# Long-Term Effects of Residue Management in Wheat–Fallow: I. Inputs, Yield, and Soil Organic Matter

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## ABSTRACT

Soil organic matter (SOM) is valuable, because of both its beneficial effect on soil quality and crop productivity and its potential to sequester C. Long-term experiments provide an opportunity to identify crop management practices that enhance or degrade soil quality. This study was initiated in 1931 to determine residue management effects on crop yield and SOM (organic C and N) in a winter wheat (*Triticum aestivum* L.)–fallow system. The soil is a coarse-silty, mixed, mesic Typic Haploxeroll. Treatments include (units $ha^{-1}$ $crop^{-1}$) 22.4 Mg manure, 2.24 Mg pea vine residue, 0, 45, and 90 kg N with and without spring burning of straw, and 0 kg N with fall burning of straw. Yearly C and N inputs and removals have been determined since 1976, and calculated for prior periods. Soil C and N have been determined at $\approx$11-yr intervals. Manure, which supplies 111 kg N $ha^{-1}$ $crop^{-1}$, has consistently produced the highest yield and maintained the highest soil C and N contents. Other treatments initially yielded from 80 to 90% of the manure treatment, but have progressively declined in direct relation to decreasing soil N content. Low-fertility treatments currently yield from 43 to 57% of the manure treatment. The change in soil C and N with time is nearly linear for all treatments, and highly correlated with residue input. Treatment effects on soil C and N have been confined to the top 30 cm of soil, but there has been a slow steady decline in C and N in the 30- to 60-cm zone that is not related to residue management.


Organic matter in soil is important, not only for its beneficial effect on soil quality and crop productivity (Stevenson, 1986), but also for its potential to sequester C from atmospheric $CO_2$ increases (Thornley et al., 1991). Grassland soils tend to lose from 30 to 50% of their original SOM in the first 40 to 50 yr of cultivation (Campbell and Souster, 1982; Tiessen et al., 1982; Mann, 1985). Rapid depletion of the easily mineralizable OM fraction is the primary reason for the initial C loss (Schimel, 1986; Bowman et al., 1990). Organic matter change thereafter largely becomes a function of soil management and erosion (Smith et al., 1946; Voroney et al., 1981; de Jong and Kachanowski, 1988; Rasmussen and Collins, 1991). The wheat–fallow system is especially sensitive to loss of C and N because of reduced vegetative production and greater opportunity for both soil erosion and microbial oxidation of SOM (Biederbeck et al., 1984). Residue and fertility inputs play an important role in controlling the rate of change in soil C and N content (Larson et al., 1972; Rasmussen and Rohde, 1988; Uhlen, 1991; Paustian et al., 1992), but there are no easy methods to determine if agricultural practices are sustaining agricultural and environmental quality. Long-term experiments are perhaps the only way to determine if new agricultural practices will enhance or degrade the productive capability of soil (Jenkinson, 1991). While not a complete panacea, they provide a perspective of change and, if adequately sampled and documented, are valuable for modeling changes in organic matter partitioning and nutrient cycling. A large field experiment was started at Pendleton, OR, in 1931 because of concern for too much soil erosion, excessive burning of stubble, and declining fertility of soil in the rolling wheat lands of the Pacific Northwest. Treatments included organic amendments, inorganic fertilizer, and stubble burning to assess their effect on wheat yield and SOM in a wheat–fallow system. The experiment was to be "carried on for many years" (Pendleton Experiment Station, 1930, unpublished annual report). Periodic summaries of crop and soil response in this study have been reported by Oveson (1966) and Rasmussen et al. (1980). We describe changes since 1976, including residue inputs, and give a comprehensive overview of long-term trends in yield and soil quality. Parton and Rasmussen (1994) describe the use of the CENTURY model to simulate treatments, calculate C and N budgets, and test the model in a semiarid winter rainfall climatic zone.

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## MATERIALS AND METHODS

The experiment was initiated in 1931 at the Columbia Basin Agricultural Research Center 15 km northeast of Pendleton, OR. It is one of the few remaining long-term experiments in the western USA (Mitchell et al., 1991). The climate consists of cool wet winters and hot dry summers. Average temperature is 10.2 °C, but ranges from −0.6 °C in January to 21.2 °C in July. Annual precipitation averages 420 mm, with 70% occurring between 1 September and 31 March. Winter precipitation falls mainly as rain, with limited duration of snow cover in most years. The soil is a Walla Walla silt loam derived from loess overlying basalt. The upper 20 cm of soil contains 18% clay and 70% silt. The pH ranges from 6.1 to 7.0, depending on treatment history, and the soil has little free $CaCO_3$. The cation-exchange capacity is 18 $cmol_c$ $kg^{-1}$. Water-holding capacity at −0.02 and −1.5 MPa tension is $\approx$300 and 70 g $kg^{-1}$, respectively. The soil contains adequate levels of P, K, and micronutrients for dryland cereal production, but is marginally deficient in S and routinely deficient in N.

### Experimental Design

The original experiment consisted of 40 plots, an ordered arrangement of two series of 10 treatments with two replications. The two series (1400 and 1500) are identical, but offset by 1 yr so that yield data can be collected each year in a wheat–fallow rotation. Data collection for Treatment 1 (a 2.24 t $ha^{-1}$ alfalfa treatment) was abandoned about 1940 because crop growth in one plot was affected by a nearby drainage ditch. The experiment was uniformly cropped to spring wheat in 1929 and harvested by plot to assess landscape variability.

**Abbreviations:** DM, dry matter; SOM, soil organic matter. *** Significant at the 0.001 level of probability.

Soil samples were taken in 1931 to establish background SOM and N levels. The bulk density of the top 30 cm of soil in 1931 was determined using a 30-cm soil cylinder. Bulk density was again determined in 1990 and 1991 using an incremental core sampler. Soil depth was determined in 1977–1978 with a hydraulic core sampler. The site was surveyed with a laser level in 1986 to establish the slope of each plot.

The present experiment consists of nine treatments (Table 1). Individual plot size is 11.6 by 40.2 m. Winter wheat is seeded in early October and harvested in mid-July. Wheat stubble is left undisturbed over winter, except for the fall-burn treatment which is burned in mid-September. Organic amendments are applied in late March or early April and stubble burned on spring-burn plots. The entire experiment is then moldboard plowed 20 cm deep and smoothed with a field cultivator and tine harrow. The experiment is then tilled three to four times between April and October with a rodweeder (an implement with a horizontal rotating rod operated 5–7 cm deep) to control weeds and maintain seed-zone moisture.

Two major changes in management have occurred since 1931. The initial experiment utilized a medium-tall soft white winter wheat variety (cv. Rex M-1) and a low rate of N application (34 kg ha$^{-1}$) for 36 yr. The experiment was revised in 1967 to change the wheat type from a medium-tall to a semidwarf variety, and to replace disking comparisons with expanded N application (from one [34 kg ha$^{-1}$] to two [45 and 90 kg ha$^{-1}$] N rates, duplicate plots of each). This change accommodated the adoption of semidwarf wheat with higher yield potential. Wheat cultivars were Nugaines from 1967 to 1973, Hyslop from 1974 to 1978, and Stephens from 1979 to present. A second change was instituted in 1979. Stubble management on one set of the 45 and 90 kg ha$^{-1}$ N treatments was changed from nonburn to spring burn. This provided a nested factorial of three N rates and two burn conditions to determine if N fertilization would alter the effects of residue burning.

## Organic and Inorganic Fertilizer Additions

The two organic residue treatments consist of pea vines and barnyard manure applied just prior to plowing in the spring of the fallow year. These additions have remained essentially unchanged for the entire period, with one exception. Pea vine material from 1931 to 1950 included seed with the pods and vines; additions since then have not included the seed. Removal of the seed significantly lowered the annual N input, with only minor influence on C input. Partially dried strawy manure for the manure treatment has been obtained from the same source, a nearby ranch feedlot, since 1931. The DM, C, and N content of pea vine and manure additions have been determined since 1976. Inorganic N fertilizer has been applied to specific treatments since 1931 as granular materials broadcast and incorporated with tillage. Nitrogen was applied as $NaNO_3$ from 1931 to 1935, as $Ca(NO_3)_2$ from 1936 to 1943, as $(NH_4)_2SO_4$ from 1944 to 1966, and as $NH_4NO_3$ from 1967 to 1986. Nitrogen was applied in April of the fallow year from 1931 to 1943. Since then, it has been applied in October just prior to seeding of winter wheat.

## Stubble Burning

Wheat stubble is not disturbed between harvest and burning. The fall-burn treatment is burned in mid-September, and the spring-burn treatments in late March or early April. Burns are implemented by tilling a 1-m border around each plot, starting a backfire on the lee side, and then igniting the windward side. Burning is rapid, with temperatures reaching 300 °C in the canopy but rarely persisting for more than 3 min (Rasmussen et al., 1986). The soil surface is not disturbed between burning and plowing, about 195 and 5 d for fall and spring burn, respectively.

## Yield and Nitrogen Uptake

Grain yield has been determined every year by combine harvesting a portion of each plot. The yield sample area was 10.1 by 40.2 m from 1931 to 1950, two 3.6- by 40.2-m swaths from 1951 and 1966, one 2.1- by 40.2-m swath from 1967 to 1980, and two 2.1- by 20.1-m swaths since 1981. Yield is taken from the center portion of each plot.

Straw yield was not determined prior to 1977. Straw yield for the 1931 to 1966 period was estimated from yearly grain yield and average straw/grain ratios for Rex M-1 obtained in a 9-yr (1952–1960) variety–N response study (Oveson, 1966). Straw/grain ratios from 1967 to 1976 were obtained by adjusting yearly straw/grain ratios from nearby variety trials by relative treatment differences obtained during the 1977 to 1986 period. Straw yield for the 1977 to 1986 period was determined yearly by hand harvesting a 1.2-m$^2$ area from two to four locations in each plot, threshing in a stationary plot thresher to obtain the straw/grain ratio, and multiplying this ratio by the combine grain yield.

Grain N uptake between 1931 and 1967 was not determined each year, but was estimated from grain protein determinations made in seven of the 36 yr (1935–1937, 1939, 1952–1953, and 1956). Grain N uptake since 1967 has been determined

**Table 1. Straw management, organic residue addition, and inorganic N fertilizer applied to the long-term residue management experiment between 1932 and 1986.**

| Treatment† | | Straw management‡ | | | Organic residue addition | | | Inorganic N fertilizer | | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. | Designation | 1931–1966 | 1967–1978 | 1979–1986 | 1931–1966 | 1967–1978 | 1979–1986 | 1931–1966 | 1967–1978 | 1979–1986 |
| | | | | | kg ha$^{-1}$ crop$^{-1}$ | | | | | |
| 6 | fB-$N_0$ | fB | fB | fB | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | sB-$N_0$ | sB | sB | sB | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | nB-$N_0$ | nB | nB | nB | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | sB-$N_{45}$ | fD | nB | sB | 0 | 0 | 0 | 0 | 45 | 45 |
| 3 | sB-$N_{90}$ | sD | nB | sB | 0 | 0 | 0 | 0 | 90 | 90 |
| 4 | nB-$N_{45}$ | fD | nB | nB | 0 | 0 | 0 | 34 | 45 | 45 |
| 5 | nB-$N_{90}$ | sD | nB | nB | 0 | 0 | 0 | 34 | 90 | 90 |
| 9 | nB-PV | nB | nB | nB | 2.24 | 2.24 | 2.24 | 0 | 0 | 0 |
| 8 | nB-MN | nB | nB | nB | 22.40§ | 22.40 | 22.40 | 0 | 0 | 0 |

† $N_x$ = N fertilizer applied at rate of $x$ kg ha$^{-1}$; PV = pea vine; MN = manure; fB = fall burn, sB = spring burn, nB = not burned, fD = fall disked, sD = spring disked.
‡ Management prior to plowing in the spring.
§ No manure applied from 1943 to 1947.

from yield and grain protein measurements. Grain protein was determined by the Udy dye method (Udy, 1971) from 1967 to 1976, and by Kjeldahl N analysis thereafter, with a 5.70 protein/N conversion factor.

## Organic Carbon and Nitrogen in Soil

Soil samples to a depth of 60 cm were taken in 1931, 1941, and 1951 in 30-cm increments, and in 1964, 1976, and 1986 in 15-cm increments. Early soil sampling intensity is not known. Samples since 1964 consisted of 8 to 16 cores from the center of each plot. Total N in the 1931 to 1964 samples was determined by standard macro-Kjeldahl procedures existing at the time of analysis. Total N in 1976 was determined by the procedure of Bremner (1965) after Kjeldahl digestion as outlined by Nelson and Sommers (1972). Total N in 1986 was determined by automated analysis (Technicon Industrial Systems, 1976) after digestion as in 1976. Inorganic N constituted <1.0% of the total in 1935, 1976, and 1986; therefore, N will be referred to as organic N rather than total N.

Organic matter determinations were made on the 1931 and 1941 soil samples by the loss-on-ignition method of Rather (1917). Because this procedure had a high standard error relative to the last two dates, individual organic C values were computed by multiplying the mean OM/N ratio (22.6 and 19.7) by 0.58 to obtain a mean C/N value and further multiplying this ratio by individual N values. This reduced the standard error for C determination to levels similar to those for combustion analysis. No method of analysis was reported for the 1951 sampling date. The 1964 samples were apparently not analyzed for C, consequently values for this date were estimated from C content in 1951 and 1976 and relative change in N content between 1951 and 1964. Organic C in 1976 and 1986 was determined by dry combustion using a Leco (Leco Corp., St. Joseph, MI) C analyzer (Tabatabai and Bremner, 1970).

## Data Analysis

Yield and nutrient addition and removal data were separated into five major periods to align with soil C and N analyses. The periods were 1932 to 1941, 1942 to 1951, 1952 to 1965, 1967 to 1976, and 1977 to 1986, and comprise 10, 10, 14, 10, and 10 yr, respectively. The 1966 crop year data were removed from evaluations because a hard freeze on 18 April drastically reduced grain yield (all yields were <0.87 t ha$^{-1}$). This partitioning accommodates the two major procedural changes as well as the soil sampling dates, yet produces time lengths adequate to minimize errors in estimates of straw/grain ratio and N content of plant tissue. In calculating C and N content in the 0- to 30-cm zone, the 1931, 1941, 1951, 1964, 1976, and 1986 soil samples were assigned bulk densities of 1.17, 1.18, 1.19, 1.20, 1.21, and 1.22 g cm$^{-3}$, respectively. The bulk density of the top 30 cm of soil in 1931 was 1.17 ± 0.03 g cm$^{-3}$ (Pendleton Experiment Station, 1931, unpublished annual report). The average bulk density in 1990–1991 was 1.22 ± 0.04, with no significant differences due to treatment or replication (Table 2). Bulk density values for intervening years were assigned values proportional between these means.

Grain yield and all 1977 to 1986 data were analyzed with years as a split block in time (Steel and Torrie, 1980). Nutrient uptake and soil C and N data were analyzed as means for specific periods since individual year data was either not calculable or nonexistent.

## RESULTS AND DISCUSSION

Results do not appear biased because of the lack of randomization of treatments. Grain yield in 1929 was not affected by treatment, replication, or series (Table 2). Soil organic N in 1931 was not related to treatment location, although a replicate difference did exist. Soil in Replicate 1, located on a nearly level landscape, contained significantly more N than soil in Replicate 2, located on a sloping upland. The relationship between organic N (kg ha$^{-1}$) in 1931 and slope was fairly strong ($Y$ = 4046 − 126 (% slope), $r^2$ = 0.57***, $n$ = 39). Lower soil organic N with steeper slopes could be due to either lower inherent productivity prior to cultivation

**Table 2. Yield and soil organic N uniformity prior to initiation of the experiment, and soil slope, depth, and bulk density in the residue management experiment.**

| Treatment no. | Grain yield, 1929 | Organic N, 0–30 cm, 1931 | Slope, 1986 | Depth, 1977–1978 | Bulk density, 1990–1991 |
|---|---|---|---|---|---|
| | t ha$^{-1}$ | t ha$^{-1}$ | % | cm | g cm$^{-3}$ |
| 2 | 2.37 | 3.75 | 1.92 | 142 | 1.19 |
| 3 | 2.33 | 3.77 | 2.02 | 142 | 1.21 |
| 4 | 2.34 | 3.81 | 2.12 | 146 | 1.20 |
| 5 | 2.27 | 3.71 | 2.90 | 143 | 1.23 |
| 6 | 2.34 | 3.71 | 2.60 | 149 | 1.23 |
| 7 | 2.41 | 3.66 | 2.97 | 161 | 1.23 |
| 8 | 2.38 | 3.73 | 2.75 | 162 | 1.20 |
| 9 | 2.31 | 3.81 | 2.20 | 165 | 1.22 |
| 0 | 2.38 | 3.83 | 1.80 | 174 | 1.27 |
| Rep. 1 | 2.34 | 3.92 | 1.48 | 119 | 1.21 |
| Rep. 2 | 2.36 | 3.58 | 3.26 | 188 | 1.23 |
| Series 1400 | 2.36 | 3.75 | 2.51 | 148 | 1.23 |
| Series 1500 | 2.34 | 3.75 | 2.22 | 158 | 1.21 |
| Avg. | 2.35 | 3.75 | 2.36 | 154 | 1.22 |
| | | Statistical Analysis | | | |
| Treatment location | NS | NS | NS | ** | NS |
| Replication | NS | ** | ** | ** | NS |
| Error $a$ mean square | 0.0119 | 0.0468 | 2.323 | 1585.1 | 0.0030 |
| Series | NS | NS | NS | ‡ | * |
| Series × treatment | NS | NS | NS | NS | NS |
| Error $b$ mean square | 0.0116 | 0.0052 | 0.320 | 798.5 | 0.0012 |

‡, *, and ** indicate statistical significance at $P$ = 0.10, 0.05, and 0.01, respectively. NS = not significant at $P$ = 0.10.

**Table 3. Estimated C and N additions for five time periods between 1932 and 1986.**

| Treatment† | 1932–1941 | 1942–1951 | 1952–1966 | 1967–1976 | 1977–1986 |
|---|---|---|---|---|---|
| | Organic C addition, t ha$^{-1}$ crop$^{-1}$ | | | | |
| fB-$N_0$‡ | 0.63 | 0.63 | 0.49 | 0.70 | 0.71 |
| sB-$N_0$§ | 0.87 | 0.90 | 0.73 | 0.97 | 1.00 |
| nB-$N_0$ | 1.82 | 1.93 | 1.60 | 2.10 | 2.19 |
| sB-$N_{45}$ | 1.79 | 1.76 | 1.50 | 1.13 | 1.33 |
| sB-$N_{90}$ | 1.81 | 1.85 | 1.48 | 1.19 | 1.44 |
| nB-$N_{45}$ | 2.18 | 2.34 | 2.12 | 2.53 | 2.95 |
| nB-$N_{90}$ | 2.13 | 2.32 | 2.07 | 2.68 | 3.13 |
| nB-PV | 3.06 | 3.27 | 2.97 | 2.91 | 3.04 |
| nB-MN | 4.17 | 3.78 | 4.30 | 4.80 | 4.80 |
| Avg | 2.05 | 1.92 | 1.92 | 2.11 | 2.29 |
| | N addition, kg ha$^{-1}$ crop$^{-1}$ | | | | |
| fB-$N_0$ | 0 | 0 | 0 | 0 | 0 |
| sB-$N_0$ | 0 | 0 | 0 | 0 | 0 |
| nB-$N_0$ | 0 | 0 | 0 | 0 | 0 |
| sB-$N_{45}$ | 0 | 0 | 0 | 45 | 45 |
| sB-$N_{90}$ | 0 | 0 | 0 | 90 | 90 |
| nB-$N_{45}$ | 34 | 34 | 34 | 45 | 45 |
| nB-$N_{90}$ | 34 | 34 | 34 | 90 | 90 |
| nB-PV | 46 | 46 | 34 | 34 | 34 |
| nB-MN | 111 | 56 | 111 | 111 | 111 |

† $N_x$ = N fertilizer applied at rate of $x$ kg ha$^{-1}$; PV = pea vine; MN = manure; fB = fall burn, sB = spring burn, nB = not burned, fD = fall disked, sD = spring disked.
‡ Rates shown assume 67% of straw C volatilized during burning.
§ Rates shown assume 55% of straw C volatilized during burning.

or the result of greater erosion in the 50-yr period of cultivation between 1881 and 1931. While there is a large difference in soil depth between replicates (119 vs. 188 cm), differences between treatments is much less (142–174 cm). Treatment differences result primarily because soil of Replicate 2 continues to deepen with upslope progression. The soil of Replicate 1 is underlain by partially cemented fractured basalt while the soil of Replicate 2 is underlain by an older loess paleosol.

Estimated C additions for five time periods is shown in Table 3. Carbon inputs consist of straw production plus organic amendments. Carbon inputs for the fall- and spring-burn treatments were reduced 67 and 55%, respectively, based on average C volatilization losses measured in these treatments (P.E. Rasmussen, 1978–1981, unpublished data). Carbon input is related to grain yield, with a noticeable 10 to 30% increase after the change from medium-tall to semidwarf wheat in 1967.

Nitrogen additions consist of inorganic N fertilizer and organic amendments, with no allowance for N that may have accrued through atmospheric deposition or been lost through volatilization in the burn treatments. While C and N input in pea vines and manure varies with year, average means based on 10 yr of data are probably fairly accurate (Table 4). Variability in C input for pea vines is less than that for manure, but the reverse is true for N input. Because each of these materials has been obtained from a single source over 55 yr, there is little reason to suspect that, except for the pea vine composition change in 1950, C and N contributions have changed substantially with time. Estimation of straw yield and grain and straw N uptake prior to 1976 were obtained from a limited data set. Based on recent yearly variability, it appears that estimates are reasonably accurate when >6 yr of data are available (Table 5). In this study, estimates of straw/grain ratio prior to 1976 were based on 9 yr of data, and estimates of N uptake on 7 yr of data. In addition, the minimum time period of consolidated data was at least 10 yr.

## Grain and Straw Yield

The manure treatment has consistently produced the highest grain and straw yield since the inception of the experiment (Table 6). Grain yield for the manure treatment increased from 2.96 t ha$^{-1}$ in the 1930s to 4.87 t ha$^{-1}$ in the 1980s, with most of the increase coming after adoption of semidwarf varieties in 1967. The zero-N treatments originally yielded about 80% of the manure treatment, but this percentage has fallen progressively with time; they currently yield 43 to 57% less than the manure treatment yield. Pea vine treatment yields are very close to those expected from the level of N input, with, in the long term, little evidence of reduced availability as experienced in Australia (Ladd et al., 1983). The 90 kg N ha$^{-1}$ treatment currently yields ≈5% less than the manure treatment, but a direct comparison is not possible since manure supplies more N (111 vs. 90 kg ha$^{-1}$) and other nutrients.

Both fall and spring burning originally tended to increase grain yield, but the effect was short-lived. By the 1950s, yields were similar to those of the comparable

**Table 4. Average input of dry matter (DM), C, N, P, and S from manure and pea vine additions, 1976 to 1987.**

| Crop year | Barnyard manure† DM | C | N | P | S | Dry pea vines‡ DM | C | N | P | S |
|---|---|---|---|---|---|---|---|---|---|---|
| | g kg$^{-1}$ | kg ha$^{-1}$ | | | | g kg$^{-1}$ | kg ha$^{-1}$ | | | |
| 1976 | 540 | 1343 | 110 | 42 | 33 | 884 | 818 | 28 | 3 | 2 |
| 1977 | 568 | 1171 | 85 | 31 | 25 | 871 | 784 | 31 | 3 | 2 |
| 1979 | 367 | 1554 | 104 | 22 | 21 | 897 | 846 | 37 | 4 | 3 |
| 1980 | 434 | 1692 | 108 | 23 | 22 | 890 | 818 | 35 | 3 | 3 |
| 1981 | 437 | 1928 | 125 | 25 | 26 | 878 | 828 | 25 | 2 | 2 |
| 1982 | 544 | 1389 | 107 | 31 | 29 | 937 | 848 | 41 | 4 | 3 |
| 1983 | 480 | 1484 | 118 | 28 | 24 | 910 | 808 | 39 | 4 | 3 |
| 1984 | 817 | 714 | 77 | 39 | 42 | 911 | 759 | 34 | 4 | 3 |
| 1985 | 470 | 1116 | 104 | 30 | 24 | 897 | 734 | 35 | 3 | 3 |
| 1986 | 468 | 1761 | 139 | 32 | 28 | 897 | 681 | 35 | 3 | 2 |
| 1987 | 468 | 2155 | 145 | 35 | 21 | 897 | 797 | 31 | 3 | 2 |
| Avg. | 508 | 1482 | 111 | 31 | 27 | 897 | 793 | 33.7 | 3.3 | 2.5 |
| CV, % | 23 | 27 | 18 | 20 | 23 | 2 | 6 | 14 | 20 | 21 |

† 22.40 t ha$^{-1}$ (fresh wt.) crop$^{-1}$.
‡ 2.24 t ha$^{-1}$ (fresh wt.) crop$^{-1}$.

**Table 5. Yearly grain yield, straw/grain ratio, grain N concentration, and straw N concentration, 1977 to 1986. Data are treatment means, statistical analysis is mean squares.**

| Crop year | Grain yield† | Straw/grain ratio | Grain N | Straw N |
|---|---|---|---|---|
| | t ha$^{-1}$ | | g kg$^{-1}$ | |
| 1977 | 3.56 | 1.83 | 15.94 | 1.98 |
| 1978 | 3.67 | 2.05 | 12.73 | 2.05 |
| 1979 | 3.99 | 1.53 | 13.94 | 1.97 |
| 1980 | 4.87 | 1.85 | 14.34 | 2.14 |
| 1981 | 5.06 | 2.07 | 14.03 | 2.18 |
| 1982 | 3.75 | 1.63 | 14.38 | 1.94 |
| 1983 | 4.54 | 2.12 | 12.38 | 1.99 |
| 1984 | 4.34 | 2.17 | 13.26 | 2.09 |
| 1985 | 3.68 | 1.22 | 16.38 | 2.81 |
| 1986 | 3.87 | 1.37 | 16.59 | 2.38 |
| Avg. | 4.13 | 1.78 | 14.39 | 2.15 |
| | | Statistical analysis | | |
| Source (df) | | | | |
| Replication (1) | 0.446* | 0.467** | 0.578 | 0.800* |
| Treatments (8) | 18.859** | 0.391** | 116.625** | 4.155** |
| Error *a* (8) | 0.065 | 0.019 | 0.243 | 0.100 |
| Years (9) | 5.228** | 1.976** | 39.288** | 1.262** |
| Error *b* (10) | 0.392 | 0.021 | 1.635 | 0.102 |
| Year × treatment (72) | 0.366** | 0.045** | 2.431** | 0.146** |
| Error *c* (72) | 0.090 | 0.019 | 0.674 | 0.046 |

*, ** Significant at $P = 0.05$ and 0.01, respectively.
† Grain yield on field-weight basis; average moisture content = 90 g kg$^{-1}$.

nonburn treatment. In recent years, the fall-burn treatment has yielded less than the unburned control. Spring burning has thus far not proven detrimental to grain production, although a trend toward lower yield may be appearing in the zero-N treatment. The first 8 yr of spring burning coupled with N fertilization of the crop have produced few conclusive yield changes. These burn treatments were initiated in 1979 on plots with no history of N fertilization prior to 1967. Grain yield tended to be less on these plots from 1967 to 1976 than on comparable plots that received N fertilizer prior to 1967. Thus, we cannot say with certainty that lower yield trends during the 1977 to 1986 period were due to burning; they could be a carryover of past N fertilization differences. There was a significant increase in grain yield after 1967 with the change from a medium-tall to a semidwarf variety. The zero-N treatments exhibited about a 40% increase in yield with little change in avail-

**Table 6. Average grain and straw yields for five time periods between 1932 and 1986.**

| Treatment designation† | 1932–1941 | 1942–1951 | 1952–1966 | 1967–1976 | 1977–1986 |
|---|---|---|---|---|---|
| | | | Grain yield‡, t ha$^{-1}$ crop$^{-1}$ | | |
| fB-$N_0$ | 2.41 de§ | 2.44 cd | 1.92 cd | 2.74 d | 2.58 f |
| sB-$N_0$ | 2.48 cd | 2.56 c | 2.08 c | 2.83 d | 2.67 ef |
| nB-$N_0$ | 2.35 d-f | 2.48 cd | 2.01 cd | 2.85 d | 2.78 e |
| sB-$N_{45}$ | 2.23 f | 2.27 e | 1.92 cd | 3.61 c | 3.92 d |
| sB-$N_{90}$ | 2.31 ef | 2.38 de | 1.91 d | 3.96 bc | 4.50 b |
| nB-$N_{45}$ | 2.66 b | 2.86 b | 2.58 b | 3.75 c | 4.10 c |
| nB-$N_{90}$ | 2.59 bc | 2.83 b | 2.53 b | 4.17 ab | 4.64 b |
| nB-PV | 2.73 b | 2.98 b | 2.67 b | 3.69 c | 3.81 d |
| nB-MN | 2.96 a | 3.33 a | 3.09 a | 4.44 a | 4.87 a |
| Avg. | 2.52 | 2.68 | 2.30 | 3.56 | 3.76 |
| | | | Straw yield, t ha$^{-1}$ crop$^{-1}$ | | |
| fB-$N_0$ | 4.45 | 4.51 | 3.55 | 5.05 | 5.11 |
| sB-$N_0$ | 4.61 | 4.74 | 3.85 | 5.14 | 5.29 |
| nB-$N_0$ | 4.33 | 4.60 | 3.80 | 5.00 | 5.21 |
| sB-$N_{45}$ | 4.26 | 4.20 | 3.56 | 5.96 | 7.04 |
| sB-$N_{90}$ | 4.30 | 4.41 | 3.53 | 6.32 | 7.59 |
| nB-$N_{45}$ | 5.18 | 5.57 | 5.04 | 6.03 | 7.03 |
| nB-$N_{90}$ | 5.06 | 5.51 | 4.93 | 6.37 | 7.46 |
| nB-PV | 5.39 | 5.91 | 5.19 | 6.21 | 6.95 |
| nB-MN | 6.40 | 7.22 | 6.71 | 6.78 | 7.94 |
| Avg. | 4.89 | 5.18 | 4.47 | 5.87 | 6.65 |
| LSD (0.05) | 0.16 | 0.09 | 0.08 | 0.24 | 0.14 |

† $N_x$ = N fertilizer applied at rate of *x* kg ha$^{-1}$; PV = pea vine; MN = manure; fB = fall burn, sB = spring burn, nB = not burned, fD = fall disked, sD = spring disked.
‡ Yield on dry-weight basis.
§ Values in each column followed by the same letter are not significantly different at $P = 0.05$.

Table 7. Average grain and straw N uptake for five time periods between 1932 and 1986.

| Treatment designation† | 1932-1941 | 1942-1951 | 1952-1965 | 1967-1976 | 1977-1986 |
|---|---|---|---|---|---|
| | | | Grain N uptake, kg ha$^{-1}$ crop$^{-1}$ | | |
| fB-$N_0$ | 37.4 | 37.9 | 29.9 | 32.2 | 29.5 |
| sB-$N_0$ | 38.7 | 39.8 | 32.3 | 32.2 | 31.6 |
| nB-$N_0$ | 36.3 | 38.5 | 31.9 | 34.2 | 33.9 |
| sB-$N_{45}$ | 34.4 | 35.1 | 29.7 | 46.2 | 55.8 |
| sB-$N_{90}$ | 36.1 | 37.1 | 29.9 | 61.8 | 78.1 |
| nB-$N_{45}$ | 44.9 | 48.3 | 43.7 | 54.4 | 60.4 |
| nB-$N_{90}$ | 44.2 | 48.2 | 43.1 | 69.4 | 81.3 |
| nB-PV | 45.6 | 50.0 | 44.6 | 50.3 | 52.2 |
| nB-MN | 64.5 | 64.7 | 67.6 | 78.9 | 77.3 |
| Avg. | 42.5 | 44.4 | 39.2 | 51.0 | 55.6 |
| LSD (0.05) | 2.73 | 2.42 | 3.00 | 3.21 | 2.66 |
| | | | Straw N uptake, kg ha$^{-1}$ crop$^{-1}$ | | |
| fB-$N_0$ | 8.9 | 9.0 | 7.1 | 9.3 | 8.8 |
| sB-$N_0$ | 9.2 | 9.4 | 7.7 | 9.5 | 8.8 |
| nB-$N_0$ | 8.6 | 9.2 | 7.6 | 9.5 | 9.4 |
| sB-$N_{45}$ | 8.5 | 8.4 | 7.1 | 12.8 | 13.9 |
| sB-$N_{90}$ | 8.6 | 8.8 | 7.0 | 14.5 | 21.4 |
| nB-$N_{45}$ | 12.4 | 13.4 | 12.1 | 13.3 | 14.3 |
| nB-$N_{90}$ | 12.1 | 13.2 | 11.8 | 15.3 | 19.4 |
| nB-PV | 13.5 | 14.8 | 11.9 | 13.7 | 13.8 |
| nB-MN | 21.7 | 20.9 | 22.8 | 16.5 | 20.7 |
| Avg. | 11.5 | 11.9 | 10.6 | 12.7 | 14.5 |
| LSD (0.05) | 0.70 | 0.49 | 0.44 | 1.79 | 1.85 |

† $N_x$ = N fertilizer applied at rate of $x$ kg ha$^{-1}$; PV = pea vine; MN = manure; fB = fall burn, sB = spring burn, nB = not burned, fD = fall disked, sD = spring disked.

able N supply. This was possible because of both higher efficiency of N translocation from vegetative to reproductive tissue and lower N content in the grain.

### Grain and Straw Nitrogen Uptake

Grain and straw N uptake patterns (Table 7) tend to resemble those of yield quite closely. Highest N uptake occurred in the manure treatment and lowest in the zero-N treatments. Nitrogen uptake with fall burning of stubble tended to be equal or higher than that with no burning in the early years (1932–1951), but lower in recent years (1977–1986). Spring burning has not affected N uptake differently from the corresponding nonburn treatments. Nitrogen uptake in grain increased and N uptake in straw decreased with the change from medium-tall to semidwarf wheat.

### Soil Carbon and Nitrogen

With the exception of the manure treatment, soil organic C and N declined with time for all treatments (Table 8). Previous declines have been linear and independent of the initial C and N levels (Rasmussen et al., 1980). This trend continues through 1986 and suggests that levels will not plateau in the near future. Error variability for N determination has been remarkably similar for each of the six sample times. Carbon analysis for recent sampling periods have coefficients of variation similar to those for N. Burn treatments have not lost soil C in proportion to the estimated C volatilized during the burn. It is likely that C remaining after the burn is less active biologically and has a longer turnover time. Shindo (1991) reported that charred residues evolved much less $CO_2$ than noncharred residue when incubated with soil. Lower microbial biomass with burning (Collins et al., 1992) tends to support this contention. Fall burning appears to have a greater detrimental effect than spring burning, which could be the result of (i) greater soil erosion due to the lack of winter cover, (ii) greater C volatilization than estimated, or (iii) substantial overwinter loss of C due to wind and water action. Personal observations suggest the latter is the most likely explanation for greater C loss. Whether stubble burning in the presence of N fertilization will eventually decrease yield and SOM cannot yet be determined. Yield has not been adversely affected in the first 8 yr since the treatments were established. But, historically, it has taken more than 20 yr of repeated burning to produce measurable change in soil C and N (Biederbeck et al., 1980).

Treatment effects on soil C and N have been confined to essentially the top 30 cm of soil. There has been, however, a slow steady decline in C and N in the 30- to 60-cm zone with time that is not related to residue management. This decline may be the result of either (i) continuing truncation of the soil profile through soil erosion, which results in progressively deeper soil sampling with time, or (ii) continued oxidation of residual SOM, which exceeds the inputs of C from wheat roots and soluble-C movement from the zone above. While quantitative resolution of either factor is not possible, the latter factor is more plausible. Soil erosion, although it has not been measured, is estimated to be well below acceptable soil-loss limits. An erosion rate of 18 t ha$^{-1}$ yr$^{-1}$ would be required to account for the change in C and N through truncation of the soil profile with time. This amount is well above any losses estimated by visual observation or calculated by the RUSLE soil loss equation (0.4 to 3.4 t ha$^{-1}$ yr$^{-1}$, depending on plot treatment and slope). The C change in the 30- to 60-cm zone between 1976 and 1986 appears excessive, and is probably the result of our sampling procedures. Soil samples from the 30- to 60-cm zone were not taken in 1986, so a

**Table 8. Soil organic C and N for two depths at six sample dates between 1931 and 1986.**

| | 0–30 cm | | | | | | 30–60 cm | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment† | 1931 | 1941 | 1951 | 1964 | 1976 | 1986 | 1931 | 1941 | 1951 | 1964 | 1976 | 1986 |
| | | | | | | Organic C, t ha$^{-1}$ | | | | | | |
| fB-N$_0$ | 48.67 | 46.44 | 42.15 | 42.45 | 40.01 | 37.01 | 33.51 | 33.97 | 32.13 | 29.71 | 28.84 | 23.93 |
| sB-N$_0$ | 48.12 | 45.74 | 42.69 | 43.18 | 41.42 | 38.96 | 34.46 | 33.71 | 32.35 | 30.51 | 29.55 | 24.02 |
| nB-N$_0$ | 50.21 | 49.23 | 44.93 | 44.00 | 42.47 | 39.65 | 36.67 | 35.68 | 33.40 | 30.40 | 30.55 | 25.12 |
| sB-N$_{45}$ | 49.24 | 48.08 | 43.78 | 42.72 | 41.31 | 38.74 | 34.87 | 33.10 | 31.85 | 30.17 | 29.17 | 24.50 |
| sB-N$_{90}$ | 49.41 | 47.08 | 42.80 | 41.81 | 41.52 | 39.95 | 35.60 | 33.08 | 31.74 | 29.94 | 30.12 | 24.74 |
| nB-N$_{45}$ | 49.90 | 48.36 | 45.96 | 44.91 | 44.24 | 41.36 | 36.12 | 34.17 | 32.65 | 30.63 | 32.27 | 26.16 |
| nB-N$_{90}$ | 48.75 | 48.59 | 46.18 | 44.09 | 43.65 | 41.90 | 35.49 | 32.92 | 31.93 | 30.63 | 31.39 | 26.26 |
| nB-PV | 49.92 | 50.48 | 50.63 | 47.01 | 46.15 | 44.49 | 36.11 | 33.93 | 32.66 | 30.97 | 30.63 | 26.07 |
| nB-MN | 48.57 | 50.88 | 53.07 | 49.39 | 50.80 | 50.18 | 33.77 | 32.26 | 31.28 | 29.94 | 29.96 | 24.21 |
| Avg. | 49.20 | 48.32 | 45.80 | 44.42 | 43.49 | 41.36 | 35.18 | 33.65 | 32.22 | 30.32 | 30.26 | 25.00 |
| LSD (0.05) | NS | NS | 5.10 | 3.69 | 3.33 | 4.76 | NS | NS | NS | NS | NS | NS |
| CV | – | – | – | – | 4.7 | 7.1 | – | – | – | – | 8.4 | 6.9 |
| | | | | | | Organic N, t ha$^{-1}$ | | | | | | |
| fB-N$_0$ | 3.71 | 3.56 | 3.28 | 3.16 | 3.02 | 2.85 | 2.88 | 2.97 | 2.86 | 2.71 | 2.71 | 2.52 |
| sB-N$_0$ | 3.66 | 3.51 | 3.32 | 3.33 | 3.20 | 3.06 | 2.96 | 2.95 | 2.88 | 2.79 | 2.80 | 2.71 |
| nB-N$_0$ | 3.83 | 3.78 | 3.50 | 3.43 | 3.29 | 3.19 | 3.15 | 3.12 | 2.97 | 2.77 | 2.89 | 2.65 |
| sB-N$_{45}$ | 3.75 | 3.69 | 3.41 | 3.41 | 3.27 | 3.20 | 2.99 | 2.89 | 2.83 | 2.75 | 2.77 | 2.61 |
| sB-N$_{90}$ | 3.77 | 3.61 | 3.33 | 3.35 | 3.33 | 3.30 | 3.05 | 2.89 | 2.82 | 2.73 | 2.81 | 2.55 |
| nB-N$_{45}$ | 3.81 | 3.71 | 3.58 | 3.62 | 3.48 | 3.46 | 3.10 | 2.98 | 2.90 | 2.79 | 2.90 | 2.65 |
| nB-N$_{90}$ | 3.71 | 3.72 | 3.59 | 3.46 | 3.41 | 3.35 | 3.04 | 2.88 | 2.84 | 2.79 | 2.84 | 2.64 |
| nB-PV | 3.81 | 3.87 | 3.94 | 3.77 | 3.66 | 3.58 | 3.10 | 2.96 | 2.91 | 2.83 | 2.85 | 2.71 |
| nB-MN | 3.73 | 3.90 | 4.13 | 4.08 | 4.18 | 4.20 | 2.90 | 2.82 | 2.78 | 2.73 | 2.86 | 2.60 |
| Avg. | 3.75 | 3.70 | 3.56 | 3.51 | 3.42 | 3.35 | 3.02 | 2.94 | 2.87 | 2.77 | 2.82 | 2.63 |
| LSD (0.05) | NS | NS | 0.40 | 0.29 | 0.32 | 0.26 | NS | NS | NS | NS | NS | NS |
| CV | 4.8 | 6.5 | 6.8 | 5.1 | 5.7 | 4.7 | 3.8 | 7.5 | 6.8 | 6.7 | 8.1 | 7.0 |

† $N_x$ = N fertilizer applied at rate of $x$ kg ha$^{-1}$; PV = pea vine; MN = manure; fB = fall burn, sB = spring burn, nB = not burned, fD = fall disked, sD = spring disked.

two-core composite taken in 1987–1988 was substituted. Carbon values for these samples appear lower than they should be. In any event, statistical analysis indicates that treatments continue to have no effect on C in the 30- to 60-cm zone.

## SUMMARY

Several general trends emerge from this long-term experiment:

1. Soil organic matter is continuing to decline with time in a wheat–fallow cropping system except where generous amounts of manure have been applied. The rate of change is directly related to the level of C input from crop residue and added amendments. Most of the loss of C with time is attributed to biological oxidation during the fallow year since soil erosion is estimated to be quite low. Nitrogen affects soil C and N content primarily through its effect on residue production.
2. Changes in soil organic C and N during a 56-yr period are nearly linear with time. There is little evidence that stationary levels will be reached in the near future, even though this soil has been cultivated for >100 yr.
3. Grain yields with time are affected by change in the organic N content of soil. Introduction of semidwarf wheats increased yield substantially, but appears not to have affected the relationship between yield and soil organic N.
4. It takes 20 to 30 yr to define any adverse effects of straw burning on soil organic matter content and crop yield.
5. Models developed to assess C and N balances in the environment need to consider soil C and N changes to at least 60 cm in cultivated grassland soils.

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