation and protection of organic matter within stable soil aggregates. Thus, while rapid losses of physically stabilized C can occur with cultivation of native grassland or old pastures, restocking this stable C pool through conversion to grassland or pastures may occur more slowly. Accordingly, increases in soil C under rotations of alternating annual and perennial crops are likely to be transient unless inclusion of the ley substantially increases C inputs over the course of the rotation, as appears to be the case in many of the European experiments.

E. FERTILIZATION

Many of the oldest field experiments in Europe (e.g., Rothamsted, Askov, Halle/Saale, Limberhof, Grossenzerdorf) were set up specifically to study crop production responses to the then newly developed mineral fertilizers. Treatments were designed to compare a variety of fertilizer additions with traditional fertility management using animal or green manure additions and controls with no added nutrients. A secondary objective was to monitor changes in soil conditions, including organic matter, as affected by mineral fertilizers. Numerous long-term studies involving fertilizers have subsequently been established; thus there is a wealth of field-based information available. Comparisons of N additions are most common, although many studies have included varying P and K additions in their designs. In this discussion we will focus on the effects of N fertilizer additions on soil C.

Nitrogen availability can influence soil C levels in a variety of ways. It is clear that by increasing crop production, and thereby residue inputs, N fertilization can contribute to increased SOM contents. By increasing plant growth, fertilization can also lead to increased transpiration, drier soils, and decreased decomposition rates. Results from many long-term studies show a general tendency of increases in soil C with substantive additions of N, compared to zero or low N additions (Table 6). The response across levels of N is less clear, although several sites show a roughly monotonic increase in C levels as N inputs increase. An exception is the site at Melfort, Saskatchewan, which shows no response to N addition in this very high organic matter soil (approximately 6% C). As discussed earlier, Campbell et al. reported that soil C contents at this site were also unaffected by different levels of C input, which suggests that the soil C holding capacity is essentially saturated. Thus, a lack of response to N at least as it affects C inputs, is not surprising.

Application of ammonium-based fertilizer in the absence of liming can promote soil acidification, resulting in decreased decomposition rates, as shown for the unlimed, NH$_4$-N fertilized plots in the Parkgrass experiment at Rothamsted.

Nitrogen additions can affect decomposition rates and C stabilization efficiency in other ways that contribute to higher SOM levels. Fog reviewed 60 papers which reported zero or negative effects of N addition on decomposition rates. He offered several possible explanations for negative effects of N additions on decomposition, including the repression of lignolytic enzymes by ammonium and an increase in the amount of amino compounds which can act as precursors in the formation of recalcitrant humic compounds. At the microbial level, insufficient N can lead to lower yield efficiencies (i.e., more CO$_2$ respired per unit C assimilated). Under such conditions addition of N could increase growth efficiency resulting in a higher proportion of C inputs retained in SOM.

In an analysis of long-term plot studies with constant above-ground C, with and without N fertilization, Paustian et al. found that increased root residue inputs could not account for observed increases in soil C in the N fertilized treatments (Figure 12). They also found that soil C:N ratios were lower in the unfertilized treatments, where straw or sawdust were added, suggesting that N limitation may have reduced C stabilization efficiency. In a study by Campbell et al., soil C was found to be similar in fertilized plots where straw was removed compared with fertilized plots where straw was retained. This was despite the fact that C inputs were estimated to be greater in the treatment with straw retention. One interpretation offered by the authors was that roots, rather than straw, were the primary source of C to build stable organic matter.

In most field experiments it is difficult, if not impossible, to partition the interacting, and potentially conflicting, effects of N addition on soil C. However, when viewed in a broad (if somewhat tautological) sense, it is reasonable that, since C and N are the major constituents of SOM and their proportionality (i.e., C:N ratio) is relatively constant across a range of agricultural soils, then an adequate supply of N is required to build SOM. If inputs of these two elements are too much out of balance then the efficiency of soil C sequestration will be reduced.
<table>
<thead>
<tr>
<th>Site</th>
<th>Years</th>
<th>Treatment</th>
<th>Soil C Change (% of Control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mandan, MT</td>
<td>7</td>
<td>Sandy loam — continuous wheat</td>
<td>0  30  60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sandy loam — crested wheatgrass</td>
<td>100 109 —</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silt loam — continuous wheat</td>
<td>100 99 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silt loam — crested wheatgrass</td>
<td>100 107 —</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wheat/fallow — moldboard plow</td>
<td>11  22  50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wheat/fallow — disk</td>
<td>100 98 102</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wheat/fallow — sweep</td>
<td>100 94 108</td>
</tr>
<tr>
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<td>Wheat/fallow — sweep</td>
<td>100 103 108</td>
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<tr>
<td>Pendleton, OR</td>
<td>44</td>
<td>Fallow/wheat/wheat</td>
<td>0  29</td>
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<tr>
<td></td>
<td></td>
<td>Continuous wheat</td>
<td>100 104</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wheat/fallow</td>
<td>100 109</td>
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<tr>
<td>Swift Current, Saskatchewan</td>
<td>24</td>
<td>Fallow/wheat/wheat</td>
<td>100 106</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuous wheat</td>
<td>100 107</td>
</tr>
<tr>
<td>Indianhead, Saskatchewan</td>
<td>29</td>
<td>Fallow/wheat</td>
<td>100 108</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fallow/wheat/wheat</td>
<td>100 109</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuous wheat</td>
<td>100 106</td>
</tr>
<tr>
<td>Melfort, Saskatchewan</td>
<td>30</td>
<td>Fallow/wheat/wheat</td>
<td>100 102</td>
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<tr>
<td></td>
<td></td>
<td>Continuous wheat</td>
<td>100 106</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fallow/wheat/hay rotation</td>
<td>100 97</td>
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<tr>
<td>Queensland, Australia</td>
<td>13</td>
<td>Cereals — conventional tillage</td>
<td>0  23  69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straw burned</td>
<td>100 101 106</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straw retained</td>
<td>100 102 105</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cereals — no-till</td>
<td>100 94 98</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straw burned</td>
<td>100 112 113</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straw retained</td>
<td></td>
</tr>
<tr>
<td>Eastern Kansas</td>
<td>8</td>
<td>Continuous soybean</td>
<td>0  252</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Corn/soybean</td>
<td>100 95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuous corn</td>
<td>100 101</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuous corn</td>
<td>100 102</td>
</tr>
<tr>
<td>Purdue, IN</td>
<td>12</td>
<td>Continuous corn</td>
<td>0  67  200</td>
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<tr>
<td>Lamberton, MN</td>
<td>19</td>
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<tr>
<td>Lexington, KY</td>
<td>20</td>
<td>Continuous corn</td>
<td>0  84  168  336</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuous corn — plow tillage</td>
<td>100 115 115 126</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuous corn — no-till</td>
<td>100 105 106 120</td>
</tr>
<tr>
<td>Askov, Denmark</td>
<td>78</td>
<td>Cereal/root crop rotation — loam</td>
<td>0  35  70  105</td>
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<tr>
<td></td>
<td></td>
<td>Cereal/root crop rotation — sand</td>
<td>100 106 109 111</td>
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<td></td>
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<tr>
<td>Southern Sweden</td>
<td>15</td>
<td>Mixed cropping</td>
<td>0  50  100  150</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uppsala, Sweden</td>
<td>30</td>
<td>Cereal/root crops</td>
<td>0  80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straw removed</td>
<td>100 118</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straw added</td>
<td>100 116</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sawdust added</td>
<td>100 115</td>
</tr>
<tr>
<td>Ås, Norway</td>
<td>20</td>
<td>Cereals</td>
<td>0  34  68  136</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straw added</td>
<td>100 98 101 103</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straw removed</td>
<td>100 101 104 103</td>
</tr>
<tr>
<td>Øsaker, Norway</td>
<td>20</td>
<td>Cereals</td>
<td>0  34  68  136</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straw added</td>
<td>100 102 100 104</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straw removed</td>
<td>100 100 99 107</td>
</tr>
</tbody>
</table>
Table 6 (continued) Summary of Long-Term Field Experiments Showing Soil C Responses to Differential Levels of N Fertilizer Application (N Levels are Shown in Bold Type)

<table>
<thead>
<tr>
<th>Site</th>
<th>Years</th>
<th>Treatment</th>
<th>Soil C Change (% of Control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ås, Norway*44</td>
<td>31</td>
<td>Cereals</td>
<td>60 120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cereal + row crops</td>
<td>100 102</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 ley + 4 arable</td>
<td>100 108</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 ley + 2 arable</td>
<td>100 104</td>
</tr>
<tr>
<td>Halle/Saale, Germany*219</td>
<td>80</td>
<td>Continuous rye</td>
<td>0 40</td>
</tr>
<tr>
<td>Gottingen, Germany*220</td>
<td>81</td>
<td>Mixed rotation</td>
<td>0 30–50</td>
</tr>
<tr>
<td>Riverside, CA*221</td>
<td>28</td>
<td>Citrus grove</td>
<td>0 310</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Urea N</td>
<td>100 105</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NH₄-N</td>
<td>100 125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NO₃-N</td>
<td>100 123</td>
</tr>
<tr>
<td>Rothamsted, U.K.*222</td>
<td>120</td>
<td>Pasture (parkgrass plots)</td>
<td>0 48 96 144</td>
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<tr>
<td></td>
<td></td>
<td>Unlimed NH₄ — fertilizer</td>
<td>100 100 138 153</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unlimed NO₃ — fertilizer</td>
<td>100 108 97 —</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limed NH₄ — fertilizer</td>
<td>100 95 101 105</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limed NO₃ — fertilizer</td>
<td>100 99 100 —</td>
</tr>
</tbody>
</table>

Note: Soil C levels represent the total change over the duration of the experiment, given as percent of the unfertilized (or least fertilized) treatment.

Figure 12 Nitrogen addition effects on the net change in soil C over the duration of a 31-year experiment with constant (~250 g C m⁻² y⁻¹) of straw or sawdust addition. Above-ground crop residues were removed from the plots. N fertilized plots received rates equivalent to 80 kg N ha⁻¹ y⁻¹ as Ca(NO₃)₂.

V. CONCLUDING REMARKS

Agricultural practices and SOM dynamics are intimately linked and, as we have discussed, virtually all facets of management impact the amount of C which can be maintained in soil. However, because the amounts of C in soils are large and change comparatively slowly, the implications of a particular management system on the soil may be apparent only after several years to decades. We are fortunate that a number of far-sighted individuals initiated and subsequently maintained long-term field experiments, providing us with a unique legacy of agricultural and ecological information.

The intelligent management of soil resources, including organic matter, is of critical importance, not only for productivity and sustainability of the farmer’s field, but also for the health and sustainability of our global environment. The practical knowledge as well as theoretical insights which have been derived from long-term field experiments provide us with some essential tools to improve the sustainability and environmental quality of agroecosystems.
ACKNOWLEDGMENTS

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REFERENCES


