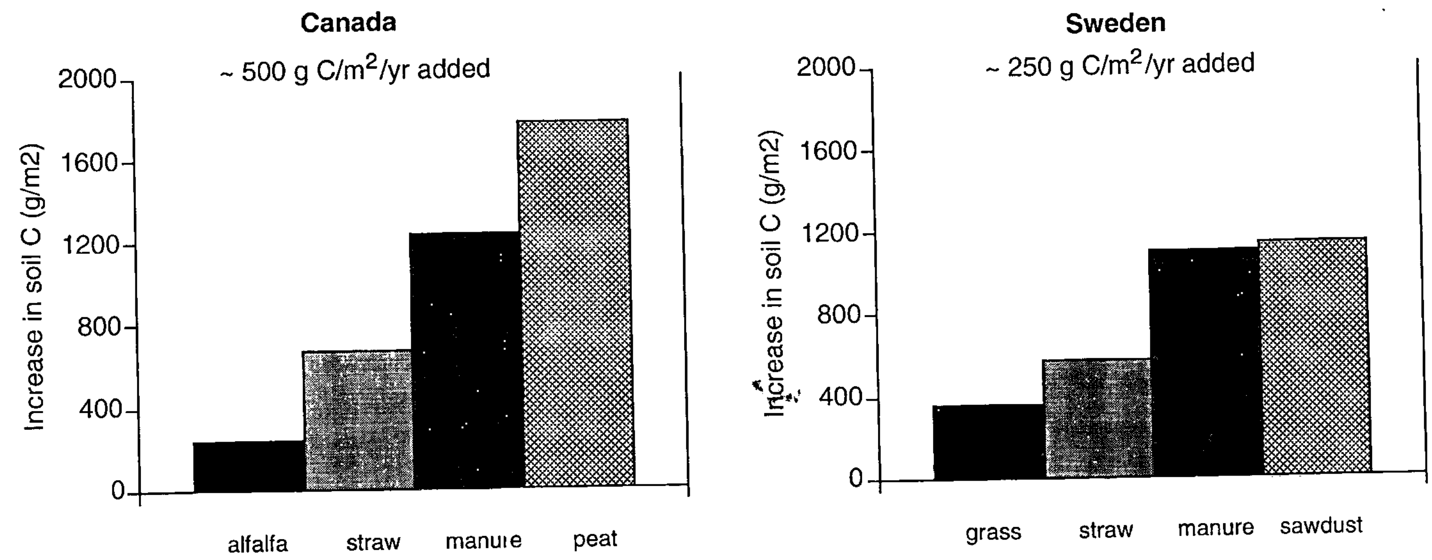

Figure 8 Influence of residue quality on soil C, showing net increment in soil C over the duration of the experiment, where constant amounts of residues were added each year. Data from Sowden and Atkinson[105] for a 20-year experiment with addition of ~500 g C m^{-2} y^{-1} to a sandy soil in Canada and from Paustian et al.[38] for a 31-year experiment with ~250 g C m^{-2} y^{-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.[63,64] 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.[118–122] While differences between various forms of intermediate tillage are less clear, aggregate stability tends to decrease with increasing tillage intensity.[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.[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[128] and the western U.S.[129]

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

Tillage Implement	Residue Remaining (%)		
	Good and Smika	Tindall and Crabtree	Stott
Moldboard plow	NI	0-5	2–4
Tandem disk	25	50	30–60
One-way disk	50	50–60	NI
Chisel plow	90	75	50–75[a]
Sweep plow	90	85	85–90
Rod weeder	85	85–95	80–85
No-till drill	NI	NI	90–95[b]

Note: Values by Good and Smika[130] and Tindall and Crabtree[131] are for wheat residues. Ranges reported by Stott[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.

[a] Chisel with straight shank.

[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.[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.[134] A number of other studies,[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^{-2} with a few site/treatments showing increases as high as 1 kg C m^{-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[148] and corn-soybean[144]). The negative results may be associated with reduced yields and residue inputs with NT on

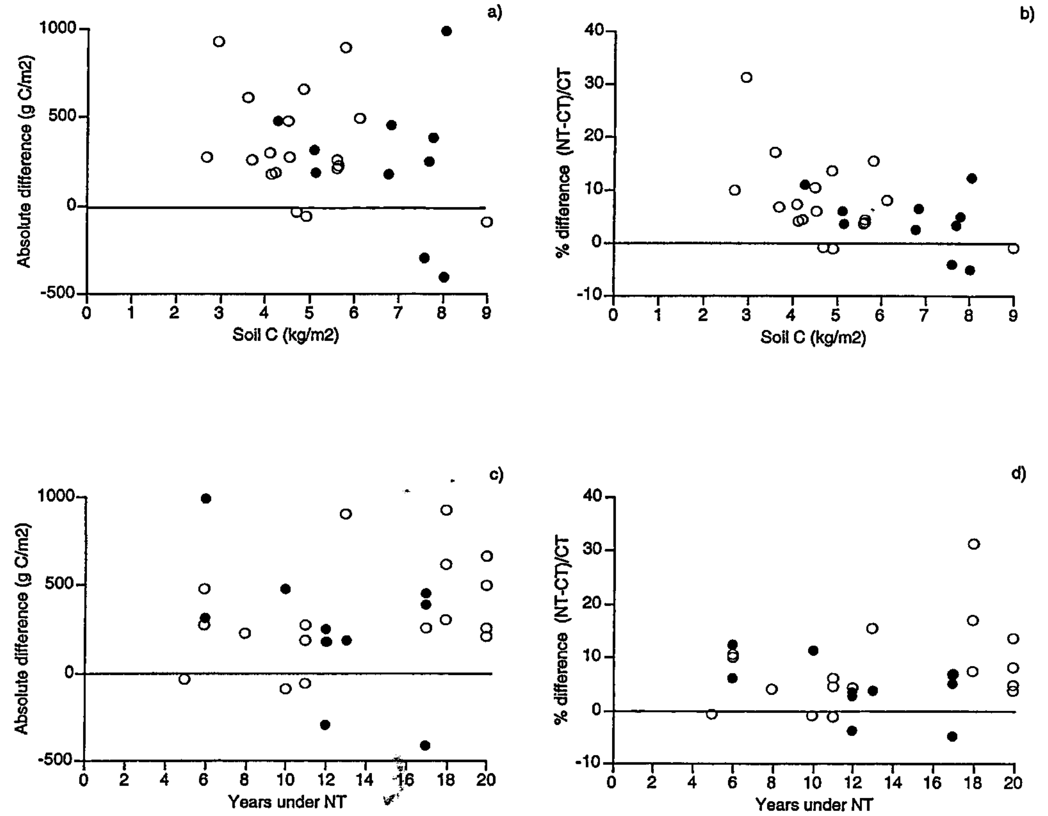

Figure 9 Soil carbon levels in pair-wise comparisons of no-till (NT) and conventional tillage (CT), with moldboard plow, from several long-term experiments. Shown are (a) absolute difference (NT-CT) and (b) relative difference ((NT-CT)/CT) as a function of soil C (under CT) and (c) absolute and (d) relative differences as a function of time under NT. Values are for total organic C to depths at or below depth of plowing and adjusted for differences in bulk density for comparison on an equivalent soil mass basis (see description in text). Filled circles are for clay and clay loam soils, all other textures shown as open circles. Each site/treatment is only represented once, by the most recent published value. Data from Powlson and Jenkinson,[134] Dick,[142] Groffman,[143] Dick et al.,[144–145] Doran,[133] Dalal,[146] Balesdent,[147] Havlin et al.,[148] Chan et al.,[89] and Ismail et al.[149]

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.[149] 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.[71] 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.[150] 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.[116] Lower yields with NT under such conditions has been cited as limiting its applicability in cool regions.[151,152] However, major yield reductions in cool climates are not universal. Riley et al.,[153] 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[154] 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.[155–157] 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.[158] However, crop rotation and use of disease-resistant cultivars can reduce disease-induced yield declines in NT.[156] 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.[121,159] 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[160–162] and higher production under no-till has been shown for well-drained soils, particularly where water use efficiency is improved.[116,163] Prasad and Power[91] 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,[7,164–165] accompanied by a reduction in the number of large pores.[165,166] 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.[160,161,166,167] Plow pans, which can impede water movement and root penetration, may not form so readily with reduced tillage.[166,168] In other cases, NT or other reduced tillage practices have had no effect on or have decreased bulk density.[122,167,169,170] In most cases, irrespective of changes in overall porosity, no-till soils have equal or increased water infiltration rates,[122,160,161,164,166] 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).

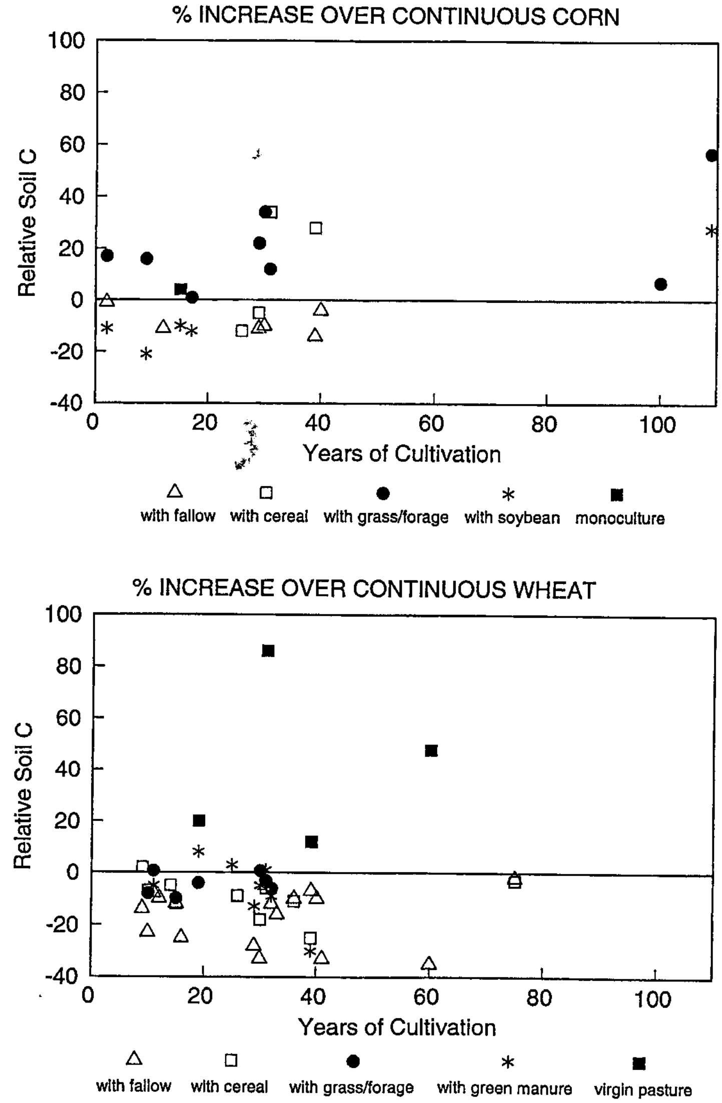

Figure 10 Summary of rotation influence on soil C levels, shown as percent of soil C under continuous corn or continuous wheat treatments in the same experiment, plotted as a function of experiment duration. Symbols depict different classes of rotations for corn- and wheat-based cropping systems. Data from Haas et al.,[11] Anderson and Peterson,[93] Barber,[16] Hooker et al.,[171] Odell et al.,[48] Upchurch et al.,[172] Dick et al.,[144,145] Soon and Broersma,[173] Insam et al.,[174] Rasmussen et al.,[45] Campbell et al.,[86,175] and Monreal and Janzen.[176]

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 C_4 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.[177–179]

Table 4 Approximate Crop Residue Yields (above Ground Only) for Different Crops Based on Average Yields for the U.S.[180]

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

Note: Estimates of harvest index values of most crops based on Anderson and Vasilas,[181] Brinkman and Rho,[182] Cox et al.,[183] Donald and Hamblin,[184] Meyers et al.,[185] Russell,[186] and Walker and Fioritto.[187] 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%)[188,189] 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 Christenson[190] 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.[148] 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 Zentner[191] 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.[192] 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.[193] 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

(Figure 11). 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.

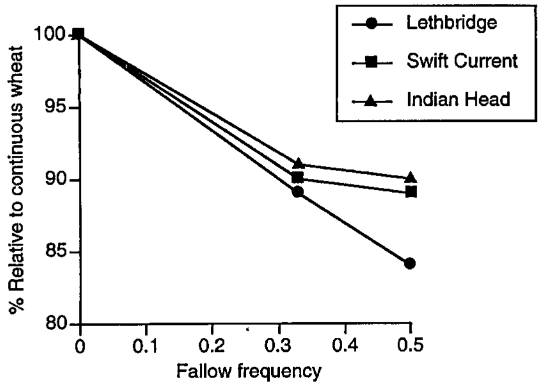

Figure 11 Soil C response to fallow frequency, as a percentage of C content under continuous cropping, for three long-term experiments with fallow-wheat, fallow-wheat-wheat, and continuous wheat rotations in Saskatchewan. Data from Campbell et al.[86,175] and Janzen.[194] Rotations at Indian Head and 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[11,80] 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[198–200] 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.[80] 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[201] 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[202] 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.[201] 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.[201] Increases in total C levels under ley cropping have been reported in a number of other European studies.[17,94,203–205] In Indiana, 7 years of continuous alfalfa or bromegrass yielded up to 25% more soil C than continuous corn.[206] 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 lespedeza, a perennial forage crop, Davidson et al.[207] found dramatic increases in soil C under lespedeza (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.[11,104] In summarizing results from 17 long-term sites in the Great Plains, Haas et al.[11] 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.[208–210] In several studies for the subhumid regions of the Canadian prairies, summarized by Campbell et al.,[211] 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.[212] As an example, Drover[197] 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.[213] 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.[214] 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[215] 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.[203] 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.[205] 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

Cropping History	Aggregate Stability (MWD)	Organic C (%)
10 year arable	1.0	2.0
4 year arable	1.2	2.4
1 year arable	1.3	2.4
1 year pasture	2.0	2.4
4 year pasture	2.5	2.5
10 year pasture	2.7	3.2

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.

Data from Haynes, R. J., Swift, R. S., and Stephen, R. C., *Soil Tillage Res.*, 19, 77, 1991.

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.[217] Accordingly, increases in soil C under rotations of alternating annual and perennial crops are likely to be transient[206] 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.[126] 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.[86] 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.[222]

Nitrogen additions can affect decomposition rates and C stabilization efficiency in other ways that contribute to higher SOM levels. Fog[223] 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[224]). 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.[38] 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.,[225] 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 6 Summary of Long-Term Field Experiments Showing Soil C Responses to Differential Levels of N Fertilizer Application (N Levels are Shown in Bold Type)

Site	Years	Treatment	N Levels (kg ha^{-1})			
			Soil C Change (% of Control)			
Mandan, MT[209]	7		**0**	**30**	**60**	
		Sandy loam — continuous wheat	100	109	—	
		Sandy loam — crested wheatgrass	100	99	100	
		Silt loam — continuous wheat	100	107	—	
		Silt loam — crested wheatgrass	—	100	102	
Pendleton, OR[218]	44		**11**	**22**	**50**	
		Wheat/fallow — moldboard plow	100	98	102	
		Wheat/fallow — disk	100	94	108	
		Wheat/fallow — sweep	100	103	108	
Swift Current, Saskatchewan[191]	24		**0**	**29**		
		Fallow/wheat/wheat	100	104		
		Continuous wheat	100	109		
Indianhead, Saskatchewan[175]	29		**0**	**24**		
		Fallow/wheat	100	104		
		Fallow/wheat/wheat	100	106		
		Continuous wheat	100	106		
Melfort, Saskatchewan[86]	30		**0**	**52**		
		Fallow/wheat/wheat	100	100		
		Continuous wheat	100	100		
		Fallow/wheat/hay rotation	100	97		
Queensland, Australia[146]	13	Cereals — conventional tillage	**0**	**23**	**69**	
		Straw burned	100	101	106	
		Straw retained	100	102	105	
		Cereals — no-till				
		Straw burned	100	94	98	
		Straw retained	100	112	113	
Eastern Kansas[148]	8		**0**	**252**		
		Continuous soybean	100	95		
		Corn/soybean	100	101		
		Continuous corn	100	102		
Purdue, IN[16]	12		**0**	**67**	**200**	
		Continuous corn	100	106	107	
Lamberton, MN[77]	19		**0**	**45**	**90**	**180**
		Continuous corn	100	104	103	105
Lexington, KY[149]	20		**0**	**84**	**168**	**336**
		Continuous corn — plow tillage	100	115	115	126
		Continuous corn — no-till	100	105	106	120
Askov, Denmark[94]	78		**0**	**35**	**70**	**105**
		Cereal/root crop rotation — loam	100	106	109	111
		Cereal/root crop rotation — sand	100	111	121	—
Southern Sweden[17]	15		**0**	**50**	**100**	**150**
		Mixed cropping	100	107	108	111
Uppsala, Sweden[38]	30	Cereal/root crops	**0**	**80**		
		Straw removed	100	118		
		Straw added	100	116		
		Sawdust added	100	115		
Ås, Norway[84]	20	Cereals	**0**	**34**	**68**	**136**
		Straw added	100	98	101	103
		Straw removed	100	101	104	103
Øsaker, Norway[84]	20	Cereals	**0**	**34**	**68**	**136**
		Straw added	100	102	100	104
		Straw removed	100	100	99	107

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)

Site	Years	Treatment	N Levels (kg ha^{-1}) Soil C Change (% of Control)			
Ås, Norway[84]	31		**60**	**120**		
		Cereals	100	102		
		Cereal + row crops	100	102		
		2 ley + 4 arable	100	108		
		4 ley + 2 arable	100	104		
Halle/Saale, Germany[219]	80		**0**	**40**		
		Continuous rye	100	108		
Gottingen, Germany[220]	81		**0**	**30–50**		
		Mixed rotation	100	111		
Riverside, CA[221]	28	Citrus grove	**0**	**310**		
		Urea N	100	105		
		NH_4-N	100	125		
		NO_3-N	100	123		
Rothamsted, U.K.[222]	120	Pasture (parkgrass plots)	**0**	**48**	**96**	**144**
		Unlimed				
		NH_4 — fertilizer	100	100	138	153
		NO_3 — fertilizer	100	108	97	—
		Limed				
		NH_4 — fertilizer	100	95	101	105
		NO_3 — fertilizer	100	99	100	—

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

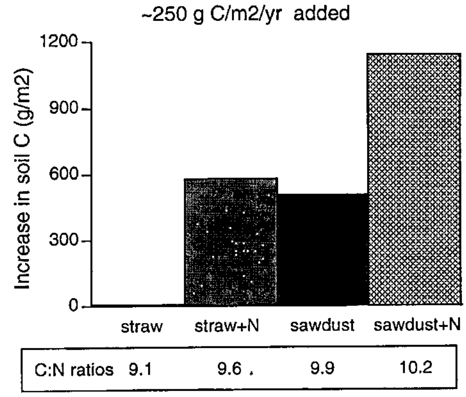

Figure 12 Nitrogen addition effects on the net change in soil C over the duration of a 31-year experiment with constant (~250 g C m^{-2} y^{-1}) of straw or sawdust addition. Above-ground crop residues were removed from the plots. N fertilized plots received rates equivalent to 80 kg N ha^{-1} y^{-1} as $Ca(NO_3)_2$.

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.

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REFERENCES

1. Grigg, D., *The Dynamics of Agriculture Change: The Historical Experience*, Hutchinson & Co., London, 1983.
2. Seebohm, M.E., *The Evolution of the English Farm*, 2nd ed., E.P. Publishing, 356 pp., 1976.
3. Fussell, G.E., *Farming Technique from Prehistoric to Modern Times*, Pergamon Press, Oxford, 1965.
4. Whitney, M., The development of man on the earth and the beginnings of organized agriculture, in *Soil and Civilization: A Modern Concept of the Soil and the Historical Development of Agriculture*, D. Van Nostrand Company, New York, 176, 1925.
5. Olsson, G., Nutrient use and productivity for different cropping systems in south Sweden during the 18th century, in *The Cultural Landscape: Past, Present and Future*, Birks, H.H., Birks, H.J.B., Kaland, P.E., and Moe, D., Eds., Cambridge University Press, Cambridge, 1988, 123.
6. Steen, E., Agricultural outlook, in *Ecology of Arable Land — Organisms, Carbon and Nitrogen Cycling*, Andrén, O., Lindberg, T., Paustian, K., and Rosswall, T., Eds., Chapter 8, Ecological Bulletins, Copenhagen, 1989, 40.
7. Curwen, E.C. and Hatt, G., *Plough and Pasture: The Early History of Farming*, Collier Books, New York, 1961.
8. Percy, D.O., Ax or plow?: Significant colonial landscape alteration rates in the Maryland and Virginia tidewater. *Agric. Hist.*, 66, 66, 1992.
9. Sandor, J.A., Gersper, P.L., and Hawley, J.W., Soils at prehistoric agricultural terracing sites in New Mexico. II. Organic matter and bulk density changes, *Soil Sci. Soc. Am. J.*, 50, 173, 1986.
10. Cochrane, W.W., *The Development of American Agriculture*, University of Minnesota Press, Minneapolis, 1979.
11. Haas, H.J., Evans, C.E., and Miles, E.F., Nitrogen and Carbon Changes in Great Plains Soils as Influenced by Cropping and Soil Treatments, Technical Bulletin No. 1164 USDA, State Agricultural Experiment Stations, 111 pp., 1957.
12. Mitchell, C.C., Westerman, R.L., Brown, J.R., and Peck, T.R., Overview of long-term agronomic research, *Agron. J.*, 83, 24, 1991.
13. Cole, C.V., Stewart, J.W.B., Ojima, D.S., Parton, W.J., and Schimel, D.S., Modelling land use effects of soil organic matter dynamics in the North American Great Plains, in *Ecology of Arable Land*, Clarholm, M. and Bergström, L., Eds., Kluwer Academic, Dordrecht, 89, 1989.
14. Persson, J., Detailed Investigation of the Soil Organic Matter in a Long Term Frame Trial, *Department of Soil Sciences Report 128*, Swedish University of Agricultural Sciences, 1980.
15. Larson, W.E., Clapp, C.E., Pierre, W.H., and Morachan, Y.B., Effects of increasing amounts of organic residues on continuous corn. II. Organic carbon, nitrogen, phosphorus, and sulfur, *Agron. J.*, 64, 204, 1972.
16. Barber, S.A., Corn residue management and soil organic matter, *Agron. J.*, 71, 625, 1979.
17. Jansson, S.L., Bördighetsstudier för Markvård. Försök i Malmöhus län 1957–74. (Long-term soil fertility studies. Experiments in Malmöhus County 1957–74), Supplement 10, Stockholm, 1975.
18. Bouwman, A.F., Ed., *Soils and the Greenhouse Effect*, John Wiley & Sons, Chichester, England, 1990.
19. Duxbury, J.M., Harper, L.A., and Mosier, A.R., Contributions of agroecosystems to global climate change, in *Agricultural Ecosystem Effects on Trace Gases and Global Climate Change*, ASA Special Publication Number 55, 1993, 1.
20. Wisniewski, J. and Lugo, A.E., Eds., *Natural Sinks of CO_2*, Kluwer Academic, Dordrecht, 1992.
21. Wisniewski, J. and Sampson, R.N., Eds., *Terrestial Biospheric Carbon Fluxes: Quantification of Sinks and Sources of CO_2*, Kluwer Academic, Dordrecht, 1993.
22. Houghton, R.A. and Skole, D.L., Carbon, in *The Earth as Transformed by Human Action*, Turner, B.L., II, Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T., and Meyer, W.B., Eds., Cambridge University Press, Cambridge, 1990, chap. 23.
23. Wilson, A.T., Pioneer agriculture explosion and CO_2 levels in the atmosphere, *Nature*, 273, 40, 1978.
24. Cole, C.V., Paustian, K., Elliott, E.T., Metherell, A.K., Ojima, D.S., and Parton, W.J., Analysis of agroecosystem carbon pools, *Water, Air, Soil Pollut.*, 70, 357, 1993a.
25. Barnwell, T.O., Jackson, R.B., Elliott, E.T., Burke, I.C., Cole, C.V., Paustian, K., Paul, E.A., Donigian, A., Patwardhan, A., Rowell, A., and Weinrich, K. An approach to assessment of management impacts on agricultural soil carbon, *Water, Air, Soil Pollut.*, 64, 423, 1992
26. Cole, C.V., Flach, K., Lee, J., Sauerbeck, D. and Stewart, B., Agricultural sources and sinks of carbon. *Water, Air, Soil Pollut.*, 70, 111, 1993b.
27. Kononova, M.M., *Soil Organic Matter. Its Nature, Its Role in Soil Formation and in Soil Fertility*, 2nd ed., Nowakowski, T.Z. and Newman, A.C.D., (Translators) Pergamon Press, Oxford, 1966.
28. Allison, F.E., *Soil Organic Matter and Its Role in Crop Production*, (Developments in Soil Science 3), Elsevier, Amsterdam, 1973.

29. Campbell, C.A., Soil organic carbon, nitrogen and fertility, in *Soil Organic Matter*, Schnitzer, M. and Khan, S.U., Eds., Elsevier, Amsterdam, 1978.
30. Tate, R.L., *Soil Organic Matter. Biological and Ecological Effects*, John Wiley & Sons, New York, 1987, 291.
31. Rasmussen, P.E. and Collins, H.P., Long-term impacts of tillage fertilizer, and crop residue on soil organic matter in temperate semiarid regions, *Adv. Agron.*, 45, 93, 1991.
32. McKaig, N., Jr. and Roller, E.M., The effects of organic matter added to lysimeters containing Norfolk coarse sand, *Soil Sci. Soc. Proc.*, 2, 195, 1938.
33. Mann, L.K., A regional comparison of carbon in cultivated and uncultivated Alfisols and Mollisols in the central United States, *Geoderma*, 36, 241, 1985.
34. Meints, V.M. and Peterson, G.A., The influence of cultivation on the distribution of nitrogen in soils of the Ustoll suborder, *Soil Sci.*, 124, 334, 1977.
35. Elliott, E.T., Janzen, H.H., Campbell, C.A., Cole, C.V., and Myers, R.J.K., An ecosystem approach to integrated nutrient management for sustainable land use, in *Sustainable Land Management in the 21st Century*, Vol. 2, Wood, R.C. and Dumanski, J., Eds., Lethbridge, Saskatchewan, 1994, 35.
36. Jenkinson, D.S., Hart, P.B.S., Rayner, J.H., and Parry, L.C., Modelling the turnover of organic matter in long-term experiments at Rothamsted, *INTECOL Bull.*, 15, 1, 1987.
37. Parton, W.J., Schimel, D.S., Cole, C.V., and Ojima, D.S., Analysis of factors controlling soil organic matter levels in Great Plains grasslands, *Soil Sci. Soc. Am. J.*, 51, 1173, 1987.
38. Paustian, K., Parton, W.J., and Persson, J., Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots, *Soil Sci. Soc. Am. J.*, 56, 476, 1992.
39. Parton, W.J. and Rasmussen, P.E., Long-term effects of crop management in wheat-fallow. II. CENTURY model simulations, *Soil Sci. Soc. Am. J.*, 58, 530, 1994.
40. USDA, SCS, Land Resource Regions and Major Land Resource Areas of the United States, Agriculture Handbook 296, 1981.
41. Jenny, H., *Factors of Soil Formation*, McGraw-Hill, London, 1941.
42. Kern, J.S. and Johnson, M.G., Conservation tillage impacts on national soil and atmospheric carbon levels, *Soil Sci. Soc. Am. J.*, 57, 200, 1993.
43. Anderson, D.W., Pedogenesis in the grassland and adjacent forests of the Great Plains, *Adv. Soil Sci.*, 7, 53, 1987.
44. Martel, Y.A. and Paul, E.A., Effects of cultivation on the organic matter of grassland soils as determined by fractionation and radiocarbon dating, *Can. J. Soil Sci.*, 54, 419, 1974.
45. Rasmussen, P.E., Collins, H.P., and Smiley, R.W., Long-Term Management Effects on Soil Productivity and Crop Yield in Semi-Arid Regions of Eastern Oregon, Station Bulletin 675, USDA-ARS and Agricultural Experiment Station, Oregon State University, Pendleton, 1989.
46. Dalal, R.C. and Mayer, R.J., Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. I. Overall changes in soil properties and trends in winter cereal yields, *Aust. J. Soil Res.*, 24, 265, 1986a.
47. Dalal, R.C. and Mayer, R.J., Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. II. Total organic carbon and its rate of loss from the soil profile, *Aust. J. Soil Res.* 24, 281, 1986b.
48. Odell, R.T., Melsted, S.W., and Walker, W.M., Changes in organic carbon and nitrogen of Morrow plot soils under different treatments 1904–1973, *Soil Sci.*, 137, 160, 1984.
49. Balesdent, J., Wagner, G.H., and Mariotti, A., Soil organic matter in long-term field experiments as revealed by carbon-13 natural abundance, *Soil Sci. Soc. Am. J.*, 52, 118, 1988.
50. Bowman, R.A., Reeder, J.D., and Lober, R.W., Changes in soil properties in a Central Plains rangeland soil after 3, 20, and 60 years of cultivation, *Soil Sci.*, 150, 851, 1990.
51. Mann, L.K., Changes in soil carbon storage after cultivation, *Soil Sci.*, 142, 279, 1986.
52. Davidson, E.A. and Ackerman, I.L., Changes in soil carbon inventories following cultivation of previously untilled soils, *Biogeochemistry*, 20, 161, 1993.
53. Tiessen, H., Stewart, J.W.B., and Bettany, J.R., Cultivation effects on the amounts and concentration of carbon, nitrogen, and phosphorous in grassland soils, *Agron. J.*, 74, 831, 1982.
54. Anderson, D.W. and Coleman, D.C., The dynamics of organic matter in grassland soils, *J. Soil Water Conserv.*, 40, 211, 1985.
55. Buyanovsky, G.A., Kucera, C.L., and Wagner, G.H. Comparative analyses of carbon dynamics in native and cultivated ecosystems, *Ecology*, 68, 2023, 1987.
56. van Veen, J.A. and Paul, E.A., Organic carbon dynamics in grassland soils. I. Background information and computer simulation, *Can. J. Soil Sci.*, 61, 185, 1981.
57. Angers, D.A., Pesant, A., and Vigneux, J., Early cropping-induced changes in soil aggregation, organic matter, and microbial biomass, *Soil Sci. Soc. Am. J.*, 56, 115, 1992.
58. Elustondo, J., Angers, D.A., Laverdière, M.R., and N'Dayegamiye, A., Étude comparative de l'agrégation et de la matière organique associée aux fractions granulométriques de sept sols sous culture de mais ou en prairie, *Can. J. Soil Sci.*, 70, 395, 1990.
59. Elliott, E.T., Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils, *Soil Sci. Soc. Am. J.*, 50, 627, 1986.

60. Tisdall, J.M. and Oades, J.M., Organic matter and water-stable aggregates in soils, *J. Soil Sci.*, 33, 141, 1982.
61. Low, A.J., The effect of cultivation on the structure and other physical characteristics of grassland and arable soils, *J. Soil Sci.*, 23, 363, 1972.
62. Rovira, A.D. and Greacen, E.L., The effect of aggregate disruption on the activity of microorganisms in the soil, *Aust. J. Agric. Res.*, 8, 659, 1957.
63. Elliott, E.T. and Coleman, D.C., Let the soil work for us, *Ecol. Bull.*, 39, 23, 1988.
64. Beare, M.H., Cabrera, M.L., Hendrix, P.F., and Coleman, D.C., Aggregate-protected and unprotected organic matter pools in conventional- and no-tillage soils, *Soil Sci. Soc. Am. J.*, 58, 787, 1994.
65. Aguilar, R., Kelly, E.F., and Heil, R.D., Effects of cultivation on soils in Northern Great Plains rangeland, *Soil Sci. Soc. Am. J.*, 52, 1081, 1988.
66. Burke, I.C., Yonker, C.M., Parton, W.J., Cole, C.V., Flach, K., and Schimel, D.S., Texture, climate and cultivation effects on soil organic matter content in U.S. grassland soils, *Soil Sci. Soc. Am. J.*, 53, 800, 1989.
67. Campbell, C.A. and Souster, W., Loss of organic matter and potentially mineralizable nitrogen from Saskatchewan soils due to cropping, *Can. J. Soil Sci.*, 58, 331, 1982.
68. Doughty, J.L., Cook, F.D., and Warder, F.G., Effect of cultivation on the organic matter and nitrogen of brown soils, *Can. J. Agric. Sci.*, 34, 406, 1954.
69. Tiessen, H., Stewart, J.W.B., and Hunt, W.H., Concepts of soil organic matter transformations in relation to organo-mineral particle size fractions, *Plant Soil*, 76, 287, 1984.
70. Gantzer, C.J., Anderson, S.H., Thompson, A.L., and Brown, J.R., Evaluation of soil loss after 100 years of soil and crop management, *Agron. J.*, 83, 74, 1991.
71. Dick, W.A., McCoy, E.L., Edwards, W.M., and Lal, R., Continuous application of no-tillage to Ohio soils, *Agron. J.*, 83, 65, 1991.
72. Slater, C.S. and Carleton, E.A., The effect of erosion on losses of soil organic matter, *Soil Sci. Soc. Proc.*, 2, 123, 1938.
73. Gregorich, E.G. and Anderson, D.W., Effects of cultivation and erosion on soils of four toposequences in the Canadian prairies, *Geoderma*, 36, 343, 1985.
74. Lucas, R.E., Holtman, J.B., and Connor, L.J., Soil carbon dynamics and cropping practices, *Agric. Energy*, 1977.
75. Kruglov, L.V. and Proshlyakov, A.A., Humus replenishment in the plowed soils of the non-Chernozem belt, *Soviet Soil Sci.*, 11, 313, 1979.
76. Rasmussen, P.E., Allmaras, R.R., Rohde, C.R., and Roager, N.C., Jr., Crop residue influences on soil carbon and nitrogen in a wheat-fallow system, *Soil Sci. Soc. Am. J.*, 44, 596, 1980.
77. Bloom, P.R., Schum, W.M., Malzer, G.L., Nelson, W.W., and Evans, S.D., Effect of N fertilizer management of organic matter in Minnesota mollisols, *Agron. J.*, 74, 161, 1982.
78. Paustian, K., Robertson, G.P., and Elliott, E.T., Management impacts on carbon storage and gas fluxes (CO_2, CH_4) in mid-latitude cropland and grassland ecosystems, in *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, in press.
79. Black, A.L., Soil property changes associated with crop residue management in a wheat-fallow rotation, *Soil Sci. Soc. Am. Proc.*, 37, 943, 1973.
80. Horner, G.M., Oveson, M.M., Baker, G.O., and Pawson, W.W., Effect of Cropping Practices on Yield, Soil Organic Matter and Erosion in the Pacific Northwest Wheat Region, Bulletin 1, Agricultural Experiment Stations of Idaho, Oregon and Washington, USDA-ARS, July 1960.
81. Uhlen, G., Effect of nitrogen, phosphorous and potassium fertilizers and farm manure in long-term experiments with rotation crops in Norway, *Ann. Agron.*, 27, 547, 1976.
82. Hooker, M.L., Herron, G.M., and Penas, P., Effects of residue burning, removal, and incorporation on irrigated cereal crop yields and soil chemical properties, *Soil Sci. Soc. Am. J.*, 46, 122, 1982.
83. Sauerbeck, D.R., Influence of crop rotation, manurial treatment and soil tillage on the organic matter content of German soils, in *Soil Degradation*, Boels, D., Davies, D.B., and Johnston, A.E., Eds., Proceedings of the Land Use Seminar on Soil Degradation, Wageningen, October 13–15, 1980, A.A. Balkema, Rotterdam, 1982, 163.
84. Uhlen, G., Long-term effects of fertilizers, manure, straw and crop rotation on total-N and total-C in soil, *Acta Agric. Scand.*, 41, 119, 1991.
85. Saffigna, P.G., Powlson, D.S., Brookes, P.C., and Thomas, G.A., Influence of sorghum residues and tillage on soil organic matter and soil microbial biomass in an Australian vertisol, *Soil Biol. Biochem.*, 21, 759, 1989.
86. Campbell, C.A., Bowren, K.E., Schnitzer, M., Zentner, R.P., and Townley-Smith, L., Effect of crop rotations and fertilization on soil biochemical properties in a thick Black Chernozem, *Can. J. Soil Sci.*, 71, 377, 1991c.
87. Dormaar, J.F., Pittman, U.J., and Spratt, E.D., Burning crop residues: effect on selected soil characteristics and long-term wheat yields, *Can. J. Soil Sci.*, 59, 79, 1979.
88. Biederbeck, V.O., Campbell, C.A., Bowren, K.E., Schnitzer, M., and McIver, R.N., Effect of burning cereal straw on soil properties and grain yields in Saskatchewan, *Soil Sci. Soc. Am. J.*, 44, 103, 1980.
89. Chan, K.Y., Roberts, W.P., and Heenan, D.P., Organic carbon and associated soil properties of a red earth after 10 years of rotation under different stubble and tillage practices, *Aust. J. Soil Res.*, 30, 71, 1992.
90. Pikul, J.L., Jr. and Allmaras, R.R., Physical and chemical properties of a Haploxeroll after fifty years of residue management, *Soil Sci. Soc. Am. J.*, 50, 214, 1986.
91. Prasad, R. and Power, J.F., Crop residue management, *Adv. Soil Sci.*, 15, 205, 1991.

92. Chater, M. and Gasser, J.K., Effects of green manuring, farmyard manure, and straw on the organic matter of soil and of green manuring on available nitrogen, *J. Soil Sci.*, 21, 127, 1970.
93. Anderson, F.N. and Peterson, G.A., Effects of continuous corn (*Zea mays* L.), manuring, and nitrogen fertilization on yield and protein content of the grain and on the soil nitrogen content, *Agron. J.*, 65, 697, 1973.
94. Kofoed, A.D. and Nemming, O., Fertilizers and manure on sandy and loamy soils, *Ann. Agron.*, 27, 583, 1976.
95. Steineck, O. and Ruckenbauer, P., Results of a 70 years long-term rotation and fertilization experiment in the main cereal growing area of Australia, *Ann. Agron.*, 27, 803, 1976.
96. Jenkinson, D.S. and Rayner, J.H., The turnover of soil organic matter in some of the Rothamsted classical experiments, *Soil Sci.*, 123, 298, 1977.
97. Sommerfeldt, T.G., Chang, C., and Entz, T., Long-term annual manure applications increase soil organic matter and nitrogen, and decrease carbon to nitrogen ratio, *Soil Sci. Soc. Am. J.*, 52, 1668, 1988.
98. N'Dayegamiye, A. and Cote, D., Effect of long-term pig slurry and soil cattle manure application on soil chemical and biological properties, *Can. J. Soil Sci.*, 69, 39, 1989.
99. Liang, B.C. and Mackenzie, A.F., Changes in soil organic carbon and nitrogen after six years of corn production, *Soil Sci.*, 153, 307, 1992.
100. Meek, B., Graham, L., and Donovan, T., Long-term effects of manure on soil nitrogen, phosphorous, potassium, sodium, organic matter, and water infiltration rate, *Soil Sci. Soc. Am. J.*, 46, 1014, 1982.
101. Christenson, B.T., Effects of animal manure and mineral fertilizer on the total carbon and nitrogen contents of soil size fractions, *Biol. Fertil. Soils*, 5, 304, 1988.
102. Angers, D.A. and N'Dayegamiye, A.N., Effects of manure application on carbon, nitrogen, and carbohydrate contents of a silt loam and its particle-size fractions, *Biol. Fertil. Soils*, 11, 79, 1991.
103. MacRae, R.J. and Mehuys, G.R., The effect of green manuring on the physical properties of temperate-area soils, *Adv. Soil Sci.*, 3, 70, 1985.
104. Krall, J.L., Army, T.J., Post, A.H., and Seamans, A.E., A summary of dryland rotations and tillage experiments at Havre, Huntley and Moccasin, Montana, *Montana Agric. Exp. Stn. Bull.*, 599, 1965.
105. Sowden, F.J. and Atkinson, H.J., Effect of long-term additions of various organic amendments on the organic matter of a clay and a sand, *Can. J. Soil Sci.*, 48, 323, 1968.
106. Boyle, M., Frankenberger, W.T., Jr., and Stolzy, L.H., The influence of organic matter on soil aggregation and water infiltration, *J. Prod. Agric.*, 2, 290, 1989.
107. Elliott, L.F. and Papendick, R.I., Crop residue management for improved soil productivity, *Biol. Agric. Hortic.*, 3, 131, 1986.
108. Campbell, C.A., Moulin, A.P., Curtin, D., Lafond, G.P., and Townley-Smith, L., Soil aggregation as influenced by cultural practices in Saskatchewan. I. Black Chernozemic soils, *Can. J. Soil Sci.*, 73, 579, 1993.
109. Adem, H.H. and Tisdall, J.M., Management of tillage and crop residues for double-cropping in fragile soils of south-eastern Australia, *Soil Tillage Res.*, 4, 577, 1984.
110. Dormaar, J.F. and Pittman, U.J., Decomposition of organic residues as affected by various dryland spring wheat-fallow rotations, *Can. J. Soil Sci.*, 60, 97, 1980.
111. Emmond, G.S., Effect of rotations, tillage treatments and fertilizers on the aggregation of a clay soil, *Can. J. Soil Sci.*, 51, 235, 1971.
112. Morachan, Y.B., Moldenhauer, W.C., and Larson, W.E., Effects of increasing amounts of organic residues on continuous corn. I. Yields and soil physical properties, *Agron. J.*, 64, 199, 1972.
113. Smika, D.E. and Greb, B.W., Nonerodible aggregates and concentration of fats, waxes, and oils in soils as related to wheat straw mulch, *Soil Sci. Soc. Am. Proc.*, 39, 104, 1975.
114. Halstead, R.L. and Sowden, F.J., Effect of long-term additions of organic matter on crop yields and soil properties, *Can. J. Soil Sci.*, 48, 341, 1968.
115. Baeumer, K. and Bakermans, W.A.P., Zero-tillage, *Adv. Agron.*, 25, 77, 1973.
116. Phillips, R.E., Blevins, R.L., Thomas, G.W., Frye, W.W., and Phillips, S.H., No-tillage agriculture, *Science*, 208, 1108, 1980.
117. Gebhardt, M.R., Daniel, T.C., Schweizer, E.E., and Allmaras, R.R., Conservation tillage, *Science*, 230, 625, 1985.
118. Chaney, K., Hodgson, D.R., and Braim, M.A., The effects of direct drilling, shallow cultivation and ploughing on some soil physical properties in a long-term experiment on spring barley, *J. Agric. Sci., Cambridge*, 104, 125, 1985.
119. Douglas, J.T. and Goss, M.J., Stability and organic matter content of surface soil aggregates under different methods of cultivation and in grassland, *Soil Tillage Res.*, 2, 155, 1982.
120. Hamblin, A.P., Changes in aggregate stability and associated organic matter properties after direct drilling and ploughing on some Australian soils, *Aust. J. Soil Res.*, 18, 27, 1980.
121. Kladivko, E.J., Griffith, D.R., and Mannering, J.V., Conservation tillage effects on soil properties and yield of corn and soya beans in Indiana, *Soil Tillage Res.*, 8, 277, 1986.
122. Prove, B.G., Loch, R.J., Foley, J.L., Anderson, V.J., and Younger, D.R., Improvements in aggregation and infiltration characteristics of a krasnozem under maize with direct drill and stubble retention, *Aust. J. Soil Res.*, 28, 577, 1990.
123. Unger, P.W., Surface soil properties after 36 years of cropping to winter wheat, *Soil Sci. Soc. Am. J.*, 46, 796, 1982.
124. Parker, D.T., Decomposition in the field of buried and surface-applied cornstalk residue, *Soil Sci. Soc. Am. Proc.*, 26, 559, 1962.

125. Brown, P.L. and Dickey, D.D., Losses of wheat straw residue under simulated field conditions, *Soil Sci. Soc. Am. Proc.*, 34, 118, 1970.
126. Andrén, O., Decomposition in the field of shoots and roots of barley, lucerne and meadow fescue, *Swed. J. Agric. Res.*, 17, 113, 1987.
127. Beare, M.H., Parmelee, R.W., Hendrix, P.F., Coleman, D.C., Crossley, D.A., Jr., and Cheng, W., Microbial and faunal interactions and effects on litter nitrogen and decomposition in agroecosystems, *Ecol. Monogr.*, 62, 569, 1992.
128. Bristow, K.L., The role of mulch and its architecture in modifying soil temperature, *Aust. J. Soil Res.*, 26, 269, 1988.
129. Aiken, R., Flerchinger, G., Nielsen, D., Alonso, C., and Rojas, K., Instrumented measure and simulated solutions for the soil energy balance under residues, *Agron. Abstr.*, 8, 1993.
130. Good, L.G. and Smika, D.E., Chemical fallow for soil and water conservation in the Great Plains, *J. Soil Water Conserv.*, 33, 89, 1978.
131. Tindall, T.A. and Crabtree, R.J., Crop Residue Management in Livestock Production and Conservation Systems. II. Agronomic Considerations of Crop Residue Removal, *Research Report P-796*, Oklahoma State University, 1980.
132. Stott, D.E., A tool for soil conservation education, *J. Soil Water Conserv.*, 46, 332, 1991.
133. Doran, J.W., Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils, *Biol. Fertil. Soils*, 5, 68, 1987.
134. Powlson, D.S. and Jenkinson, D.S., A comparison of the organic matter, biomass, adenosine triphosphate and mineralizable nitrogen contents of ploughed and direct-drilled soils, *J. Agric. Sci.*, 97, 713, 1981.
135. Granatstein, D.M., Bezdicek, D.F., Cochran, V.L., Elliott, L.F., and Hammel, J., Long-term tillage and rotation effects on soil microbial biomass, carbon and nitrogen, *Biol. Fertil. Soils*, 5, 265, 1987.
136. Gallaher, R.N. and Ferrer, M.B., Effect of no-tillage vs. conventional tillage on soil organic matter and nitrogen contents, *Commun. Soil Sci. Plant Anal.*, 18, 1061, 1987.
137. Fleige, H. and Baeumer, K., Effect of zero-tillage on organic carbon and total nitrogen content, and their distribution in different N-fractions in Loessial soils, *Agro-Ecosystems*, 1, 19, 1974.
138. Hargrove, W.L., Reid, J.T., Touchton, J.T., and Gallaher, R.N., Influence of tillage practices on the fertility status of an acid soil double-cropped to wheat and soybeans, *Agron. J.*, 74, 684, 1982.
139. Agenbag, G.A. and Maree, P.C.J., The effect of tillage on soil carbon, nitrogen and soil strength of simulated surface crusts in two cropping systems for wheat (*Triticum aestivum*), *Soil Tillage Res.*, 14, 53, 1989.
140. Arshad, M.A., Schnitzer, M., Angers, D.A., and Ripmeester, J.A., Effects of till vs no-till on the quality of soil organic matter, *Soil Biol. Biochem.*, 22, 595, 1990.
141. Campbell, C.A., Biederbeck, V.O., Schnitzer, M., Selles, F., and Zentner, R.P., Effect of 6 years of zero tillage and N fertilizer management on changes in soil quality of an orthic brown Chernozem in southwestern Saskatchewan, *Soil Tillage Res.*, 14, 39, 1989.
142. Dick, W.A., Organic carbon, nitrogen and phosphorus concentrations and pH in soil profiles as affected by tillage intensity, *Soil Sci. Soc. Am. J.*, 47, 102, 1983.
143. Groffman, P.M., Nitrification and denitrification in conventional and no-tillage soils, *Soil Sci. Soc. Am. J.*, 49, 329, 1984.
144. Dick, W.A., Van Doren, D.M., Jr., Triplett, G.B., Jr., and Henry, J.E., Influence of Long-Term Tillage and Rotation Combinations on Crop Yields and Selected Soil Parameters. I. Results Obtained for a Mollic Ochraqualf Soil, Research Bulletin 1180, The Ohio State University, Ohio Agricultural Research and Development Center, Wooster, OH, December 1986a.
145. Dick, W.A., Van Doren, D.M., Jr., Triplett, G.B., Jr., and Henry, J.E., Influence of Long-Term Tillage and Rotation Combinations on Crop Yields and Selected Soil Parameters. II. Results Obtained for a Typic Fragiudalf soil, Research Bulletin 1181, The Ohio State University, Ohio Agricultural Research and Development Center, Wooster, OH, December 1986b.
146. Dalal, R.C., Long-term effects of no-tillage, crop residue, and nitrogen application on properties of a vertisol, *Soil Sci. Soc. Am. J.*, 53, 1511, 1989.
147. Balesdent, J., Mariotti, A., and Boisgontier, D., Effect of tillage on soil organic carbon mineralization estimated from ^{13}C abundance in maize fields, *J. Soil Sci.*, 41, 587, 1990.
148. Havlin, J.L., Kissel, D.E., Maddux, L.D., Claassen, M.M., and Long, J.H., Crop rotation and tillage effects on soil organic carbon and nitrogen, *Soil Sci. Soc. Am. J.*, 54, 448, 1990.
149. Ismail, I., Blevins, R.L., and Frye, W.W., Long-term no-tillage effects on soil properties and continuous corn yields. *Soil Sci. Soc. Am. J.*, 58, 193, 1994.
150. Staley, T.E., Edwards, W.M., Scott, C.L., and Owens, L.B., Soil microbial biomass and organic component alterations in a no-tillage chronosequence, *Soil Sci. Soc. Am. J.*, 52, 998, 1988.
151. Amemiya, M., Conservation tillage in the western Corn Belt, *J. Soil Water Conserv.*, 32, 29, 1977.
152. Karlen, D.L., Conservation tillage research needs, *J. Soil Water Conserv.*, 45, 365, 1990.
153. Riley, H., Børresen, T., Ekeberg, E., and Rydberg, T., Trends in reduced tillage research and practice in Scandinavia, in *Conservation Tillage in Temperate Regions*, Lewis Publishers, Chelsea, MI, 1992.
154. Knight, C.W. and Lewis, C.E., Conservation tillage in the subarctic, *Soil Tillage Res.*, 7, 341, 1986.
155. Boone, F.R., Slager, S., Miedema, R., and Eleveld, R., Some influences of zero-tillage on the structure and stability of a fine-textured river levee soil, *Neth. J. Agric. Sci.*, 24, 105, 1976.

156. Dick, W.A. and Van Doren, D.M., Jr., Continuous tillage and rotation combinations effects on corn, soybean, and oat yields, *Agron. J.*, 77, 459, 1985.
157. Hughes, K.A., Horne, D.J., Ross, C.W., and Julain, J.F., A 10-year maize/oats rotation under three tillage systems. II. Plant population, root distribution and forage yields, *Soil Tillage Res.*, 22, 145, 1992
158. Cook, R.J. and Haglund, W.A., Wheat yield depression associated with conservation tillage caused by root pathogens in the soil not phytotoxins from the straw, *Soil Biol. Biochem.*, 23, 1125, 1991.
159. Griffith, D.R., Kladivko, E.J., Mannering, J.V., West, T.D., and Parsons, S.D., Long-term tillage and rotation effects on corn growth and yield on high and low organic matter, poorly drained soils, *Agron. J.*, 80, 599, 1988.
160. Francis, G.S., Cameron, K.C., and Swift, R.S., Soil physical conditions after six years of direct drilling or conventional cultivation on a silt loam soil in New Zealand, *Aust. J. Soil Res.*, 25, 517, 1987.
161. Coote, D.R. and Malcolm-McGovern, C.A., Effects of conventional and no-till corn grown in rotation on three soils in eastern Ontario, Canada, *Soil Tillage Res.*, 14, 67, 1989.
162. White, P.F., The influence of alternative tillage systems on the distribution of nutrients and organic carbon in some common Western Australian wheatbelt soils, *Aust. J. Soil Res.*, 28, 95, 1990.
163. Carefoot, J.M., Nyborg, M., and Lindwall, C.W., Tillage-induced soil changes and related grain yield in a semi-arid region, *Can. J. Soil Sci.*, 70, 203, 1990.
164. Gantzer, C.J. and Blake, G.R., Physical characteristics of Le Sueur clay loam soil following no-till and conventional tillage, *Agron. J.*, 70, 853, 1978.
165. Hamblin, A.P. and Tennant, D., Effect of tillage on soil water behaviour, *Soil Sci.*, 132, 233, 1980.
166. Tollner, E.W., Hargrove, W.L., and Langdale, G.W., Influence of conventional and no-till practices on soil physical properties in the southern Piedmont, *J. Soil Water Conserv.*, 39, 73, 1984.
167. Edwards, J.H., Wood, C.W., Thurlow, D.L., and Ruf, M.E., Tillage and crop rotation effects on fertility status of a Hapludult soil, *Soil Sci. Soc. Am. J.*, 56, 1577, 1992.
168. Tanchandrphongs, S. and Davidson, J.M., Bulk density, aggregate stability, and organic matter content as influenced by two wheatland soil management practices, *Soil Sci. Soc. Am. Proc.*, 34, 302, 1970.
169. Carter, M.R. and Kunelius, H.T., Comparison of tillage and direct drilling for Italian ryegrass on the properties of a fine sandy loam soil, *Can. J. Soil Sci.*, 66, 197, 1986.
170. Blevins, R.L., Smith, M.S., Thomas, G.W., and Frye, W.W., Influence of conservation tillage on soil properties, *J. Soil Water Conserv.*, 38, 301, 1983.
171. Hooker, M.L., Gwin, R.E., Herron, G.M., and Gallagher, P., Effects of long-term, annual applications of N and P on corn grain yields and soil chemical properties, *Agron. J.*, 75, 94, 1983.
172. Upchurch, W.J., Kinder, R.J., Brown, J.R., and Wagner, G.H., Sanborn Field, Research Bulletin 1054, University of Missouri, Columbia, 1985.
173. Soon, Y.K. and Broersma, K., A study of cropping systems on gray and dark gray luvisols in the Peace River Region of Alberta, Agriculture Canada, Research Station Beaverlodge, Bulletin 86-94, 1986.
174. Insam, H., Parkinson, D., and Domsch, K.H., Influence of macroclimate on soil microbial biomass, *Soil Biol. Biochem.*, 21, 211, 1989.
175. Campbell, C.A., Biederbeck, V.O, Zentner, R.P., and Lafond, G.P., Effect of crop rotations and cultural practices on soil organic matter, microbial biomass and respiration in a thin Black Chernozem, *Can. J. Soil Sci.*, 71, 363, 1991b.
176. Monreal, C.M. and Janzen, H.H., Soil organic-carbon dynamics after 80 years of cropping a Dark Brown Chernozem, *Can. J. Soil Sci.*, 73, 133, 1993.
177. Buyanovsky, G.A. and Wagner, G.H., Post-harvest residue input to cropland, *Plant Soil*, 93, 57, 1986.
178. Paustian, K., Bergström, Jansson, P.-E., and Johnson, H., Ecosystem dynamics, in *Ecology of Arable Land — Organisms, Carbon and Nitrogen Cycling*, Andrén, O., Lindberg, T., Paustian, K., and Rosswall, T., Eds., Chapter 7, Ecological Bulletins, Copenhagen, 40, 153, 1989.
179. van Veen, J.A., Merckx, R., and Van de Geijn, S.C., Plant- and soil-related controls of the flow of carbon from roots through the soil microbial biomass, in *Ecology of Arable Land*, Clarholm, M. and Bergström, L., Eds., Kluwer Academic, Dordrecht, 1989, 43.
180. USDA, Agricultural Statistics 1992, United States Department of Agriculture, National Agricultural Statistics Service, U.S. Government Printing Office, Washington, DC, 1992.
181. Anderson, L.R. and Vasilas, B.L., Effects of planting date on two soybean cultivars: seasonal dry matter accumulation and seed yield, *Crop Sci.*, 25, 999, 1985.
182. Brinkman, M.A. and Rho, Y.D., Response of three oat cultivars to N fertilizer, *Crop Sci.*, 24, 973, 1984.
183. Cox, T.S., Shroyer, J.P., Ben-Hui, L., Sears, R.G., and Martin, T.J., Genetic improvement in agronomic traits of hard red winter wheat cultivars from 1919 to 1987, *Crop Sci.*, 28, 756, 1988.
184. Donald, C.M. and Hamblin, J., The biological yield and harvest index of cereals as agronomic and plant breeding criteria, *Adv. Agron.*, 28, 361, 1976.
185. Meyers, K.B., Simmons, S.R., and Stuthman, D.D., Agronomic comparison of dwarf and conventional height oat genotypes, *Crop Sci.*, 25, 964, 1985.
186. Russell, W.A., Genetic improvement of maize yields, *Adv. Agron.*, 46, 245, 1991.
187. Walker, A.K. and Fioritto, R.J., Effect of cultivar and planting pattern on yield and apparent harvest index in soybean, *Crop Sci.*, 24, 154, 1984.

188. Fox, D.G., Sniffen, C.J., O'Connor, J.D., Russell, J.B., and Van Soest, P.J., The Cornell Net Carbohydrate and Protein System for Evaluating Cattle Diets. I. A Model for Predicting Cattle Requirements and Feedstuff Utilization. Search:Agriculture, Ithaca, NY, Cornell University Agricultural Experiment Station No. 34, 1990.
189. Theander, O. and Åman, P., Anatomical and chemical characteristics, in *Straw and Other Fibrous By-Products as Feed*, Sundstol, F. and Owen, E., Eds., (Developments in Animal and Veterinary Sciences, 14), Elsevier, Amsterdam, 1984, chap. 4.
190. Zielke, R.C. and Christenson, D.R., Organic carbon and nitrogen changes in soil under selected cropping systems, *Soil Sci. Soc. Am. J.*, 50, 363, 1986.
191. Campbell, C.A. and Zentner, R.P., Soil organic matter as influenced by crop rotations and fertilization, *Soil Sci. Soc. Am. J.*, 57, 1034, 1993.
192. Guernsey, C.W., Fehrenbacher, J.B., Ray, B.W., and Miller, L.B., Corn yields, root volumes, and soil changes on the Morrow plots, *J. Soil Water Conserv.*, 24, 101, 1969.
193. Crookston, R.K., Kurle, J.E., Copeland, P.J., Ford, J.H., and Lueschen, W.E., Rotational cropping sequence affects yield of corn and soybean, *Agron. J.*, 83, 108, 1991.
194. Janzen, H.H., Soil organic matter characteristics after long-term cropping to various spring wheat rotations, *Can. J. Soil Sci.*, 67, 845, 1987.
195. Biederbeck, V.O., Campbell, C.A., and Zentner, R.P., Effect of crop rotation and fertilization on some biological properties of a loam in southwestern Saskatchewan, *Can. J. Soil Sci.*, 64, 355, 1984.
196. Ridley, A.O. and Hedlin, R.A., Soil organic matter and crop yields as influenced by the frequency of summer fallowing, *Can. J. Soil Sci.*, 48, 315, 1968.
197. Drover, D.P., The influence of various rotations on coarse-textured soils at Chapman and Wongan Hills Research Stations, western Australia. I. Nitrogen and organic-carbon contents of the soils, *J. Soil Sci.*, 7, 219, 1956.
198. Silvius, J.E., Johnson, R.R., and Peters, D.B., Effect of water stress on carbon assimilation and distribution in soybean plants at different stages of development, *Crop Sci.*, 17, 713, 1977.
199. Sharp, R.E. and Davies, W.J., Solute regulation and growth by roots and shoots of water-stressed maize plants, *Planta*, 147, 43, 1979.
200. Hall, M.H., Sheaffer, C.C., and Heichel, G.H., Partitioning and mobilization of photoassimilate in alfalfa subjected to water deficits, *Crop Sci.*, 28, 964, 1988.
201. Johnston, A.E., Soil organic matter, effects on soils and crops, *Soil Use Manage.*, 2, 97, 1986.
202. Clement, C.R. and Williams, T.E., Leys and soil organic matter. I. The accumulation of organic carbon in soils under different leys, *J. Agric. Sci.*, 63, 377, 1964.
203. Tyson, K.C., Roberts, D.H., Clement, C.R., and Garwood, E.A., Comparison of crop yields and soil conditions during 30 years under tillage or grazed pasture, *J. Agric. Sci., Cambridge* 115, 29, 1990.
204. Kooistra, M.J., Lebbink G., and Brussaard, L., The Dutch programme on soil ecology of arable farming systems. II. Geogenesis, agricultural history, field site characteristics and present farming systems at the Lovinkhoeve Experimental Farm, *Agric. Ecosyst. Environ.*, 27, 361, 1989.
205. Paustian, K., Andrén, O., Clarholm, M, Hansson, A.-C., Johansson, G., Lagerlöf, J., Lindberg, T., Pettersson, R., and Sohlenius, B., Carbon and nitrogen budgets of four agroecosystems with annual and perennial crops, with and without N fertilization, *J. Appl. Ecol.*, 27, 60, 1990.
206. Gupta, U.C. and Reuszer, H.W., Effect of plant species on the amino acid content and nitrification of soil organic matter, *Soil Sci.*, 104, 395, 1967.
207. Davidson, J.M., Gray, F., and Pinson, D.I., Changes in organic matter and bulk density with depth under two cropping systems, *Agron. J.*, 59, 375, 1967.
208. Hobbs, J.A. and Brown, P.L., Effects of Cropping and Management on Nitrogen and Organic Carbon Contents of a Western Kansas Soil, Technical Bulletin 144, Agricultural Experiment Station, Kansas State University of Agriculture and Applied Science, Manhattan, 1965.
209. Haas, H.J., Power, J.F., and Reichman, G.A., Effect of Crops and Fertilizer on Soil Nitrogen, Carbon, and Water Content, and on Succeeding Wheat Yields and Quality, ARS-NC-38, 1976.
210. Granatstein, D.M., Long-Term Tillage and Rotation Effects on Soil Microbial Biomass, Carbon, and Nitrogen, Masters Thesis, Department of Agronomy and Soils, Washington State University, Pullman, 1986.
211. Campbell, C.A., Zentner, R.P., Janzen, H.H., and Bowren, K.E., *Crop Rotation Studies on the Canadian Prairies*, Canadian Publishing Center, Ottawa, 1990, 29.
212. Russell, J.S., Soil fertility changes in long-term experimental plots at Kybybolite, South Australia. I. Changes in pH, total nitrogen, organic carbon, and bulk density, *Aust. J. Agric. Res.*, 11, 902, 1960.
213. Grace, P.R., Ladd, J.N., and Skjemstad, J.O., The effect of management practices on soil organic matter dynamics, in *Soil Biota: Management in Sustainable Farming Systems*, Pankhurst, C.E., Doube, B.M., Gupta, V.V.S.R., and Grace, P.R., Eds., CSIRO, Melborne, 1994, 162.
214. Garwood, E.A., Clement, C.R., and Williams, T.E., Leys and soil organic matter. III. The accumulation of macro-organic matter in the soil under different swards, *J. Agric. Sci.*, 78, 333, 1972.
215. Oades, J.M. and Turchenek, L.W., Accretion of organic carbon, nitrogen and phosphorus in sand and silt fractions of a red-brown earth under pasture, *Aust. J. Soil Res.* 16, 351, 1978.
216. Haynes, R.J., Swift, R.S., and Stephen, R.C., Influence of mixed cropping rotations (pasture-arable) on organic matter content, water stable aggregation and clod porosity in a group of soils, *Soil Tillage Res.*, 19, 77, 1991.

217. Dormaar, J.F. and Smoliak, S., Recovery of vegetative cover and soil organic matter during revegetation of abandoned farmland in a semiarid climate, *J. Range Manage.*, 38, 487, 1985.
218. Rasmussen, P.E. and Rohde, C.R., Long-term tillage and nitrogen fertilization effects on organic nitrogen and carbon in a semiarid soil, *Soil Sci. Soc. Am. J.*, 52, 1114, 1988.
219. Welte, E. and Timmermann, F., Fertilite du sol et bilan de l'azote dans l'essai permanent de fumure < Ewinger Roggenbau > (culture continue de seigle) a Halle/Saale, *Ann. Agron.*, 27, 721, 1976.
220. Timmermann, F. and Welte, E., Effects de la fumure sur les rendements et l'absorption des éléments minéraux par les cultures dans l'essai a long terme du champ < E > de Gottingen, *Ann. Agron.*, 27, 703, 1976.
221. Pratt, P.F., Goulben, B., and Harding, R.B., Changes in organic carbon and nitrogen in an irrigated soil during 28 years of differential fertilization, *Soil Sci. Soc. Proc.*, 21, 215, 1957.
222. Thurston, J.M., Williams, E.D., and Johnston, A.E., Modern developments in an experiment on permanent grassland started in 1856: effects of fertilizers and lime on botanical composition and crop and soil analyses, *Ann. Agron.*, 27, 1043, 1976.
223. Fog, K., The effect of added nitrogen on the rate of decomposition of organic matter, *Biol. Rev.*, 63, 433, 1988.
224. Tempest, D.W. and Neijssel, O.M., The status of Y_{ATP} and maintenance energy as biologically interpretable phenomena, *Ann. Rev. Microbiol.*, 38, 459, 1984.
225. Campbell, C.A., Lafond, G.P., Zentner, R.P., and Biederbeck, V.O., Influence of fertilizer and straw baling on soil organic matter in a thin Black Chernozem in western Canada, *Soil Biol. Biochem.*, 23, 443, 1991a.