Soil Organic Carbon and Nitrogen After Application of Nine Organic Amendments

Stewart B. Wuest*
Hero T. Gollany
USDA-ARS
P.O. Box 370
Pendleton, OR 97801

The amount and type of C-containing amendments applied to soil can have an influence on soil organic carbon (SOC) levels. To test the hypothesis that amendment type is more important than amount, we applied 250 g C m^{-2} as manure, legume foliage, wheat (*Triticum aestivum* L.) residue, municipal biosolid, wood sawdust, brassica (*Brassica napus* L.) residue, composted wheat residue, sucrose, and cotton linters to both fallow soil and an annual winter wheat crop for five consecutive years. After an additional 3.5 yr with no inputs and all plots being fallow, the SOC of biosolid, manure, and wood amended plots were significantly ($P < 0.0001$) greater than the unamended check. The application of biosolid increased SOC 492 g m^{-2}, and manure increased SOC 316 g m^{-2}, over the fallow check plots in the top 300 kg m^{-2} of soil (approximately 0–25 cm). The increase in SOC relative to the check ranged from 0 to 39% of the amendment C applied. The SOC content was 482 g m^{-2} greater under continuous winter wheat than under fallow. The amendment and wheat crop effects on soil C and N changed little during the 3.5 yr after treatments ended, indicating that decomposition occurred soon after application. Wood sawdust was unique in that it increased SOC even though it was low in N content, and it changed the soil C/N ratio from 12.3 to 13.4. This field research demonstrated that amendments applied at the same C rate can have variable effects on SOC accretion.

Abbreviations: SOC, soil organic carbon.

Non-irrigated wheat–fallow cropping systems of semiarid North America are losing SOC even as biomass productivity increases with the use of modern varieties, weed control, and fertilizers (Campbell et al., 1996; Machado, 2011). This may be due to the relatively high levels of soil C that were originally present in the natural perennial grassland soils, which have only been cultivated for about a hundred years. It could also be due to the nature of wheat root and shoot residues themselves, or that in much of the region a crop–fallow rotation has been practiced, leaving the soil bare for 14 mo between crops. Soil tillage is another factor that has been considered a likely cause of the decrease in SOC, but according to some studies, recent conversion from tilled systems to untilled cropping systems has not stopped the decline under wheat–fallow crop rotations (West and Post, 2002; Wright and Hons, 2005).

Long-term experiments are ideal for following patterns of change in SOC, because year-to-year changes tend to be very small and methodological errors are substantial. The problem with many existing long-term experiments is that they do not include enough controlled treatment variables to answer questions of cause

Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Soil Sci. Soc. Am. J. 77:237–245
doi:10.2136/sssaj2012.0184
Received 7 June 2012.
*Corresponding author (Stewart.Wuest@ars.usda.gov).

and effect. A recent report from Pendleton, OR, analyzed three separate long-term experiments involving dryland winter wheat (Machado, 2011). Of particular interest here were data concerning applications of farmyard manure, and pea vine (*Pisum sativum* L.) remaining after immature green pea harvest for the frozen pea market. The manure amendments added the largest amounts of C (about 169 g m^{-2} yr^{-1}) and N (14 g m^{-2} yr^{-1}), and increased SOC the most. The relatively small input of pea vine (about 82 g m^{-2} yr^{-1}) produced substantially more SOC than winter wheat–fallow plots which received equal or greater amounts of N fertilizer (see also Wuest et al., 2005). Synthetic fertilizer rates in the experiment have increased over the decades to reflect modern farming systems, and therefore SOC may have changed from one equilibrium state or input rate to another. Also, in the past the pea vine amendment represented a relatively large input of C, but in recent decades wheat residue inputs have increased while the pea vine additions have remained the same.

This presents a question. Are pea vine and manure additions more effective in maintaining SOC than wheat residues, or is it simply a matter of more material having been applied over the course of the experiment? This issue is important if maintenance or increases in SOC are desired because many farmers have the option of using a wheat–pea rotation, but their total biomass yield might be greater if they remain in a wheat–fallow or wheat–wheat–fallow rotation.

In a 27-yr study, Doyle et al. (2004) found that a wheat–wheat rotation produced as much soil C and N as a wheat–soybean or soy–sorghum rotation. This would indicate that the legumes did not improve the rate of C accretion. But in a study where equal amounts of C were added, manure increased SOC compared to maize–soybean residues, and legume green manure incorporation was also shown to increase SOC (Drinkwater et al., 1998). Similarly, Bhogal et al. (2011) found that manure was quickly stabilized and increased SOC for more than 2 yr. A major difference between wheat and legume residues or manure would be in N content. In a study comparing residues of low and high N content, Gentile et al. (2010) found that they gave the same SOC result after a number of years, with or without fertilizer N additions. Furthermore, Gregorich et al. (1997) concluded that fertilizer did not affect the turnover of either the free or physically protected light fraction organic matter, and the location of organic matter in the soil aggregates was a main factor in its susceptibility to decomposition.

Light fraction organic matter, which is a transitory pool between fresh residue and humified stable soil organic matter (Gregorich and Janzen, 1996) is known to be a significant pool for soil organic matter turnover. Many researchers have concluded that practically all C compounds are susceptible to metabolism by microorganisms within a relatively short time of being introduced to soil (Kiem and Kögel-Knabner, 2003; Lutzow et al., 2006; Marschner et al., 2008). If this is true, the idea of recalcitrant compounds resisting breakdown and thereby becoming part of the slow turnover pool of soil organic matter can be tested by adding an assortment of compounds and determining how long they persist and increase SOC. A complicating factor, however, is the availability of N and other elements needed for microbial growth. There is evidence that N availability influences the metabolism of recent plant residue additions (Moran et al., 2005) and N additions can accelerate turnover of both recent and older SOC. On the other hand, added fertilizer N is often found to have little net effect on SOC in the long-term (Gentile et al., 2010).

Most studies concentrate on inputs from aboveground sources because measuring the contribution of roots is difficult. Roots add an unknown but very important quantity of C to soil (Allmaras et al., 2004; Johnson et al., 2006). Sanaullah et al. (2010) measured 30 to 40% of labeled wheat root C as having been stabilized after 20 mo, and still present after 3 yr. Plant growth, however, can induce priming of SOC mineralization (Paterson et al., 2008), so net gains might relate more to the availability of protected sites than to C additions.

Climate and soil texture influence SOC. Precipitation and temperature are correlated to SOC and soil organic N, and much of the wheat–fallow region of the western United States and Canada can be classified as Western Desert Shrub, where the mean soil C/N ratio is about 11.5 in the top 20 cm (Homann et al., 2007). This agrees with the finding that Mollisols (grassland soils) have a C/N ratio of 12 both before and after conversion to cultivated cropping systems (Post and Mann, 1990).

Soil texture influences accessibility of C compounds to microbes because SOC can be protected by bonds to clay minerals (Emerson, 1959; Tisdall and Oades, 1982). Grandy et al. (2009) found that soil texture strongly predicted both the abundance of N-containing compounds and lignin derivatives, which are more prone to organo-mineral interactions than many other C compounds. If soil organic N is largely composed of peptides produced through degradation of biomass, this would explain the narrow C/N ratio of SOC. Heike (2011) concluded that a large proportion of soil organic matter must be peptide-like compounds directly derived from plant or microbe tissue. The above is evidence for both the ability of soil microbes to break down and mineralize all common forms of carbonaceous substances, leaving no lasting differences in SOC, and at the same time the possibility of quick stabilization and protection of even easily mineralized compounds on mineral surfaces (Heike, 2011).

In most field experiments the amount of crop residue returned to each treatment is determined by the growth of that same crop in the same plot the season before. The experiments are often ongoing, resulting in soil C data that is influenced by the timing of the sampling in relation to crop rotation and the amount of time residues had to mineralize before the sample was taken. Our field experiment was designed to test the hypothesis that different types of amendment, applied at equal C amounts, can have different effects on SOC. A wide range of C-containing amendments were included to make the experiment more robust. The C amendments were applied once a year for 5 yr to both continuous fallow plots and plots planted annually to winter wheat.

At the end of the 5-yr treatment period, all plots were left fallow to allow organic matter mineralization for an additional 3.5 yr.

MATERIALS AND METHODS

The research site was located 15 km northeast of Pendleton, OR (45°43′ N, 118°38′ W, elevation 458 m). Annual precipitation averages 420 mm and falls mostly as rain during the winter. Air temperatures average 0.6°C in January. Summers are hot and dry, with an average temperature of 21°C in July. The soil was a Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll) containing 21% fine to very fine sand, 69% silt, 10% clay, and about 12 g kg^{-1} organic C in the top 10 cm. Soil pH ranged from 5 to 5.4 at the surface and increased to 6.0- at 30-cm depth. Before this experiment, the field was planted to spring wheat, followed by winter canola, which was killed in the spring with herbicides and the field planted to spring wheat again. The field was then fallow for an entire winter and summer before the experiment began in 2002. In this area, winter wheat is planted in October and harvest is in late July.

The treatment design was a factorial arrangement of two factors, one (fallow or cropped) assigned to main plots and the other (amendments and intercrops) assigned to subplots in a split-plot design, replicated in four complete blocks (Fig. 1). The two main plot treatments were continuous fallow and an annual winter wheat crop. Main plot location was randomized within each block. Each main plot was divided into 12 9.29-m^2 subplots (1.52 by 6.10 m), and 12 soil amendments randomly assigned to subplots within main plots. Two of the amendments were actually living crops of perennial grass (*Festuca arundinacea* Schreb.) and winter brassica (*B. napus* or *B. juncea* L.). These were intended to be intercrops in the wheat main plots, but their poor performance as intercrops in this experiment led us to exclude them from this analysis. The fallow main plot–grass subplot data will be presented briefly, but not included in the statistical analysis. The other 10 soil amendment treatments were (i) check (no amendment), (ii) cotton (*Gossypium hirsutum* L.) linters, in the form of shredded, unfinished paper-making sheets, (iii) sucrose, (iv) wheat residue, (v) composted wheat residue, (vi) *Brassica* residue (*B. napus* or *B. juncea*), (vii) wood sawdust (bark-free, western United States conifer species, 90% passing a 1-mm sieve), (viii) alfalfa (*Medicago sativa* L.) foliage in the form of feed pellets, (ix) cattle (*Bos taurus*) manure, un-aged and free of straw or soil, and (x) dry biosolid from a municipal sewage treatment plant (Table 1). All 10 amendments were applied at a target rate of 250 g C m^{-2}, except for the compost, where an amount of wheat residue equal to 250 g C m^{-2} was composted with N fertilizer in a turned drum. The resulting compost was applied to the plots at the same time as all other treatments. On average, at the time of application the compost contained 353 g C kg^{-1} and 19 g N kg^{-1}.

The rate of 250 g C m^{-2} is equivalent to the C content of aboveground crop residue left after harvest in an annual winter wheat production system yielding 3760 kg grain ha^{-1}. Amendments were applied at the end of summer, immediately before planting the winter wheat main plots. All amendments were in small pieces (<5 cm), spread uniformly, and had good soil contact. The fallow subplots planted to perennial grass were well established after the first year with the addition of a small amount of supplemental fertilizer and water. Grass subplots in the wheat main plots were largely out-competed by the wheat and remained in only a small proportion of the plot area. This stand failure created an interaction between main plots and subplots, so, as mentioned above, the perennial grass crop treatment was not included in statistical analysis.

The wheat was planted using a chisel drill without any other tillage following the previous harvest. The drill had two openers, one to place fertilizer at about 7-cm depth and another to place seed at about 4-cm depth and slightly to the side of the fertilizer placement. Seed rows were 30 cm apart. The chisel drill was also driven through the fallow main plots without seed or fertilizer so they would have equal soil disturbance. Since alfalfa, manure, and biosolid amendments contained more than enough N to supply a wheat crop, it was decided to not apply any additional N fertilizer when seeding these treatments. At harvest, grain was removed from each plot and all straw and chaff exiting from the harvester was collected and weighed. Stubble mass was also measured to within 2 cm of the soil surface. All residues were returned to each plot, and the residue C content was assumed to be 42% C based on multiple measurements.

Both main plot and subplot treatments were applied for five consecutive years, and then the entire plot area kept fallow and weed-free for another 3.5 yr to monitor SOC changes after

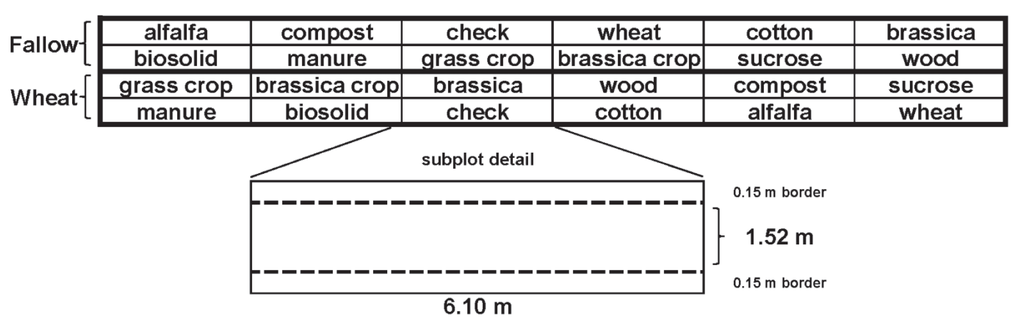

Fig. 1. Schematic of field layout, showing one of the four blocks and the dimensions of one subplot. The fallow and wheat main plot treatments were continuous in the same main plots all 5 yr (not rotated). Grass crop and brassica crop subplot treatments performed poorly as intercrops, and were therefore not included in the statistical analysis.

Table 1. Five-year total C, N, and S applied to subplots in amendments, amount of fertilizer N and S applied, aboveground wheat crop C returned to soil, and grain removed at harvest. Total amendment C varies slightly from the targeted 250 g C m^{-2} yr^{-1} due to adjustment for post-application measurement of moisture and C content. In the case of compost, the C, N, and S additions are based on the pre-composted wheat straw plus fertilizer used to speed composting. Values in a column not followed by the same letter are significantly different at *P* = 0.05, with the Type I error rate protected at 0.05.

Treatment		Additions						
Main plot	Subplot	Amendment C	Amendment N	Amendment S	Fertilizer N	Fertilizer S	Crop C	Grain removed
		g m^{-2}						
Fallow	biosolid	1253	167	50	0	0	0	0
	manure	1229	86	16	0	0	0	0
	wood	1247	4	0	0	0	0	0
	alfalfa	1253	90	7	0	0	0	0
	brassica	1253	20	5	0	0	0	0
	wheat	1239	15	3	0	0	0	0
	compost	1250	39	8	0	0	0	0
	sucrose	1244	3	0	0	0	0	0
	check	0	0	0	0	0	0	0
	cotton	1242	4	0	0	0	0	0
Wheat	biosolid	1253	167	50	0	0	1727ab	2268
	manure	1229	86	16	0	0	1556b	2063
	wood	1247	4	0	58	9	1693ab	2214
	alfalfa	1253	90	7	0	0	1611ab	2137
	brassica	1253	20	5	58	9	1657ab	2105
	wheat	1239	15	3	58	9	1644ab	1966
	compost	1250	39	8	58	9	1766a	2350
	sucrose	1244	3	0	58	9	1618ab	2165
	check	0	0	0	58	9	1751ab	2161
	cotton	1242	4	0	58	9	1634ab	2013
	SE						48	90
	P > *F*						0.0181	0.1092
Main plot means								
Fallow		1121	43	9	0	0	0	0
Wheat		1121	43	9	41	6	1666	2144

termination of amendment application. A baseline soil sample was taken from each plot at the beginning of the experiment before amendments were applied. Additional samplings were performed immediately after the last cycle of amendment and wheat harvest, 2 yr after the last harvest, and 3 yr after the last harvest (not all of the data from these samples will be presented, for reasons explained below). Soil samples consisted of 10 2-cm diam. cores from each plot from 0 to 10 cm, and three 4.4-cm diam. cores in 10-cm increments from 10- to 50-cm depth. The dry weight of each sample was used to calculate soil bulk density. Samples were oven dried at 60°C and ground with a rolling pin. The ground soil was then passed through a 2-mm sieve and then through a 1-mm sieve. Any visible organic matter not collected in the sieves was removed using tweezers. Total C, N, and S were determined using a combustion analyzer (Thermo Finnigan FlashEA 1112 Elemental Analyzer, Rodano, Italy). The samples were also analyzed for extractable NO_3 and NH_4 using an injection pump analyzer (Astoria Analyzer, Clackamas, OR). Nitrate and NH_4 were subtracted from total N to determine organic N. These soils have virtually no inorganic C near the surface, so total C is equal to SOC.

Equivalent Mass Samples

The experiment was designed in 2002 without an understanding of the importance of equivalent mass sampling techniques for overcoming bulk density and sampling bias artifacts (Ellert and Bettany, 1995; McGarry and Malafant, 1987; VandenBygaart and Angers, 2006; Wuest, 2009). When we examined our data, it was evident that treatments had different effects on soil bulk density. For this reason we took a final soil sample in March, 3.5 yr after the final harvest and 4.5 yr after the last amendment application, in a way that results in samples of equivalent mass per unit area. We collected 4.47-cm diam. intact soil cores and wrapped them in paper. After drying at 60°C, each core was gently fractured without mixing depths and soil removed from the surface end until a weight of 470 g±0.2 g dry soil was obtained. This resulted in samples that represented a soil depth of 300 kg dry soil m^{-2} (0.470 kg soil from a 0.001567 m^2 core) regardless of plot-to-plot or treatment differences in soil bulk density. This mass depth is approximately equal to a 0- to 25-cm sample at an average bulk density. After sieving and mixing, subsamples from two cores from each plot were combined for C, N, S, and extractable NO_3 and NH_4 analysis as described above.

The data were analyzed using a mixed model with main plot and subplot treatments as fixed effects, and block and block × main plot interaction as random effects. When analyzing soil samples the pretreatment soil sample (top 30 cm, with 20- to 30-cm depth weighted 50%) was used as a baseline covariate, and means were separated using the SAS Simulate adjustment to maintain the Type I error rate at <0.05 (Littell et al., 2006).

RESULTS

Table 2 gives SOC means and statistical differences. Use of the pre-treatment soil sample as a baseline reduced experimental error slightly. There was no interaction between the main plot and subplot treatment factors. This means that the amendments had the same effect on organic C, organic N, and S on fallow soil and under a wheat crop. In comparison to the fallow main plots the average difference in SOC credited to the wheat crop treatment was 482 g m^{-2}. Much of this difference is due to loss of SOC from fallow treatments over the 9-yr period. At the start of the experiment the fallow treatment receiving no amendments (check) had a baseline measurement of 4020 g SOC m^{-2} in the top 300 kg m^{-2} soil depth and ended with 3460 g SOC m^{-2} after 9 yr (Table 2). The wheat main plots receiving no amendment started at the same baseline, and after 9 yr was virtually unchanged at 4018 g SOC m^{-2}.

The SOC in the subplot treatments ranged from 3678 to 4230 g C m^{-2} (Table 2). Biosolid, manure, and wood contributions to SOC were significantly (P < 0.05) greater than the check and cotton. Amendment effects on grain yields ("Grain removed", Table 1) were not significant (P = 0.109). While the amounts of C in crop residues returned to the soil at harvest time ("Crop C") were influenced by the amendments ($P < 0.0181$, Table 1), they were not correlated to SOC ($r = 0.03$). These aboveground wheat biomass inputs, averaging 1666 g C m^{-2}, were 1.3 times greater than the total amount of amendment C applied over the 5-yr period (about 1250 g C m^{-2}).

When the SOC mean of each treatment is compared to the check, it can be seen that the treatment effects represent large differences in treatment efficiency. For example, the increase in SOC attributable to biosolid was 4230 − 3738 = 492 g C m^{-2}, which is 39% of the biosolid C applied. Treatment efficiencies were in the following order: biosolid (39%), manure (26%), wood (24%), alfalfa (14%), and brassica residue (11%). Wheat, compost, and sucrose were about 5%. Cotton efficiency was −5% because of the very low SOC content in the wheat main plots.

The large main plot treatment effect of the wheat crop compared to fallow on SOC, organic N, and S can be attributed mostly to roots. This reasoning is based on the fact that the wheat residue amendment (subplot treatment) did not substantially increase SOC over the check treatment (4147 vs. 4018 in wheat main plots, and 3489 vs. 3460 in fallow main plots, Table 2). If aboveground residue was a major factor in maintaining SOC in this wheat cropping system, we would expect to see a significant effect of added wheat residue on SOC both in the fallow main plots (where no roots were present) and in the wheat mainplots. In wheat mainplots, the wheat residue treatment provided 1.6 times the amount of aboveground residue back to the soil compared to the check treatment (1239 + 1644 g C m^{-2} vs. 1751 g C m^{-2}, Table 1), but there was a relatively small response in measured SOC. This leads us to conclude that the large effect of the wheat crop (482 g m^{-2}) must have been due to effects of belowground C.

The alfalfa treatment did not produce significantly different SOC from brassica, wheat, compost, sucrose, or the check (Table 2). The mean SOC of alfalfa was, however, greater than all but biosolid, manure, and wood. Concerning our hypothesis, we have not shown conclusively that legume foliage like alfalfa increases SOC more than an equivalent amount of wheat residue. Biosolid contained the largest amendment N and S, and increased SOC, organic N, and total S more than other amendments. In terms of our hypotheses, however, we have not shown at a 5% statistical confidence level that manure is more effective in increasing SOC than an equivalent amount of C in wheat residue. Biosolid, manure, and alfalfa treatments contained high N levels and along with wood produced the greatest measurements of SOC, while the treatments with less N differed little from unamended soil.

Organic C and N in the 0- to 10-cm soil depth at the end of the 5-yr treatment period are shown in Fig. 2. Except for the wood treatment and two of the fallow-biosolid plots, the data demonstrate a narrow C/N ratio. It is noteworthy that this tendency is not only due to treatment differences in C and N contents; replications within each treatment also tend to lie along this line. This means that there is relatively little random variation in C/N ratio between samples, even when there are large differences in C and N content of soil samples within the same treatment. This tendency was consistent for all samples taken during the experiment. Average C/N ratios at different soil depths did not change from the beginning to the end of the 5-yr treatment period. There were no substantial changes in C/N ratio below 10-cm depth. Average C/N ratios were 12.7 for 0- to

Table 2. Soil organic carbon (SOC), organic N, and total S to a depth of 300 kg m^{-2} (approximately 25 cm) 4 yr after the treatments had stopped. Main plot and subplot effects were highly significant but their interaction was not ($P > F = 0.21$ for SOC, 0.23 for organic N, and 0.71 for S). Values in a column not followed by the same letter are significantly different at $P = 0.05$, with the Type I error rate protected at 0.05.

Treatment		Final soil sample		
Main plot	Subplot	SOC	Organic N	Total S
		– g m^{-2} in top 300 kg m^{-2} soil –		
Fallow	biosolid	3984	333	41.0
	manure	3696	306	31.2
	wood	3941	299	29.7
	alfalfa	3658	304	27.7
	brassica	3692	294	29.3
	wheat	3489	284	26.3
	compost	3597	293	26.1
	sucrose	3548	288	26.1
	check	3460	277	26.9
	cotton	3469	285	26.1
Wheat	biosolid	4477	371	45.1
	manure	4413	355	35.2
	wood	4137	305	29.7
	alfalfa	4162	337	32.6
	brassica	4069	320	30.0
	wheat	4147	330	31.0
	compost	4015	327	31.1
	sucrose	4024	319	30.3
	check	4018	324	31.2
	cotton	3887	312	30.3
	SE	90	8	1.5
Main plot means				
Fallow		3653	296	29.0
Wheat		4135	330	32.6
	SE	30	2	0.6
	P > *F*	<0.0001	<0.0001	<0.0001
Subplot means				
	biosolid	4230a	352a	43.0a
	manure	4054ab	331ab	33.2b†
	wood	4038ab	302c	29.7 b
	alfalfa	3909bc	320bc	30.2b
	brassica	3880bc	307bc	29.7b
	wheat	3818bc	307bc	28.7b
	compost	3805bc	310bc	28.6b
	sucrose	3786bc	304 c	28.2b
	check	3738c	300c	29.0b
	cotton	3678c	299c	28.2b
	SE	63	5	1.1
	P > *F*	<0.0001	<0.0001	<0.0001

† For total S, in addition to the indicated mean differences, manure and sucrose are significantly different at $P < 0.05$.

10-cm, 11.9 for 10- to 20-cm, 9.7 for 20- to 30-cm, 8.6 for 30- to 40-cm, and 8.3 for 40- to 50-cm depths.

To eliminate the effect of soil bulk density on estimates of soil C, N, and S, the final soil samples (Table 2 and Fig. 3) were taken to depths equivalent to a mass of 300 kg m^{-2}. This was done 4.5 yr after the last amendment application and 3.5 yr after the last wheat harvest. The difference in the ranges of C and N concentrations between Fig. 2 and 3 are due to the different depths of sampling. The relative positions of the treatments (shown as treatment means in Fig. 3) are similar to those of the 0 to 10 cm sampling in Fig. 2. Carbon-to-nitrogen ratios are confined to a narrow range, except in the case of the wood treatment. Excluding the wood and grass treatments, a regression line fit to the data is: SOC = 0.035 + 12.00 × organic N, $r = 0.98$. This means that the C/N ratio was 12 for the 0 to 300 kg m^{-2} equivalent mass-depth (surface to approximately 25 cm).

Wood stands apart from the other treatments (Fig. 3). There was a trend of high N amendments producing greater SOC, but in fallow plots wood had low N and increased SOC nearly as much as biosolid (Table 2). The effect of wood was evident both at the end of the treatment period (Fig. 2) and 3.5 yr later (Fig. 3). The wood amendment was the only treatment to have a relatively modest increase in C and very little increase in N when comparing fallow vs. wheat main plots (Fig. 3).

The wood sawdust was in very small pieces with very good soil contact. Some of the largest particles could still be seen on the surface of the fallow plots months after application, but they represented only a small fraction of what was applied and did not accumulate year to year. Visible evidence of all the amendments disappeared a year or two after treatments ended, except for some wheat crop residue, a small amount of the cotton, and the crowns of the perennial grass crop. By the time of the final soil sampling, the entire experimental area appeared bare with only a hint of wheat crop residue remaining visible on wheat main plots.

Mineral N in the top 30 cm of soil at the end of the 5-yr treatment period ranged from 9 to 15 g m^{-2} in the fallow brassica, manure, alfalfa, and biosolid plots. We measured about 2 g m^{-2} mineral N in all other fallow plots and all main plots cropped to wheat. Three-and-a-half years later in the final soil sample all plots contained about 2 g m^{-2} mineral N.

The original plan was to have two subplot treatments which were not amendments, but instead seeded with canola and perennial grass. These would have been intercrops in the main plots planted to wheat. Failure to maintain adequate intercrops prevented us from including them in the statistical analysis. We present data for the perennial grass planted in fallow main plots, even though it was not statistically analyzed with the other treatments, because some readers may find it of interest. While growth was poor when intercropped with wheat, a good stand was established in all four replications in the fallow main plots. The levels of SOC and organic N at the end of the 5-yr treatment period and at the end of the experiment (after being killed and 3.5 yr of fallow) are shown in Fig. 2 and 3 (the lowercase "g"). The amount of N applied to the fallow main plot, grass subplots was 15 g N m^{-2}, and the amount of aboveground plant biomass C cut and returned was 1370 g C m^{-2}. The result was among the top three treatments for SOC (4187 g C m^{-2}) and top four for organic N (334 g N m^{-2}) (Fig. 3). This is despite relatively little N fertilizer being applied. It appears that perennial grass can match or exceed a fertilized winter wheat crop for SOC accretion over a 5-yr period. Compared to other treatments receiving greater total N additions, the perennial grass appears to have made efficient use of the small amount of applied N plus soil-available N to increase SOC and maintain the soil C/N ratio.

DISCUSSION

This study could be considered a pulse experiment, in the sense that the main plot and subplot treatments were introduced for a short period of time (5 yr), and then a period of time was allowed (3.5 yr) for short-term monitoring of the effects. Both of the main plot treatments were a departure from common cropping systems for this experiment site, which for this soil

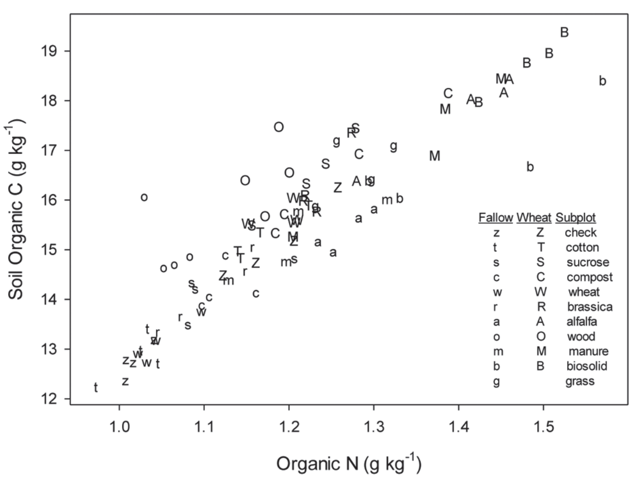

Fig. 2. Soil organic C and N concentrations in 0- to 10-cm samples taken at the end of the 5-yr treatment period. Individual replications are shown.

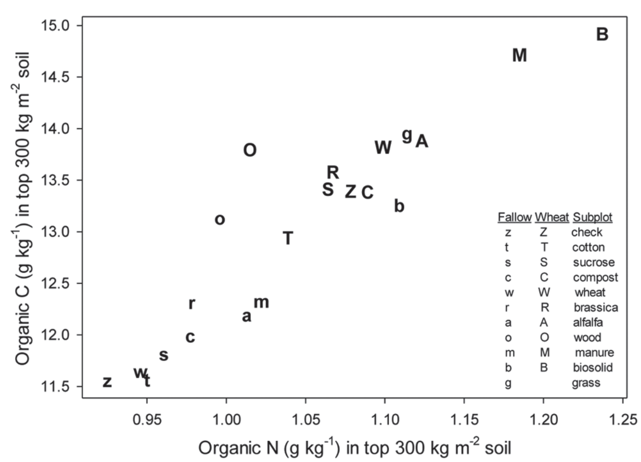

Fig. 3. Final soil samples taken 3.5 yr after the end of the 5-yr treatment period. Samples were taken to an equivalent mass depth of 300 kg m^{-2} (dry soil basis) to overcome confounding of soil bulk density differences. This is equivalent to 0 to about 25 cm. These C and N concentrations can be converted to g m^{-2} by multiplying by 300.

was primarily winter or spring wheat rotated with fallow. One main plot treatment was continuous winter wheat, and the other continuous fallow, so these represent extremes for inputs to the soil, which normally rotates between the two every other year. Because of the short duration of the study, we assume that none of the treatments were in equilibrium. In addition, most of the amendments were new to this soil system, and there may have been changes to the soil microbial communities over time. Our primary goal was to compare surface additions of wheat, manure, legume foliage, and other amendments for potential long-term effects on SOC.

Precise comparisons between soil samples taken at different times are not possible in this study because only the final sample was performed at equivalent mass depths. With the changes in soil bulk density over time and the resulting inaccuracy of sampling by linear depth from the existing soil surface, we cannot accurately estimate the gain or loss of SOC from the pre-treatment sample to the post-treatment or final samples. For that reason, this dataset probably has limited use in accurately predicting C budgets.

Wheat crop growth under all subplot treatments was relatively uniform, despite relying on organic forms of N in the unfertilized alfalfa, manure, and biosolid plots. Aboveground crop residue C at harvest differed somewhat among treatments (Table 1), but did not result in large differences in C or correlate with final SOC. Given the relative uniformity of grain yield and aboveground biomass, we might assume that belowground root mass and C contributions were uniform also. This is supported by the lack of an interaction between main plot treatments and the subplots (amendments). If there were differences in plant nutrition due to immobilization, timing of N availability, or other factors, it did not appear to have an effect on SOC levels.

The lack of statistical differences in SOC levels for most of the amendments could be due to the relatively short timeframe and the inherent difficulty in measuring changes in SOC. On the other hand, the biosolid, manure, and wood treatments, applied at the same C rate, produced responses that were both statistically different and substantial. A comparison of Fig. 2 and 3 reveals that the relative differences between treatments was quite stable, even after 3.5 yr. This indicates that amendment effects were in place and perhaps nearly complete soon after the treatments ended, and remained unchanged for the next 3.5 yr while the entire plot area was fallow. Buyanovsky and Wagner (1997) reported that 80% of the crop residue added was oxidized and returned to atmosphere as CO_2 within 2 yr. Other research indicates that the initial decay stage for forest litter takes 3 to 4 yr (Aber et al., 1990). In agricultural systems the differences in initial decay between a variety of substances including farm yard manure appear to last only for several months (Anderson and Domsch, 1989). Even in controlled incubations, Sanaullah et al. (2010) measured a quick loss of C followed by no significant loss after 3 yr of further incubation.

The lack of response to some of the residue inputs might be an important consideration when studying the effects of residue removal on soil quality. While wheat residue is considered a slowly degraded organic matter source because of its high C/N ratio, Steffens et al. (2009) found that increased grass residue inputs only increased light fraction detritus, not long-term soil organic matter, in a soil where the organo-mineral associations appeared to be close to saturation.

Like the wheat residue amendment, compost, sucrose, and cotton were not substantially different from the check. In fallow plots these treatments lost SOC compared to the pre-experiment level. In the plots cropped to wheat the maintenance of SOC can be attributed to the crop because most amendments showed no substantial difference from the unamended check. The contribution of cotton to SOC is somewhat lower than the check (Table 2). Figure 3 reveals that it is only in the wheat main plot (symbol = T) that the cotton amendment produced substantially lower SOC than the check. We do not have an explanation for this. The shredded cotton linters were in the form of a loosely matted paper, and even when shredded this formed a white layer over the soil surface. This might have altered soil or canopy conditions, but grain and residue yields were not substantially different from other treatments (Table 1). There were visible amounts of cotton still on the soil surface at the end of the 5-yr application period, but virtually none left 4 yr later. None of the treatments had significant losses of amendment due to wind.

Biosolid, manure, and wood were more effective in maintaining SOC than the other treatments. Wood affected soil C/N ratio more than all the other treatments, which will be discussed later. Biosolid, manure, and alfalfa were all high in N content, but alfalfa did not change SOC or organic N content as much as the other two. Biosolid and manure are extensively decomposed materials, whereas the alfalfa was undecomposed dried plant matter. Heike (2011) provides evidence that microbial peptides can be a major part of stabilized SOC. Machado (2011) reported elevated SOC due to manure and legume foliage applications to a winter wheat–fallow rotation in an 80-yr experiment. From that same experiment we know that manure applications caused an increase in several measures of glomalin (Wuest et al., 2005).

The composted wheat residue treatment was another amendment subjected to pre-application microbial processing, but its effect on SOC was similar to the unamended check and nearly identical to wheat residue (Table 2). This could be due to the amount of compost applied, which was 250 g C m^{-2} yr^{-1} as pre-composted wheat residue weight. It would have been interesting to compare the effect of compost at 250 g C m^{-2} yr^{-1} of post-composted C content to the effects of manure and biosolid.

In addition to the different environment for fungal and bacterial activity, composting would be expected to alter potential particulate organic matter interactions that depend on the size of detritus and its availability to be infected by fungus or bacteria within soil aggregates. As measured here, the effect of compost on SOC was not substantially different from the effect of wheat residue, sucrose, cotton, or the check.

High levels of extractable mineral N were available at the end of the 5-yr application period in the fallow plots amended with biosolid, manure, and alfalfa (see Results). It is likely that relatively high levels of N were also available in the wheat plots treated with these high N amendments, especially before the wheat crop began to compete with microbes for available N. The same would be true of the availability of fertilizer N in the wheat plots between planting and extensive establishment of wheat roots. If high levels of available N helped microbes to mineralize or stabilize the low-N amendments, we might expect to see an interaction between low-N amendments (cotton, sucrose, wood) in the fertilized wheat main plots vs. unfertilized fallow main plots. Except, perhaps, in the case of wood, we detected no interaction of amendment with the wheat crop. Our results support the results of Triberti et al. (2008) where they found that large additions of mineral N increased SOC only slightly, and found no interaction with organic amendments.

In fallow main plots the wood amendment increased SOC substantially (481 g m^{-2}) compared to the check, whereas in wheat main plots the wood amendment did not increase SOC as much (119 g m^{-2}) above the check (Table 2 and Fig. 3). This might be evidence that, in the case of wood, low N availability in fallow decreased loss of C. Fungal species that degrade wood in forest ecosystems work under very low N supply, but can increase wood decomposition with modest increases in N availability (Allison et al., 2009). The plots receiving wood amendments had greater C/N ratio (treatment mean = 13.4) than any other plots. The difference in soil C/N ratio could be because wood supplied a different form of C compound (lignin) that was stable enough to remain and increase SOC at the time of the final sampling, or perhaps the wood was decomposed by organisms producing compounds with a different C/N ratio. Fungal/bacterial ratios are greater at forest sites where lignin is abundant and lower where certain N-bearing compounds are abundant (Grandy et al., 2009). Cleveland and Liptzin (2007) reported that molar C/N ratios of fungal biomass ranged from 5 to 17 compared to a ratio of 6.5 for bacteria.

In hindsight, there are some additional treatments that would have proven useful. One would be a treatment where all aboveground residues from the wheat crop main plot were removed to determine how much of the SOC could be credited to aboveground vs. belowground inputs. Our results indicate the addition of extra wheat residue to the surface did not influence SOC much, if any, so roots may be the dominant source of soil C in this wheat system. Rhizodeposition is difficult to estimate, but it is believed to be equal to or greater than aboveground C production (Allmaras et al., 2004; Johnson et al., 2006). Another possible treatment would be to apply the amendments at equal N rates instead of equal C rates to help clarify the influence of amendment N on SOC.

CONCLUSIONS

Application of a wide variety of C-containing amendments at the same C rate to field plots produced SOC changes ranging from −5 to 39% of applied C. Some amendments had very similar, and some very different effects on SOC. Complex compounds like wheat straw did not necessarily have a greater effect than simple compounds like sucrose. Nitrogen content may have played an important role. Alfalfa foliage, an easily decomposed material with a high N content, showed a tendency to increase SOC more than the low N content amendments (excepting wood), but to a lesser degree than the other high N amendments manure and biosolid.

Five years of winter wheat or perennial grass cropping increased SOC about the same as the most effective amendment (biosolid), indicating that wheat and perennial grass roots have a greater influence than a crop's surface residue in a no-till continuous cropping system under semiarid conditions. This supports previous research conclusions that calculation of a reasonable soil C budget is not possible without better estimates of belowground contributions to the plant-soil system. Aboveground wheat residues may be a reasonable proxy for relative C input from a wheat cropping system, but the surface residues may actually play a minor role.

REFERENCES

Aber, J.D., J.M. Melillo, and C.A. McClaugherty. 1990. Predicting long-term patterns of mass loss, nitrogen dynamics, and soil organic matter formation from initial fine litter chemistry in temperate forest ecosystems. Can. J. Bot. 68:2201–2208. doi:10.1139/b90-287

Allison, S.D., D.S. LeBauer, M.R. Ofrecio, R. Reyes, A.M. Ta, and T.M. Tran. 2009. Low levels of nitrogen addition stimulate decomposition by boreal forest fungi. Soil Biol. Biochem. 41:293–302. doi:10.1016/j.soilbio.2008.10.032

Allmaras, R.R., D.R. Linden, and C.E. Clapp. 2004. Corn-residue transformations into root and soil carbon as related to nitrogen, tillage, and stover management. Soil Sci. Soc. Am. J. 68:1366–1375. doi:10.2136/sssaj2004.1366

Anderson, T.H., and K.H. Domsch. 1989. Ratios of microbial biomass carbon to total organic carbon in arable soils. Soil Biol. Biochem. 21:471–480. doi:10.1016/0038-0717(89)90117-X

Bhogal, A., F.A. Nicholson, I. Young, C. Sturrock, A.P. Whitmore, and B.J. Chambers. 2011. Effects of recent and accumulated livestock manure carbon additions on soil fertility and quality. Eur. J. Soil Sci. 62:174–181. doi:10.1111/j.1365-2389.2010.01319.x

Buyanovsky, G.A., and G.H. Wagner. 1997. Crop residue input to soil organic matter on Sanborn field. In: E.A. Paul et al., editors, Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Campbell, C.A., B.G. McConkey, R.P. Zentner, F. Selles, and D. Curtin. 1996. Tillage and crop rotation effects on soil organic C and N in a coarse-textured Typic Haploboroll in southwestern Saskatchewan. Soil Tillage Res. 37:3–14. doi:10.1016/0167-1987(95)01002-5

Cleveland, C.C., and D. Liptzin. 2007. C:N:P stoichiometry in soil: Is there a "Redfield ratio" for the microbial biomass? Biogeochemistry 85:235–252.

Doyle, G.L., C.W. Rice, D.E. Peterson, and J. Steichen. 2004. Biologically defined soil organic matter pools as affected by rotation and tillage. Special issue: Natural resource management to offset greenhouse gas emissions. Environ. Manage. 33 (Suppl. 1):S528–S538. doi:10.1007/s00267-003-9160-z

Drinkwater, L.E., P. Wagoner, and M. Sarrantonio. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature (London) 396:262–265. doi:10.1038/24376

Ellert, B.H., and J.R. Bettany. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75:529–538. doi:10.4141/cjss95-075

Emerson, W.W. 1959. The structure of soil crumbs. J. Soil Sci. 10:235–244. doi:10.1111/j.1365-2389.1959.tb02346.x

Gentile, R., B. Vanlauwe, P. Chivenge, and J. Six. 2010. Trade-offs between the short- and long-term effects of residue quality on soil C and N dynamics. Plant Soil 338:159–169. doi:10.1007/s11104-010-0360-z

Grandy, A.S., M.S. Strickland, C.L. Lauber, M.A. Bradford, and N. Fierer. 2009. The influence of microbial communities, management, and soil texture on soil organic matter chemistry. Geoderma 150:278–286. doi:10.1016/j.

geoderma.2009.02.007
Gregorich, E.G., C.F. Drury, B.H. Ellert, and B.C. Liang. 1997. Fertilization effects on physically protected light fraction organic matter. Soil Sci. Soc. Am. J. 61:482–484. doi:10.2136/sssaj1997.03615995006100020016x
Gregorich, E.G., and H.H. Janzen. 1996. Storage of soil carbon in the light fraction and macroorganic matter. In: M.R. Carter and B.A. Stewart, editors, Structure and soil organic matter storage in agricultural soils. CRC Press, Boca Raton, FL. p. 167–190.
Heike, K. 2011. Soil organic N- An under-rated player for C sequestration in soils? Soil Biol. Biochem. 43:1118–1129. doi:10.1016/j.soilbio.2011.02.020
Homann, P.S., J.S. Kapchinske, and A. Boyce. 2007. Relations of mineral-soil C and N to climate and texture: Regional differences within the conterminous USA. Biogeochemistry 85:303–316.
Johnson, J.M., R.R. Allmaras, and D.C. Reicosky. 2006. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. Agron. J. 98:622–636. doi:10.2134/agronj2005.0179
Kiem, R., and I. Kögel-Knabner. 2003. Contribution of lignin and polysaccharides to the refractory carbon pool in C-depleted arable soils. Soil Biol. Biochem. 35:101–118. doi:10.1016/S0038-0717(02)00242-0
Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS for mixed models. 2nd ed. SAS Inst., Cary, NC.
Lutzow, M.v., I. Kogel-Knabner, K. Ekschmitt, E. Matzner, G. Guggenberger, B. Marschner, and H. Flessa. 2006. Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions-A review. Eur. J. Soil Sci. 57:426–445. doi:10.1111/j.1365-2389.2006.00809.x
Machado, S. 2011. Soil organic carbon dynamics in the Pendleton long-term experiments: Implications for biofuel production in Pacific Northwest. Agron. J. 103:253–260. doi:10.2134/agronj2010.0205s
Marschner, B., S. Brodowski, A. Dreves, G. Gleixner, A. Gude, P.M. Grootes et al. 2008. How relevant is recalcitrance for the stabilization of organic matter in soils? Topical issue: Mechanisms and regulation of organic matter stabilization in soils. J. Plant Nutr. Soil Sci. 171:91–110. doi:10.1002/jpln.200700049
McGarry, D., and K.W.J. Malafant. 1987. A cumulative mass coordinate to determine water profile changes in variable volume soil. Soil Sci. Soc. Am. J. 51:850–854. doi:10.2136/sssaj1987.03615995005100040002x
Moran, K.K., J. Six, W.R. Horwath, and C. van Kessel. 2005. Role of mineral-nitrogen in residue decomposition and stable soil organic matter formation. Soil Sci. Soc. Am. J. 69:1730–1736. doi:10.2136/sssaj2004.0301
Paterson, E., B. Thornton, A.J. Midwood, S.M. Osborne, A. Sim, and P. Millard. 2008. Atmospheric CO2 enrichment and nutrient additions to planted soil increase mineralisation of soil organic matter, but do not alter microbial utilisation of plant- and soil C-sources. Soil Biol. Biochem. 40:2434–2440. doi:10.1016/j.soilbio.2008.06.005
Post, W.M., and L.K. Mann. 1990. Changes in soil organic carbon and nitrogen as a result of cultivation. In: A.F. Bouwman, editors, Soils and the greenhouse effect. John Wiley & Sons, New York. p. 401–406.
Sanaullah, M., A. Chabbi, J. Leifeld, G. Bardoux, D. Billou, and C. Rumpel. 2010. Decomposition and stabilization of root litter in top- and subsoil horizons: What is the difference? Plant Soil 338:127–141. doi:10.1007/s11104-010-0554-4
Steffens, M., A. Kölbl, and I. Kögel-Knabner. 2009. Alteration of soil organic matter pools and aggregation in semi-arid steppe topsoils as driven by organic matter input. Eur. J. Soil Sci. 60:198–212. doi:10.1111/j.1365-2389.2008.01104.x
Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water stable aggregates in soils. J. Soil Sci. 33:141–164. doi:10.1111/j.1365-2389.1982.tb01755.x
Triberti, L., A. Nastri, G. Giordani, F. Comellini, G. Baldoni, and G. Toderi. 2008. Can mineral and organic fertilization help sequestrate carbon dioxide in cropland? Eur. J. Agron. 29:13–20. doi:10.1016/j.eja.2008.01.009
VandenBygaart, A.J., and D.A. Angers. 2006. Towards accurate measurements of soil organic carbon stock change in agroecosystems. Can. J. Soil Sci. 86:465–471. doi:10.4141/S05-106
West, T.O., and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Sci. Soc. Am. J. 66:1930–1946. doi:10.2136/sssaj2002.1930
Wright, A.L., and F.M. Hons. 2005. Soil carbon and nitrogen storage in aggregates from different tillage and crop regimes. Soil Sci. Soc. Am. J. 69:141–147.
Wuest, S.B. 2009. Correction of bulk density and sampling method biases using soil mass per unit area. Soil Sci. Soc. Am. J. 73:312–316. doi:10.2136/sssaj2008.0063
Wuest, S.B., T.C. Caesar-TonThat, S.F. Wright, and J.D. Williams. 2005. Organic matter addition, N, and residue burning effects on infiltration, biological, and physical properties of an intensively tilled silt-loam soil. Soil Tillage Res. 84:154–167. doi:10.1016/j.still.2004.11.008