Carbon Balance of the Breton Classical Plots over Half a Century

R. C. Izaurralde,* W. B. McGill, J. A. Robertson, N. G. Juma, and J. J. Thurston

ABSTRACT

We related C input and management to soil organic C (SOC) dynamics over 51 yr (1939–1990). We used two rotations from the Breton Classical Plots at Breton, Canada, on a Typic Cryoboralf: (i) wheat (*Triticum aestivum* L.)–fallow (WF) and (ii) wheat–oat (*Avena sativa* L.)–barley (*Hordeum vulgare* L.)–hay (primarily alfalfa, *Medicago sativa* L.)–hay (WOBHH), in factorial combination with three fertility levels: no added fertilizer [Nil], N-P-K-S fertilizers [F], and farmyard manure [M]. Net aboveground C productivity (NAGCP, kg ha^{-1} yr^{-1}) averaged 576 in WF–Nil and 1078 in WF–F and SOC decreased in both, but NAGCP averaged 1208 in WF–M, where SOC increased. A NAGCP of 853 in WOBHH–Nil maintained SOC, while both 1831 in WOBHH–F and 1714 in WOBHH–M increased SOC. After 51 yr, WOBHH–M had 25 Mg ha^{-1} more SOC than did WF–Nil. Because of contrasting decay rates and root/shoot ratios, C input needed to maintain the original SOC was twofold greater in WF than in WOBHH, which required a fourfold increase in NAGCP to attain these inputs. A three-compartment model fitted to the data suggested loss of C from the active compartments and gain of C by the passive compartments. Inputs of C that maintained SOC over 51 yr would lead to a steady state of 2.9 times more C than in 1939, and 26% higher than the native SOC content. Return of 30% of the crop C as manure would sustain SOC sequestration in all WOBHH rotations with NAGCP > 400 kg ha^{-1} yr^{-1} and in those WF rotations with NAGCP > 1000 kg ha^{-1} yr^{-1}.

The global loss of SOC as CO_2 to the atmosphere has been historically important. Cole et al. (1996) estimated the loss of SOC at 55 Pg, including 11 Pg from wetland soils. However, there is increasing evidence that loss of SOC can be reversed when soil management (Janzen et al., 1998) or land use (Poulton, 1996) is changed to increase input of C or reduce soil C loss.

Long-term field studies provide the foundation to understand and the record to test models of SOC dynamics (Smith et al., 1997; Lal et al., 1998a, 1998b; Paul et al., 1997). In Canada, sites remaining from continuous field experiments aid understanding of SOC dynamics in soils and climates characteristic of the northern prairie region (Campbell et al., 1990). The Breton Plots are one such site. They were started in 1930 near Breton, Alberta, to find "a system of farming suitable for the wooded soil belt" (Wyatt et al., 1930). The Breton Plots research site has had several long-term crop rotation and tillage experiments (Wani et al., 1994), with the Breton Classical Plots, started in 1930, holding the longest agronomic and soil records for this soil type in North America.

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There is a need to improve quantitative understanding of C inputs to and retention by soil under diverse combinations of soil, climate, and management. This understanding is required both for management practices that improve soil quality and for auditing soil C sequestration. Documentation of SOC changes in long-term field experiments has become an essential task to improve quantitative understanding of the C cycle. The objectives of this study were (i) to document the changes in SOC during a 51-yr (1939–1990) period on the Breton Classical Plots by using historical records of yield, management, and soil C measurements; (ii) to examine the influence of C inputs and manure on SOC content over diverse management; and (iii) to test the utility of a simple model to describe SOC content and its distribution among kinetic soil compartments of increasing stability. For a test of a complex ecosystem model using these data, see Grant et al. (2000).

MATERIALS AND METHODS

Location and History

The Breton Classical Plots are located near Breton, AB, Canada, at latitude 53° 06′ N, longitude 114° 26′ W, and altitude 854 m above sea level. The long-term annual precipitation at the experimental site is 547 mm, while the annual air temperature averages 2.1°C. The soil is an Orthic Gray Luvisol (Typic Cryoboralf) developed on glacial till parent material under boreal forest vegetation. Cryoboralfs occur on ≈15% of the cultivated area in Alberta, have low fertility status, and may have excess acidity in both their surface and subsurface (Robertson and McGill, 1983).

The Breton Classical Plots were initiated in 1930 on an area that was cleared from its native forest vegetation about 1919. There is no record of the method of clearing, but based on methods used at the time, we believe that the area was cleared by hand and seeded to pasture crops.

Plot Topographic Maps and Treatments

An original map of the Breton Classical Plots was digitized and the data transferred to a file in GRASS format (United States Army Corps of Engineers, 1993) (Fig. 1A). Topographic data were transferred to GRASS format and used to generate a contour-line map (Fig. 1B) and a slope-class map (Fig. 1C).

Sixty-six plots accommodate two nonreplicated crop rotations (Series A–F) in factorial combination with nine soil fertility treatments (Fig. 1A) (McGill et al., 1986; Juma et al., 1997; and Wani et al., 1994). Plots on Series A through D and F are 269 m^2, while those on Series E are one-half this area. The first rotation (WOBHH) is a 5-yr cycle (Series A, B, C, D, and F) of spring wheat, oat, barley underseeded to alfalfa–brome (*Bromus inermis* Leyss.) mixture followed by 2 yr of the hay mixture (Izaurralde et al., 1996). In the second rotation (WF, Series E), a spring wheat crop is grown on

Abbreviations: F, N-P-K-S fertilizers treatment; M, farmyard manure treatment; NAGCP, net aboveground C productivity; Nil, no fertilizer treatment; WF, wheat–fallow; WOBHH, wheat–oat–barley–hay–hay.

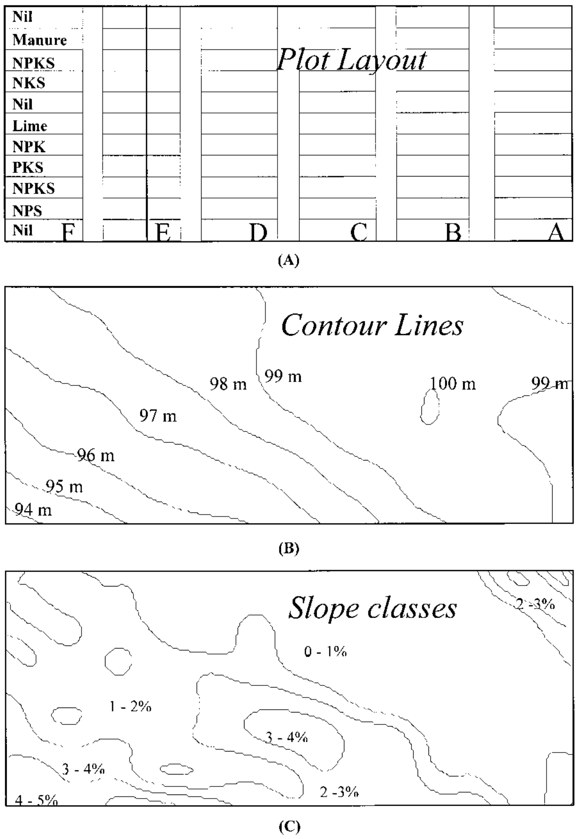

Fig. 1. (A) Plot layout, (B) contour lines spaced at 1-m vertical interval, and (C) slope classes of the Breton Classical Plots.

summer fallow land every second year. Each rotation phase is divided into 11 plots entailing nine fertility treatments, including three controls (or check treatments), various nutrient combinations (N, P, K, and S), and amendments (lime and composted farmyard manure). We used three fertility treatments: (i) Nil (Plot 1); (ii) commercial fertilizers (F) containing N, P, K, and S (Plot 3); and (iii) cattle manure (M) (Plot 2). Detailed information on rates of N application is in Izaurralde et al. (1996); a soil map, plot layout, and crop by year grid are in Wani et al. (1994). Fertilizer N is added to the cereal crops within each rotation. Manure rates are calculated to add the same amount of N as applied with commercial fertilizers. Prior to 1980, farmyard manure was added in the fall once every 5 yr, while plowing down the alfalfa–brome mixture in the WOBHH rotation, and across both fallow and cropped phases of the WF rotation. After 1980, the manure application in the WOBHH rotation was split equally into two and applied in fall after harvesting the oat crop and the alfalfa–brome mixture, while in the WF rotation it was applied after harvesting the wheat crop. From the start of the experiment, all grain, straw (cut by binder), and forage cuts were removed from the plots at harvest.

Plant Yields and Calculations of Additions or Removals of Carbon

Data were obtained from logbooks, reports (Bentley et al., 1971; Wyatt, 1945), CanSIS (1999), and Izaurralde et al. (1996). We extracted the following variables: year (1939–1994); series (A–F) (Fig. 1); fertility treatment (Nil: Plots 1 and 5, M: Plot 2, and F: Plot 3) (Fig. 1); crop (spring wheat [SWHT], oat [OATS], barley [BARL]; grass–legume mixture [HAY_1 and HAY_2]), grain yield (GRNYLD, kg ha^{-1}), and straw yield (STRYLD, kg ha^{-1}). Total aboveground dry matter (TADM) for the grass–legume mixture was

$$\mathrm{TADM} = \mathrm{HAY}_1 + \mathrm{HAY}_2 \ (\mathrm{kg\ ha^{-1}}) \quad [1]$$

and for the cereal crops

$$\mathrm{TADM} = \mathrm{GRNYLD} + \mathrm{STRYLD} \ (\mathrm{kg\ ha^{-1}}) \quad [1a]$$

When only grain yields were recorded, straw yields were estimated from grain yield data

$$\mathrm{STRYLD} = \mathrm{GRNYLD} \times \mathrm{SGR} \quad [2]$$

where SGR is the straw/grain ratio measured at this site (1.5 for spring wheat, 1.55 for oat, and 1.00 for barley).

Total aboveground C (TAC) was calculated as

$$\mathrm{TAC} = 0.44 \times \mathrm{TADM} \quad [3]$$

Root dry matter (RDM) estimates used literature values for root/shoot ratios (RSR) (Table 1). A RSR of 0.24 was used for nonfertilized cereal crops. A RSR of 0.12 was used for cereals receiving either commercial fertilizer or cattle manure. These estimates were obtained by Izaurralde et al. (1992) in field experiments on a Typic Cryoboralf that measured above- and belowground spring wheat productivity under a combination of amendments and erosion levels. The RSR for hay crops was 0.43 during the first year of growth and 0.53 during the second, regardless of fertility treatment. The RDM was calculated as

$$\mathrm{RDM} = \mathrm{RSR} \times \mathrm{TADM} \quad [4]$$

$$\mathrm{RC} = \mathrm{RDM} \times 0.44 \quad [5]$$

Based on root mass distribution with depth determined at sites adjacent to the Breton Classical Plots (Izaurralde et al., 1993), the amount of root C (RC) entering the cultivated layer in the first 0.15-m depth was estimated to be 80% of the C contained in RDM.

$$\mathrm{RC}_{15} = \mathrm{RC} \times 0.8 \quad [6]$$

An amount equivalent to 10% of TADM (Eq. [1]) was estimated to enter the soil because most plant biomass is removed from the plots as forage, grain, or straw, but a small amount is always left behind.

The amount of C entering the soil (CPLAN) or the top 15 cm of soil (CPLAN_{15}) was

$$\mathrm{CPLAN} = \mathrm{RC} + 0.1 \times \mathrm{TAC} \quad [7]$$

$$\mathrm{CPLAN}_{15} = \mathrm{RC}_{15} + 0.1 \times \mathrm{TAC} \quad [7a]$$

Before 1980, the only data recorded about the cattle manure was the application rate. Since 1980, manure was from well-decomposed piles, and samples were analyzed yearly for moisture, total N by colorimetry on a H_2SO_4–H_2O_2 digest (Technicon Industrial System, 1977), and total C by combustion on a LECO Carbon Determinator CR12 (LECO Corp., St. Joseph, MI).[1] On average, manure (FYM; kg ha^{-1} yr^{-1}) contained water at 0.7 ± 0.07 kg kg^{-1} (wet basis); with N = 0.024 ± 0.002 kg kg^{-1}, and C = 0.311 ± 0.06 kg kg^{-1} (dry basis). Using these concentrations C inputs via manure (CFYM; kg ha^{-1} yr^{-1}) were

$$\mathrm{CFYM} = \mathrm{FYM} \times (1 - 0.7) \times 0.311 \quad [8]$$

Total C input to the soil (CTOT; kg ha^{-1} yr^{-1}) or to the top 15 cm (CTOT_{15}; kg ha^{-1} yr^{-1}) was

[1] Trade names are mentioned here for the benefit of the reader and imply neither our endorsement by their inclusion, nor criticism of similar ones by their omission.

Table 1. Root/shoot ratios obtained on Gray Luvisolics for spring wheat, barley, and fescue.

Crop	Soil	Treatment	Root/shoot ratio	Reference
Spring wheat	Orthic Gray Luvisol	Control	0.24	Izaurralde et al. (1992)
		Manure	0.12	Izaurralde et al. (1992)
		Fertilizer	0.11	Izaurralde et al. (1992)
	Rego Black Chernozem		0.35	Campbell et al. (1991)
	Orthic Brown Chernozem		0.29	Campbell et al. (1977)
Barley	Orthic Gray Luvisol	Fertilizer	0.12	Izaurralde et al. (1993)
	Orthic Gray Luvisol	Fertilizer	0.13	Gu (1988)
Alfalfa	Orthic Gray Luvisol	1st year	0.43	estimated from Jones et al. (1991)
		2nd year	0.52	estimated from Jones et al. (1991)
	Pachic Udic Haploboroll		0.80	Curran et al. (1993)
	Orthic Gray Luvisol		1.10	Broersma (1991)

$$\mathrm{CTOT} = \mathrm{CPLAN} + \mathrm{CFYM} \qquad [9]$$

$$\mathrm{CTOT}_{15} = \mathrm{CPLAN}_{15} + \mathrm{CFYM} \qquad [9a]$$

Soil Sampling and Analyses

No soil sampling was conducted in 1930 when the two rotations, at that time a 4-yr rotation and continuous wheat, were initiated. The first archived Ap horizon soil samples are from 1936 (on Series C), the second from 1938 (Series E). Further samplings occurred in 1957 (Bentley et al., 1971) and in 1968 (Khan, 1969), but no soil samples were archived. Three complete sets of Ap soil samples were taken and archived in 1972, 1979, and 1990.

We retrieved all archived samples (Ap horizons) for the treatments studied (Nil, F, and M) and analyzed them for total C and N using a Carlo-Erba NA-1500 analyzer (Carlo Erba Inc., Milan, Italy). Total C and N concentrations were corrected for moisture content (0.03 kg kg^{-1}). All soil samples lacked carbonates (pH < 6); consequently, total C values, including any charcoal that may have been present represented the organic C fraction.

In fall 1979, samples were taken at 0 to 0.15 m from all series and plots of the Breton Classical Plots (Cannon et al., 1984), together with horizon depth (cm) and bulk density (D_b, Mg m^{-3}) in the plots and in an undisturbed area under poplar (*Populus* spp.) immediately north of the plots. Information from that sampling used in this study includes horizon description and depth, D_b, and concentrations of organic C and total N (Table 2).

Soil Organic Carbon Modeling

The parameters of a three-compartment model (C1, crop residues; C2, active; and C3, passive) were estimated from soil organic C (C_t) and input C (A_t) data using PROC NLIN in SAS (SAS Institute, 1985).

$$C_t = F_1C_t[\exp(-k_1t)] + (A_tR_1)/k_1[1 - \exp(-k_1t)] + F_2C_t[\exp(-k_2t)] + (A_tR_2)/k_2[1 - \exp(-k_2t)] + F_3C_t[\exp(-k_3t)] + (A_tR_3)/k_3[1 - \exp(-k_3t)] \qquad [10]$$

where C_t = total SOC (kg ha^{-1}) at time t (yr); $C_1 + C_2 + C_3 = C_t$; F_1, F_2, F_3 = fraction of original SOC in each of the kinetic compartments (C_1, C_2, and C_3), respectively, at time 0; $F_1 + F_2 + F_3 = 1$; k_1, k_2, k_3 = specific decay rate (yr^{-1}) for each of the kinetic compartments (C_1, C_2, and C_3), respectively; A_t = annual addition of C (kg ha^{-1} yr^{-1}); R_1, R_2, R_3 = fraction of the added C that is partitioned to each of compartments (C_1, C_2, and C_3), respectively; $R_1 + R_2 + R_3 = 1$.

The values for F and R each sum to one and those for C sum to C_t, so we defined Compartment 3 in terms of Compartments 1 and 2. Equation [10] then becomes

$$C_t = F_1C_t[\exp(-k_1t)] + (A_tR_1)/k_1[1 - \exp(-k_1t)] + F_2C_t[\exp(-k_2t)] + (A_tR_2)/k_2[1 - \exp(-k_2t)] + [1 - (F_1 + F_2)]C_t[\exp(-k_3t)] + \{A_t[1 - (R_1 + R_2)]\}/k_3[1 - \exp(-k_3t)] \qquad [11]$$

Equation [11] has seven parameters to be fitted, two less than Eq. [10].

The above model, herein referred to as the Cum model, describes the cumulative mass of SOC over time. Models should be fitted to data in which the values at time $t + 1$ are independent of the values at time t. To assure that such a condition is met, incremental data are often used (Jans-Hammermeister and McGill, 1997). Although the data used here meet the condition of independence, we fitted the model to incremental (Change) data as an additional check on the parameter values derived from the cumulative data. Consequently the equation for change in SOC since $t = 0$ yr (Eq. [12]) is referred to as the Change model and was used to estimate parameter values as above.

$$\text{Change in } Ct = F_1C_t[\exp(-k_1t) - 1] + (A_tR_1)/k_1[1 - \exp(-k_1t)] + F_2C_t[\exp(-k_2t) - 1] + (A_tR_2)/k_2[1 - \exp(-k_2t)] + [1 - (F_1 + F_2)]C_t[\exp(-k_3t) - 1] + \{A_t[1 - (R_1 + R_2)]\}/k_3 [1 - \exp(-k_3t)] \qquad [12]$$

Model parameter values were estimated using C_t at 1938 ($t = 0$), 1972 ($t = 33$), 1979 ($t = 40$), and 1990 ($t = 51$) together with average annual addition of C for the periods 0 to 33, 0 to 40, and 0 to 51 yr. We realize that this procedure unavoidably hides some variation in addition rates among the three intervals.

Table 2. Quantitative description of a soil profile of the Breton loam series as found adjacent to the Breton Classical Plots under native vegetation.

Horizon	Depth	D_b†	Carbon		Nitrogen	
	cm	Mg m^{-3}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}
LFH‡	10-0	0.15	296	44.4	10.6	1.6
A_{e1}	0-6	1.16	15	10.7	1.0	0.7
A_{e2}	6-18	1.44	4	6.2	0.3	0.5
AB	18-27	1.52	3	4.7	0.4	0.5
B_{t1}	27-58	1.53	3	16.1	0.4	1.9
B_{t2}	58-94	1.58	3	14.0	0.3	1.2
(A + B)				95.1	12	

† Bulk density.
‡ For comparison, Howitt and Pawluk (1985) reported a thickness of 8 cm for the LFH horizon and 13 cm for the A horizon.

Table 3. Horizon thickness and bulk density (D_b) as measured in 1979 on selected treatments of the Breton Classical Plots.

		Ap Horizon				AB Horizon			
Rotation	Treatment	Thickness		D_b		Thickness		D_b	
		Cm		Mg m^{-3}		cm		Mg m^{-3}	
WF	Nil	14.1	a,y†	1.31	a,x	11.9	a,x	1.63	a,x
	Fertilizer	12.2	a,y	1.33	a,x	10.8	a,x	1.59	a,x
	Manure	14.2	a,x	1.40	a,x	10.0	a,y	1.62	a,x
WOBHH	Nil	16.9	a,x	1.37	a,x	14.0	a,x	1.52	b,y
	Fertilizer	18.0	a,x	1.29	b,x	15.2	a,x	1.61	a,x
	Manure	17.0	a,x	1.33	ab,x	14.2	a,x	1.54	b,x

† a,b: means within each column and rotation group followed by the same letter are not significantly different following a *t*-test procedure at 0.05 level of probability; x,y: means within each column and fertility treatment followed by the same letter are not significantly different following a *t*-test procedure at 0.05 level of probability.

RESULTS AND DISCUSSION

Site Characteristics

Wyatt (1945) provided a general characterization of gray wooded soils (Gray Luvisols, Cryoboralfs) based on soil survey reports. The top three horizons included a "moss to leaf mould" organic A_0, 5 cm thick; followed by a "brownish to black platy" mineral A_1, 5 cm thick; and a "light gray...platy..." A_2, 23 cm thick. Cultivation of these soils changed the color of surface soil layers to light gray due to the mixing action of plowing (Wyatt, 1945). Howitt and Pawluk (1985) excavated and described, in 1977, a soil profile north of and adjacent to the Breton Plots. The site vegetation was a mixture of trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), white birch (*Betula papyrifera* Marsh.), and white spruce [*Picea glauca* (Moench) Voss]. The soil profile had an organic layer (LFH) 8 cm thick, and the three A horizons (A_{eh}, A_{e1}, and A_{e2}) had a combined thickness of 13 cm. Results from the 1979 quantitative soil description at an undisturbed site immediately north of the Breton Plots (Table 2) revealed an LFH horizon 10 cm thick and an A horizon 18 cm thick. Given the ranges recorded in 1979 and the descriptions by Wyatt (1945) and Howitt and Pawluk (1985) we infer (i) that the site of the Breton plots is representative of Gray Luvisols and (ii) that the thickness of the A horizon at the beginning of cultivation around 1920 varied between 13 and 18 cm.

From the data for horizon depth and D_b sampled at the end of the 1979 growing season (Table 3) it appears the Ap horizons under the WF rotation were ≈3 cm thinner than those under the WOBHH rotation. Such a difference is not expected. The thickness of an Ap should be determined mostly by tillage. We can't confirm whether equipment went deeper when soil conditions were better or alternatively if the soil compacted more so the Ap depth is thinner on plots under the WF rotation. Although the depth range of these determinations (12–18 cm) falls within that determined on the native sites just north of the plots (13–18 cm), it is likely that there was some soil movement by either tillage or erosion in the WF rotation. The fallow frequency dictated that these plots were tilled frequently, especially before 1979, to control weeds and to prepare the seedbed. This could have induced some soil movement by tillage implements within the plot area or outside the plot area. The ^{137}Cs data reported for these plots by Monreal et al. (1995) are consistent with such movement. Another possibility is that some soil was lost by water erosion. On the basis of the contour lines and slope classes of Fig. 1B determined on the upper half of the experimental area—that includes the plots for which horizon depth and D_b are reported—we conclude that soil transport by water erosion was small if any at all. Wind erosion was not a factor at this site.

On the basis of data in Tables 2 and 3 we estimate that the mass of SOC present in the LFH and A horizons around 1920 when cultivation began was ≈60 Mg ha^{-1}. Using SOC concentrations (g kg^{-1}) measured on soil samples taken during 1936 to 1938 and a D_b of 1.33 Mg m^{-3} to the 0.15-m depth, our calculations yield a SOC mass of 26 Mg ha^{-1}. Precise determinations of soil D_b are lacking, but measurements from Table 3 together with those reported by Izaurralde et al. (1993) and Nyborg et al. (1995) support this approximation. Using these values, we estimated that the proportion of SOC lost by oxidation processes, burning, or transport during clearing in the early years of cultivation was ≈57%.

Plant Carbon Productivity

There were substantial differences in plant C productivity between the WF and the WOBHH rotations (Fig. 2). The 91 Mg ha^{-1} of aboveground plant C accumulated in WOBHH treatments during the period 1939 to 1994 was 86% greater than the 49 Mg ha^{-1} accumulated in WF treatments. There were clear differences in C pro-

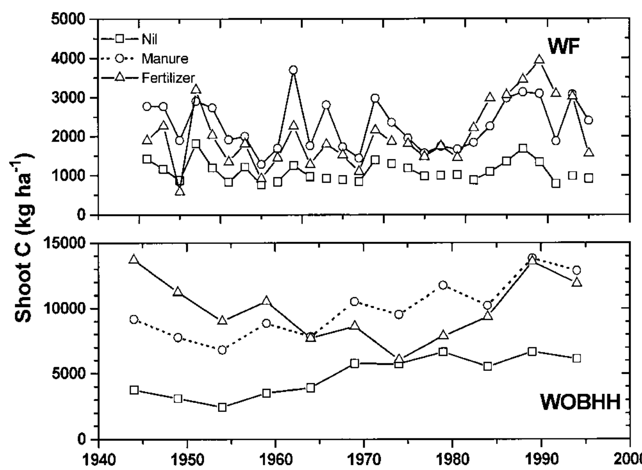

Fig. 2. Aboveground plant C productivity per rotation cycle at the Breton Classical Plots.

ductivity induced by fertility treatments. In the WF rotation, the Nil treatment had a low (≈1000 kg C ha^{-1} per rotation cycle) but stable aboveground C productivity during the entire study period. Additions of either fertilizer or farmyard manure increased C productivity over the Nil treatment but without clear differences between them. Carbon productivity of both addition treatments varied during the first 35 yr of the study, and a productivity increase occurred during the 1980s followed by a decline early in the 1990s. It is not the intent here to ascribe this variability to climatic events because the values presented are for rotation cycles and not individual years. However, the influence of weather variability or potential S fertilization from local petroleum production on plant productivity cannot be discounted.

In the WOBHH rotation, the productivity of the Nil treatment increased with time (Fig. 2). Carbon productivity in both the fertilizer and the manure treatments was greater than that in the Nil treatment. Although the fertilizer treatment had a greater productivity than the manure treatment during the early years of the study, its productivity declined and reached its lowest point during the mid 1970s. This decline in production was caused by soil acidity induced by additions of ammonium fertilizers and in the change of legume in the forage crop from clover (*Trifolium* spp.)–alfalfa to alfalfa alone (McCoy and Webster, 1977; Robertson and McGill, 1983). The problem was corrected by addition of agricultural lime. The productivity of the WOBHH rotation receiving manure steadily increased. Currently, both treatments receiving fertilizers, either synthetic or organic, have a similar productivity. Additions of C to soil vary with aboveground plant C productivity and manure C, so fertilizer additions should have increased SOC mass.

Soil Organic Carbon and Total Soil Nitrogen

The average SOC concentration in 1938 (calculated from one sample taken in 1936 and two in 1938) was 13.2 g kg^{-1}, while that of total soil N was 1.21 g kg^{-1}, yielding a C/N ratio in Ap horizons of ≈11 (Table 4).

Between 1938 and 1990, SOC concentration decreased in the WF–Nil and WF–F treatments and increased in the other four (WF–M and the Nil, F, and M treatments of the WOBHH rotation). The greatest decrease in SOC concentration (−4.2 g kg^{-1} from 1938 to 1990) was in the WF–Nil treatment, and the greatest increase (8.4 g kg^{-1}) was in the WOBHH–M treatment. Therefore, the divergence in SOC concentration created by these contrasting management systems reached 12.6 g kg^{-1}, which in terms of SOC mass translates into ≈25 Mg C ha^{-1} (using a D_b of 1.33 Mg m^{-3} to a depth of 0.15 m). These results demonstrate both avoided loss of C, and net gain of C. Avoided loss is the difference in mass of C between treatments, one that lost C and one that gained C after a fixed time, whereas net gains are based on comparisons of the same treatment over time (Izaurralde et al., 2000). The net gain in soil C from 1938 to 1990 in the WOBHH–M treatment was 8.4 g kg^{-1}, or ≈17 Mg ha^{-1} (using a D_b of 1.33 Mg m^{-3} to a depth 0.15 m). The avoided loss when comparing WF–Nil and WOBHH–M is ≈25 Mg C ha^{-1}.

We emphasize that the changes in SOC just discussed arose mostly as a result of root and manure C additions. The contribution of litter C was small because most of the aboveground plant biomass was removed from the plots. The role of manure in soil C sequestration is discussed below. In agreement with Balesdent and Balabane (1996), Campbell et al. (1991), and Solberg et al. (1998), these results continue to confirm the important contribution of roots to conserving or increasing SOC.

Total soil N followed similar trends as SOC, with the greatest decline in concentration (−0.3 g kg^{-1}) in the WF–Nil treatment, while the greatest increase (0.8 g kg^{-1}) was in the WOBHH–M. The management imposed created two groups of soil samples based on their C/N ratios. The WF rotation narrowed the C/N ratio from ≈11 to ≈10, while the WOBHH rotation main-

Table 4. Soil organic C and total soil N of Ap horizons of the Breton Classical Plots from 1936 to 1990.

Year	Rotation†	Treatment	N	Soil organic C Mean	Soil organic C SE	Total soil N Mean	Total soil N SE	C/N ratio Mean	C/N ratio SE
				g kg^{-1}					
1936	WOBHH	Nil	1	12.00	0.00	1.07	0.00	11.22	0.00
1938	WF	Nil	2	13.85	0.15	1.28	0.01	10.86	0.08
1972	WF	Nil	2	11.33	0.69	1.15	0.06	9.84	0.08
1972	WF	Fertilizer	1	13.00	0.00	1.29	0.00	10.08	0.00
1972	WF	Manure	1	13.85	0.00	1.34	0.00	10.34	0.00
1972	WOBHH	Nil	9	14.35	0.22	1.34	0.02	10.68	0.17
1972	WOBHH	Fertilizer	5	16.28	0.33	1.53	0.03	10.67	0.14
1972	WOBHH	Manure	5	18.55	0.46	1.74	0.03	10.66	0.28
1979	WF	Nil	8	11.15	0.48	1.14	0.04	9.75	0.11
1979	WF	Fertilizer	4	12.22	0.33	1.23	0.03	9.97	0.14
1979	WF	Manure	4	14.63	0.46	1.47	0.03	9.93	0.09
1979	WOBHH	Nil	40	14.80	0.22	1.40	0.02	10.56	0.07
1979	WOBHH	Fertilizer	20	16.46	0.38	1.79	0.25	10.29	0.42
1979	WOBHH	Manure	20	20.14	0.48	1.88	0.04	10.71	0.10
1990	WF	Nil	4	9.05	0.76	0.94	0.05	9.59	0.27
1990	WF	Fertilizer	2	10.69	0.21	1.10	0.05	9.73	0.26
1990	WF	Manure	2	15.60	1.50	1.52	0.11	10.28	0.21
1990	WOBHH	Nil	20	14.60	0.26	1.39	0.02	10.54	0.09
1990	WOBHH	Fertilizer	10	16.90	0.31	1.58	0.02	10.67	0.09
1990	WOBHH	Manure	10	21.65	0.60	2.03	0.05	10.68	0.09

† WF, wheat–fallow; WOBHH, wheat–oat–barley–hay–hay.

Table 5. Annual rates of plant- or manure-derived C added to a Breton loam during three periods from 1939 to 1990.†

C additions on periods	WF–Nil	WF–F	WF–M	WOBHH–Nil	WOBHH–F	WOBHH–M
	kg ha^{-1} y^{-1}					
			Plant C			
1939–1972	167	174	231	277	619	500
1972–1979	82	90	93	445	428	619
1979–1990	227	400	346	338	499	566
Avg. (weighted)	168	211	237	313	567	531
			Manure C			
1939–1972	0	0	783	0	0	926
1972–1979	0	0	1140	0	0	1136
1979–1990	0	0	560	0	0	821
Avg. (weighted)	0	0	784	0	0	932
Avg. Total C	168	211	1021	313	567	1463

† For fertility treatment details see Wani et al. (1994). WF, wheat–fallow; WOBHH, wheat–oat–barley–hay–hay; F, fertilizer; M, manure.

tained the C/N ratio closer to the original (≈11), suggesting cropping systems with ability to retain more C.

Soil Organic C Dynamics

Model Fitting

We calculated the annualized rates of plant and manure C additions to soil during three periods from 1939 to 1990 (Table 5). While on average the largest difference in plant C additions among the six treatments varied fourfold, the difference increased up to 10-fold when manure additions were considered.

We converted the SOC concentrations into SOC mass using a constant D_b of 1.33 Mg m^{-3} and a depth of 0.15 m. We used the SOC concentration and mass in the period 1936 to 1938 to represent SOC in 1939. While not exact, we consider these approximations acceptable. The three-compartment model was fitted to the data for t, A_t, and Ct derived from Tables 4 and 5 and recorded in Table 6. It yielded parameter values shown in Table 7.

The nonlinear least squares procedures for the Cum model estimated that in 1939 ≈2.2% of the SOC was in the very labile (crop residues) compartment (C_1), 75.4% in an active compartment (C_2), and 22.4% in a passive compartment (C_3) (Table 7). The decomposition rate constants for these three compartments were 0.2692, 0.0037, and 0.0005 yr^{-1}. In this model, ≈80% of the C input to soil cycles through C_1, while the C_2 and C_3 cycle about 10% each (See R in Table 7).

We then used the parameterized model and the annualized C input rates for each treatment–period to simulate the change in SOC. The Cum model described ≈70% of the variation in gain or loss of SOC. Observed changes regressed on predicted changes had a slope (1.02) that was not significantly different from one and the y-intercept (−237 kg ha^{-1}) was not significantly different from 0 (Fig. 3A).

Simulations of total SOC using the Cum model diverge from the data by as much as 35% at the lowest value of SOC in the WF–Nil treatment (only one value was so extreme). The model tended to overpredict the SOC values of the WF rotation and under predict those of the WOBHH rotation. The correlation was highly

Table 6. Values of A_t, C_t (Ap horizons at end of period), and t used to derive parameter values for the three compartment model.†

Period	Time (t)	At (kg ha^{-1} yr^{-1})	Ct (kg ha^{-1})
		WF–Nil	
Start	0	0	26401
1939–1972	33	167	22593
1939–1979	40	164	22247
1939–1990	51	178	18060
		WF–F	
Start	0	0	26401
1939–1972	33	174	25935
1939–1979	40	171	24369
1939–1990	51	221	21317
		WF–M	
Start	0	0	26401
1939–1972	33	1014	27631
1939–1979	40	1067	29182
1939–1990	51	1005	31122
		WOBHH–Nil	
Start	0	0	26401
1939–1972	33	277	28633
1939–1979	40	307	29532
1939–1990	51	328	29134
		WOBHH–F	
Start	0	0	26401
1939–1972	33	618	32479
1939–1979	40	585	32829
1939–1990	51	584	33708
		WOBHH–M	
Start	0	0	26401
1939–1972	33	1426	37006
1939–1979	40	1485	40173
1939–1990	51	1443	43184

† Values for A_t are derived from Table 5, and for C_t from Table 4 using a D_b = 1.33 Mg m^{-3} and a depth of 0.15 m. WF, wheat–fallow; WOBHH, wheat–oat–barley–hay–hay; F, fertilizer; M, manure.

Table 7. Parameter values for the three-compartment model derived from data for SOC (Cum) or from data for change in soil organic C (SOC) (Change).

	C_1	C_2	C_3	Total
		Cum		
F	0.022	0.754	0.224	1.0
R	0.803	0.099	0.098	1.0
k (yr^{-1})	0.2692	0.0037	0.0005	
$1/k$ (yr)	3.7	270	2000	
R/k (yr)	3.0	26.8	196.0	226
F_{ss}	0.01	0.12	0.87	1.0
		Change		
F	0.072	0.540	0.388	1.0
R	0.803	0.148	0.0484	1.0
k (yr^{-1})	0.2962	0.0026	0.0005	
$1/k$ (yr)	3.4	384.6	2000	
R/k (yr)	2.7	57.1	96.8	157
F_{ss}	0.02	0.36	0.62	1.0

significant ($R^2 = 0.71$; $P = 10^{-5}$), and the slope of the observed regression on simulated SOC (1.02) was not significantly different from one, and the y-intercept (-864 kg ha^{-1}) was not significantly different from zero, so there is little systematic error.

We compared the Cum and Change models on the basis of their simulations of total SOC using parameter values shown in Table 7. We accounted for about the same amount of variation in SOC in both cases (71%), but the observed values regressed on predicted values had a y-intercept of -1298 kg ha^{-1} for the Change model compared with -864 kg ha^{-1} for the Cum model. The above is not a test of either model against independent data. It describes how the parameters obtained from the data when used in a variety of ways estimate the original data set. We used the values Cum model (Eq. [11]) for the remaining analyses.

A Test of Two Hypotheses

One purpose of using a simple model to describe all the variation in SOC was to test the hypotheses: (i) that the amount of C stored or lost is regulated by the initial mass and distribution of SOC among compartments, and by the mass of C inputs as distinct from the nature of the rotation, and (ii) that at this site the decay rates of SOC compartments and the proportions of C entering them did not vary among rotations. The model should fail to the extent that the nature of the rotation, which is tied to timing, quality, or location of C input, and to frequency or intensity of tillage, regulates SOC storage. The model should fail to the degree that decay rates or apportioning of C into SOC compartments vary among rotations and cropping systems.

Overall, the three-compartment model explained slightly more than 70% of the total variation induced by the treatments (C loss of 8300 vs. gain of 16 700 kg ha^{-1} = 25 Mg ha^{-1}) (Fig. 3A). Consequently, ≈70% of the variation in SOC gain or loss under conditions of the same climate and soil across all treatments appears to be related to variation in mass of C input. The remaining 30% appears to be related to variations in decay rates and apportioning C inputs to compartments or to variations in nature, timing, or location of C inputs among the rotations used here. We hypothesized higher decay rates in the WF rotation than in WOBHH because of more frequent soil disturbance and perhaps better moisture regime. To test this hypothesis we multiplied the values of k_1, k_2, and k_3 by factors ranging from 1.1 to 2 to calculate SOC in WF rotations and divided them by the same number to calculate SOC in WOBHH treatments. Adjusting the decay rates up by a factor of 1.3 for WF treatments and down by the same factor for WOBHH rotations caused the predicted values to converge more closely on the observed (Fig. 3B). The regression equation was Observed = 0.99 Predicted − 31.8 kg ha^{-1} ($r^2 = 0.85$; $P = 10^{-8}$). Although the correlation could be further improved by increasing the difference in decay rates between WF and WOBHH, the slopes of the relationships diverged from one, and the y-intercepts increased and differed from zero. This simple test of sensitivity to decay rates suggests that an additional 15% of the variation in SOC contents at this site may be associated with differing decay rates between WF and WOBHH rotations. Apparently, the nature of the rotation influences both amount of C entering soil and its behavior once there.

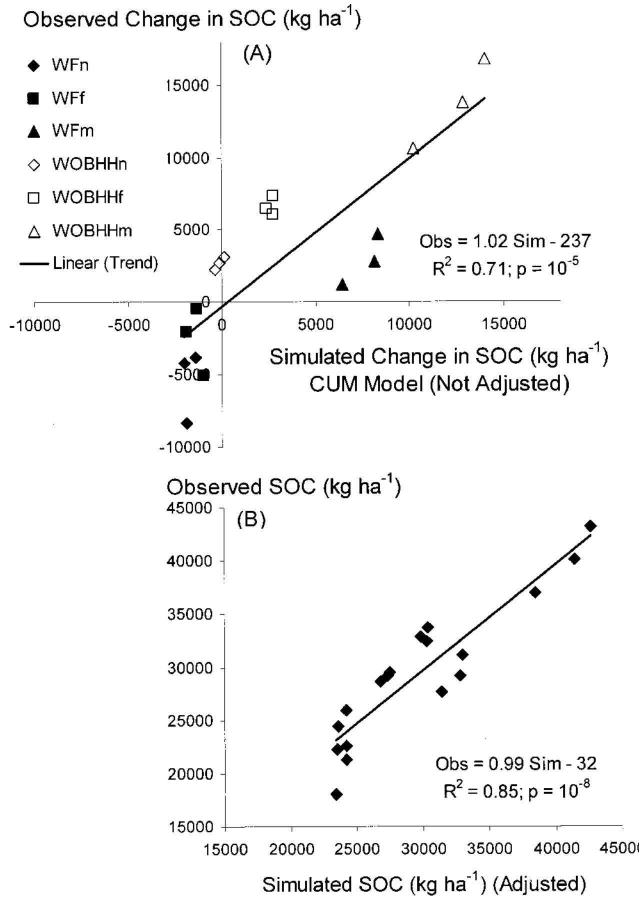

Fig. 3. (A) Relationship between simulated and observed changes in soil organic C (SOC) (kg C ha^{-1} yr^{-1}). Change in SOC is the SOC at each sampling date minus SOC at 1939. Simulated SOC at each date was calculated with Eq. [10] using parameter values reported in Table 7 for the Cum model. (B) Mass of SOC was simulated using adjusted values of k to distinguish wheat–fallow (WF) from wheat–oat–barley–hay–hay (WOBHH) rotations and compared with observed values for the Breton plots over 51 years. Adjustment entailed multiplying each k by 1.3 for the WF rotations and dividing them by 1.3 for the WOBHH rotations.

Maintenance Carbon Inputs

We plotted the 51-yr mean annual change in SOC in the top 15 cm against mean annual addition of C (A_t) (Fig. 4). For a simplified first-order system with constant rates of addition and decay, such a plot is linear. However, the line appears to be logarithmic, indicating departure from the simplified system.

We estimated input C needed to maintain initial SOC in the top 15 cm using the equation from the above plot. For the combined 51-yr data set (Fig. 4) it was 334 kg ha^{-1} yr^{-1}. The linear equation from the model output ($Y = 0.246X - 81.4$) yielded 331 kg ha^{-1} yr^{-1} and agreed well with the data plot even though the data line is

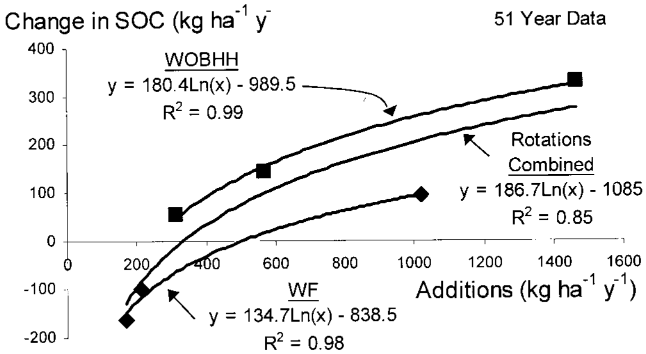

Fig. 4. Relationship between annual addition rate of C and measured annual change in soil organic C (SOC) over 51 yr.

logarithmic and the model is linear. The data for the WF and the WOBHH rotations fall into two populations. The WF rotation required 505 kg ha^{-1} yr^{-1} estimated from the equation from the data and 437 kg ha^{-1} yr^{-1} estimated from the equation from the model output ($Y = 0.229X - 100$). In contrast, the WOBHH rotation required only 241 kg ha^{-1} yr^{-1} based on the data plot and 251 kg ha^{-1} yr^{-1} from the equation from model output ($Y = 0.265X - 66.4$) to maintain the original SOC content.

Only a portion of the plant C enters the top 15 cm of soil ($CPLAN_{15}$). When CFYM = 0 we express $CPLAN_{15}$ as a fraction (FI) of the total aboveground C (TAC), such that $CPLAN_{15}$ = TAC × FI. From this and Eq. [3] to [7]

$$CPLAN_{15} = TAC \times (RSR \times 0.80 + 0.1) \quad [13]$$

$$FI = RSR0.8 + 0.1 \quad [14]$$

Using our root/shoot ratios the value of FI was 0.29 for the WF–Nil, 0.2 for the WF–F, 0.37 for WOBHH–Nil, and 0.31 for WOBHH–F. The higher values for FI in WOBHH rotations compared with the WF rotations reflect differences in RSR. Hence, higher root/shoot ratios of crops translates into lower total aboveground C productivity needed to maintain the same SOC content. The low-yielding rotations (WF) are hit doubly hard. They have the highest requirements for C input because of high decay rates, and the highest required aboveground C productivity per unit of C input because of low root/shoot ratios of cereals. For example, equating the C input needed to maintain SOC with $CPLAN_{15}$ in Eq. [13], the required aboveground net C productivity (kg ha^{-1} yr^{-1}) is 1730 for WF–Nil and 2578 for WF–F, but only 656 for WOBHH–Nil, and 779 for WOBHH–F. Consequently, based on data for 51 yr, in the absence of manure additions, the aboveground productivity needed to maintain the original SOC content at this site might vary through crop rotation and management by fourfold (2578/656).

Carbon Allocation Arising from Parameter Values for the Model

The parameter values estimated for the model from the data for this site suggest that in 51 yr the system has not reached steady state, and C may continue to accumulate in the passive component. The following discussion shows why.

Mass (M, kg ha^{-1}), addition rate (A, kg ha^{-1} yr^{-1}), decay rate (k, yr^{-1}) and turnover time (T, yr) are all related at steady state: $M = A/k$; $T = 1/k$; $T = M/A$, and $A = M/T$.

At steady state, Eq. [10] reduces to

$$M_{SOC} = A_1/k_1 + A_2/k_2 + A_3/k_3$$
$$= A_t(R_1/k_1 + R_2/k_2 + R_3/k_3) \quad [15]$$

Using Eq. [15] and $T = M/A$

$$T_{SOC} = (R_1/k_1 + R_2/k_2 + R_3/k_3) \quad [16]$$

From the original model parameters (no adjustment between treatments) and Eq. [16], the steady-state turnover time for soil + litter components ($C_1 + C_2 + C_3$) is 226 yr (0.803/0.2692 + 0.099/0.0037 + 0.098/0.0005). Based on the global budget of Rodhe (1992), global soil C turnover time is ≈385 yr. Global turnover times for combined soil C + litter C + peat C are estimated to be ≈28 yr (Holmén, 1992; Rodhe, 1992).

Using 226 yr as the turnover time, the annual input of C needed to maintain the original SOC is 117 kg ha^{-1} yr^{-1} (26 401/226). In contrast, the maintenance calculations above, which used the equation in Fig. 4 from the 51-yr data, estimated a C input of 334 kg ha^{-1} yr^{-1} to maintain the original SOC. From $M = AT$ and the 51-yr values for maintenance C, the steady-state SOC content will be 334 × 226 = 75 484 kg ha^{-1}, or ≈2.9-fold greater than in 1939. If, as we estimated, the native SOC was ≈60 Mg ha^{-1}, this steady state is ≈26% higher than the native SOC.

Why does a constant addition of C appear to maintain the original C for 51 yr, but appear to sequester C after that time? It does so mainly because of interactions between parameters F and R. The parameters F describe initial distribution of C among compartments. Parameters R describe subsequent allocation of input C to compartments. For a fixed input, dynamics during the early decades are dominated by F, the long-term trend is dominated by R; and steady-state values are independent of F, depending only on R/k. Given the parameter values in Table 7, component C_2 will lose C with time and component C_3 will gain C.

Given the estimates of F, ≈75% of the original SOC is in compartment C_2 (active) with only 22% in C_3 (passive). However, at steady state the situation reverses, with (0.098/0.0005)/M = 87% in compartment C_3 and only (0.099/0.0037)/M = 12% in compartment C_2 (See F_{SS} in Table 7). The trend observed is the balance of losses from C_2 and gains in C_3 (Fig. 5A).

The trend is for early increases in SOC due to adjustments in C_1. This is followed by a decrease in SOC after C_1 reaches steady state when loss from C_2 exceeds gains in C_3. Finally, SOC increases again when C_2 nears its steady state with small losses from it, which are exceeded by gains in C_3 (Fig. 5B). The final increase in SOC in the WQOBHH rotation (not shown in plot) is delayed because the modeled inputs are lower in that rotation. Examination of Fig. 5B indicated that prior to 51 yr ago

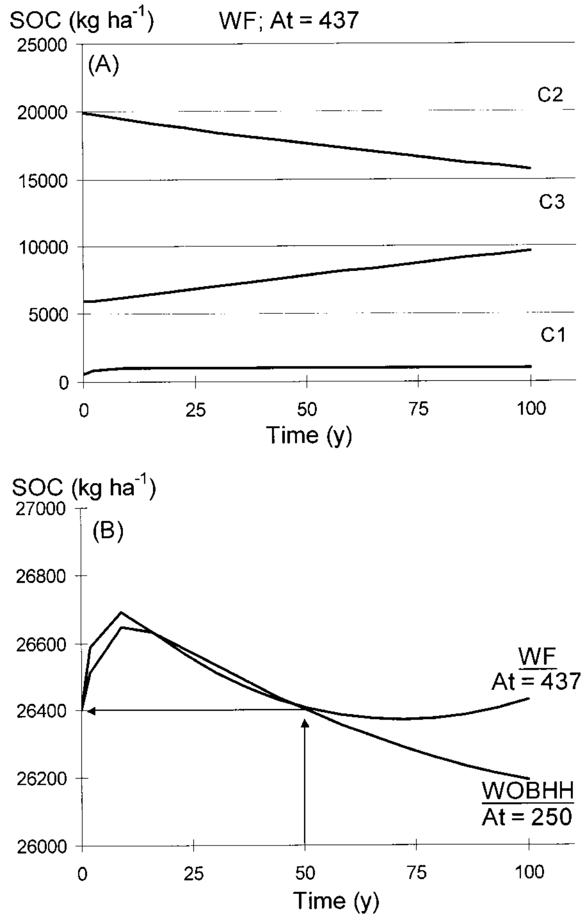

Fig. 5. (A) Carbon content of each of compartments C_1, C_2, and C_3 in the wheat–fallow (WF) rotation using adjusted k values and model-derived additions that maintain original SOC content at 51 yr. See Table 7 and Fig. 3 and 4 for model information. (B) Trend of total soil organic C (SOC) in each rotation as calculated using the three-compartment model with model-derived additions that maintain the original SOC at 51 yr. Additions needed to maintain the original SOC are greater for the WF than the wheat–oat–barley–hay–hay (WOBHH) rotations.

a smaller input of C would have maintained the original SOC. To test this we plotted the observed data for 33 yr and calculated the maintenance input of C as above. The result for the WF rotation did not change, but for the WOBHH rotation, it dropped from 241 to 182 kg ha^{-1} yr^{-1}, while for the combined rotations it dropped from 334 to 242 kg ha^{-1} yr^{-1}. This simple model predicts the inputs of C required to maintain SOC should vary with time, and we found that they did vary with time. It appears that these plots may not be at steady state, and they may continue to sequester C.

Can Manure Additions Sequester Carbon?

Addition of farmyard manure was a key management component leading to SOC increases (greatest two C additions in Table 5). Using data from Buyanovski and Wagner (1999), Schlesinger (1999) argued that manuring is not a valid method for soil C sequestration because of the extra land required to produce the manure. This means crops produced on a unit area of land yield insufficient manure to maintain or increase SOC.

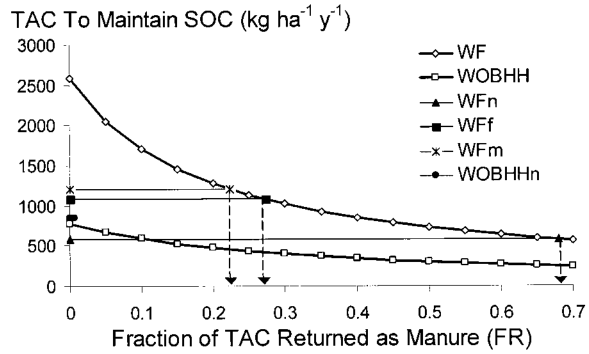

Fig. 6. Relationship between the fraction of net aboveground C (TAC) that is returned as manure (FR) and the net C productivity required to meet C inputs that maintain the original soil organic C (SOC) in the wheat–fallow (WF) and wheat–oat–barley–hay–hay (WOBHH) rotations (from Eq. [18]). The greater inputs needed to maintain the original SOC in the WF rotation compared to the WOBHH rotation in combination with the lower proportion of TAC returned as roots in WF rotations result in a greater TAC needed to maintenance SOC. The actual values of TAC for three WF rotations and the WOBHH–Nil rotation are plotted as horizontal lines. When the WF lines reach the TAC line for the WF rotation they proceed down to the corresponding value of FR. The TAC for the WOBHH rotations are all above the TAC necessary to maintain SOC in the WOBHH rotation so only the point is shown. Values of FR at which the TAC meets maintenance requirements can be calculated with Eq. [19].

We tested this proposition with data from the Breton site. The key is to focus on maintenance C requirements (values at 51 yr; Equations in Fig. 4) and not on experimental manure application rates. We related CFYM to total aboveground C (TAC) using the fraction of TAC converted to manure (FR)

$$\mathrm{CFYM} = \mathrm{FR} \times \mathrm{TAC} \quad [17]$$

We used Eq. [9a] with substitutions from Eq. [13] for CPLAN_{15} and from Eq. [17] for CFYM and rearranged to yield

$$\mathrm{TAC} = \mathrm{CTOT}_{15}/(0.8 \times \mathrm{RSR} + 0.1 + \mathrm{FR}) \quad [18]$$

$$\mathrm{FR} = (\mathrm{CTOT}_{15}/\mathrm{TAC}) - 0.8 \times \mathrm{RSR} - 0.1 \quad [19]$$

We set CTOT_{15} = to maintenance C after 51 yr for WF (505 kg ha^{-1} yr^{-1}) and WOBHH (241 kg ha^{-1} yr^{-1}) rotations and used the RSR for manured treatments in Eq. [18] to calculate TAC for increasing FR. As manure return (FR) increases the net C productivity (TAC) needed to maintain SOC drops (Fig. 6). Given actual TAC, what FR would be needed to achieve net soil C sequestration?

We set TAC equal to the actual TAC and used RSR for manured treatments in Eq. [19] to calculate FR (Fig. 6). In all cases FR < 1: it was 0.68 for WF–Nil; 0.27 for WF–F; 0.22 for WF–M; and negative for all WOBHH rotations (e.g., −0.17 for WOBHH–Nil). So using actual TAC, net soil C sequestration would be expected if 27% or more of the C (FR = 0.27) in the aboveground dry matter of the WF–F and 68% in the WF–Nil treatments had been returned as manure. This would have been the case if the added manure did not increase TAC. But manure does increase TAC. For example, TAC in WF–Nil = 576 kg ha^{-1} yr^{-1}, and in WF–M it was 1208 kg ha^{-1} yr^{-1}. When TAC = 1208 kg ha^{-1} yr^{-1} FR drops to 0.22 (Fig. 6). Given the negative values for FR in the WOBHH rotations even with no manure return C input from this rotation was sufficient to increase SOC. So in the WOBHH rotations, conversion of any TAC to manure would result in net soil C sequestration.

If FR > 1 clearly means extra land is needed to produce manure, then is any value of FR < 1 acceptable? No. First, some of TAC (0.1) is already input to the soil, so only 0.9 remains. Second, it is impossible for all TAC to be converted to manure because of conversion to livestock products or CO_2. So how much conversion of TAC to manure is realistic? If 60% of animal feed is oxidized or converted to animal products (Schlesinger, 1999) then ≈40% might be left for conversion to manure. So FR up to 0.36 [0.9(1 − 0.6)] might be achievable. With the exception of the WF–Nil, all rotations had FR < 0.36. Consequently, the crops produced in them would provide enough manure to achieve net C sequestration with observed TAC. The actual FR for the WF–M treatment was 0.65 (784/1208). This was higher than would normally be expected with all manure produced on site and was higher than necessary (FR = 0.22).

We show a feedback between the fraction of aboveground C that is returned as manure and net C productivity. Increasing the fraction returned reduces the C productivity necessary for a fixed C input to soil, and return of manure increases C productivity. We conclude that return of 30% of the crop C at this site as manure would sustain net soil C sequestration in all WOBHH rotations with net C productivity >400 kg ha^{-1} yr^{-1}; it would sustain net soil C sequestration in all WF rotations with net aboveground C productivity >1000 kg ha^{-1} yr^{-1}.

SUMMARY AND CONCLUSIONS

Net aboveground C productivity of the WF system averaged 576 kg ha^{-1} yr^{-1} without fertilizer, and 1078 with fertilizer, SOC decreased in both; it was 1208 in WF–M, which gained SOC. The WOBHH rotation, had net aboveground C productivity of 853 kg ha^{-1} yr^{-1} (Nil, maintained SOC), and 1831 (F), and 1714 (M) both of which increased SOC. The range in masses of SOC within the 0- to 0.15-m depth after 51 yr was 25 Mg ha^{-1}.

About 70% of the variation in SOC content was described using C inputs alone, and 85% by using C inputs and rotation-specific decay rates. Decay rates may vary by a factor of 1.69 between these rotations. Because C inputs are a dominant control on SOC content, it may be more appropriate to use measured crop yields when available than to try to simulate them for use as inputs to SOC models.

After 51 yr the soil in some rotations at this site appears still to be gaining C. Use of a simple kinetic model to describe the data suggests that C is lost from the active compartment and accumulates in the passive compartment. Potential steady-state accumulations of SOC are ≈2.9 times the SOC in 1939 and 26% above the native SOC content.

High decay rates in the WF rotation necessitate more C input (505 kg ha^{-1} yr^{-1}) to maintain the original SOC in this rotation compared with the WOBHH rotation (241 kg ha^{-1} yr^{-1}); and low root/shoot ratios in WF increase the net aboveground C productivity needed to attain these maintenance inputs (range: 2578 kg ha^{-1} yr^{-1} in WF–F to 656 in WOBHH–Nil). Increasing the fraction of aboveground C that is returned as manure reduces the C productivity necessary for a fixed C input to soil, and return of manure increases C productivity. Return of 30% of the crop C at this site as manure would sustain net soil C sequestration in all WOBHH rotations with net C productivity >400 kg ha^{-1} yr^{-1}, and in all WF rotations with net aboveground C productivity >1000 kg ha^{-1} yr^{-1}.

Insights from these long-term experiments are pertinent for long-term farm productivity, soil C storage, and the global environment.

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