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Long-Term Cropping System Effects on Carbon Sequestration in Eastern Oregon

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ABSTRACT

Soil organic carbon (SOC) has beneficial effects on soil quality and productivity. Cropping systems that maintain and/or improve levels of SOC may lead to sustainable crop production. This study evaluated the effects of long-term cropping systems on C sequestration. Soil samples were taken at 0- to 10-, 10- to 20-, 20- to 30-, and 30- to 40-cm soil depth profiles from grass pasture (GP), conventional tillage (CT) winter wheat (*Triticum aestivum* L.)–fallow (CTWF), and fertilized and unfertilized plots of continuous winter wheat (WW), spring wheat (SW), and spring barley (*Hordeum vulgare* L.) (SB) monocultures under CT and no-till (NT). The samples were analyzed for soil organic matter (SOM) and SOC was derived. Ages of experiments ranged from 6 to 73 yr. Compared to 1931 SOC levels (initial year), CTWF reduced SOC by 9 to 12 Mg ha^{-1} in the 0- to 30-cm zone. Grass pasture increased SOC by 6 Mg ha^{-1} in the 0- to 10-cm zone but decreased SOC by 3 Mg ha^{-1} in the 20- to 30-cm zone. Continuous CT monocultures depleted SOC in the top 0- to 10-cm zone and the bottom 20- to 40-cm zone but maintained SOC levels close to 1931 SOC levels in the 10- to 20-cm layer. Continuous NT monocultures accumulated more SOC in the 0- to 10-cm zone than in deeper zones. Total SOC (0- to 40-cm zone) was highest under GP and continuous cropping and lowest under CTWF. Fertilizer increased total SOC only under CTWW and CTSB by 13 and 7 Mg ha^{-1} in 13 yr, respectively. Practicing NT for only 6 yr had started to reverse the effect of 73 yr of CTWF. Compared to CTWF, NTWW and NTSW sequestered C at rates of 2.6 and 1.7 Mg ha^{-1} yr^{-1}, respectively, in the 0- to 40-cm zone. This study showed that the potential to sequester C can be enhanced by increasing cropping frequency and eliminating tillage.

Soil organic matter (SOM) is essential for sustaining soil and crop productivity. Soil organic matter consists of carbon (C) based compounds that improve soil structure, nutrient storage, and water holding capacity. In agricultural lands, tillage, fertility, crop rotations, and cropping intensity influence the rate at which C is added to or removed from soil (Franzluebbers, 2004). In eastern Oregon, the predominant cropping system is conventional tillage (CT) winter wheat (WW)–summer fallow (CTWF). This system is used primarily to store moisture, and allow for better weed control and better seedbed conditions (McGregor, 1989; Brumfield, 1997). The CTWF system also accumulates nutrients (N, S) and is economical where average annual rainfall is less than 325 mm (Leggett et al., 1974; Bolton and Glen, 1983). However, this system depletes soil organic matter (SOM) and renders the soil susceptible to wind and water erosion (McGregor, 1989). Growing one crop every 2 yr adds less SOC than annual cropping. Furthermore, CT enhances biological oxidation of SOC (Rasmussen et al., 1980, 1998; Rasmussen and Parton, 1994; Reicosky et al., 1995). No-tillage coupled with annual cropping has been proposed to minimize or halt the loss of SOC and maintain soil productivity. Soil organic matter and biological sustainability can also be improved by intensifying crop production through annual cropping. Greater biomass production and greater percent of plant residue have been measured under intensive cropping systems (Wood et al., 1991). By combining intensive or continuous cropping with NT systems, farmers may reduce soil organic matter loss (Collins et al., 1992) and maintain or improve soil productivity.

Convincing growers to adopt NT cropping systems on the basis of amount of C sequestered is not an easy task. This is primarily because ecological processes are slow and determinations of the amount of C sequestered take many years and require long-term experimentation. Fortunately the Oregon State University, Columbia Basin Agricultural Research Center (CBARC) near Pendleton, Oregon, is home to long-term experiments that were initiated in 1931. These experiments have different tillage, fertility, cropping intensity, and crop rotation treatments that can shed light on effects of cropping systems on C sequestration. Information that compares the effects of CT and NT cropping systems under fallow and continuous cropping on C sequestration under eastern Oregon conditions is minimal (Rasmussen et al., 1998). The objective of this study was to determine the effects of tillage, fertility, crop intensity, and crop species on C sequestration under eastern Oregon conditions.

MATERIALS AND METHODS

Experiments

Development of sustainable cropping systems relies heavily on the understanding of numerous and complex interactions among plant, soil, water, and pest factors. The effects of cropping systems on these interactions occur slowly and only well-established long-term experiments provide the setup for identifying and understanding the processes involved. Data were collected from long-term experiments at CBARC, Pendleton, Oregon (45.7° N, 118.6° W, elevation of 438 m above mean sea level). The soil at CBARC is a Walla Walla silt loam (coarse, silty, mixed, mesic Typic Haploxeroll). Average annual crop-year (1 September to 31 August) precipitation is about 406 mm. The CBARC is home to some of the oldest agricultural experiments in the western United States, with experiments dating back to 1931. These long-term experiments, consisting of experiments that have different tillage, fertility, cropping intensity, and crop rotation treatments, can shed light on C sequestration

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Abbreviations: CBARC, Columbia Basin Agricultural Research Center; CT, conventional tillage; D_b, bulk density; GP, grass pasture; NT, no-tillage; SB, spring barley; SOC, soil organic carbon; SOM, soil organic matter; SW, spring wheat; WF, winter wheat–fallow; WW, winter wheat.

of various cropping systems. The grass pasture (GP), which has not been cultivated since 1931, serves as a baseline for evaluating changes in other cropping systems, and has been occasionally fertilized. The dominant grass species are currently bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Á. Löve var. 'Secar'] and Idaho fescue (*Festuca idahoensis* Elmer var. 'Joseph'). The CTWF land has been in crop production since 1931 and receives 90 kg N ha^{-1} yr^{-1}. The continuous CTWW, CTSW, and CTSB monocultures were initiated in 1931, 1977, and 1982, and currently receive 100, 90, and 90 kg N ha^{-1} yr^{-1}, respectively. Plots of CTWW, CTSW, and CTSB that received no fertilizer were initiated in 1993. The CT plots were moldboard-plowed to a depth of about 20 cm. Continuous NTWW, NTSW, and NTSB experiments were initiated in 1997 and consist of unfertilized plots and fertilized plots that currently receive 112, 100, and 100 kg N ha^{-1} yr^{-1}, respectively. The NT plots were established on ground that was under CTWF since 1931. All these experiments have different cropping histories (Table 1) dating back to 1931.

Soil Organic Matter Determination

2003

To determine the effects of these cropping systems on C sequestration, four soil cores were taken from the 0- to 40-cm depth in each plot using a hand probe (40-cm length and 18-cm i.d.) in 2003. Each core was sectioned into 10-cm increments to obtain samples from the 0- to 10-, 10- to 20-, 20- to 30-, and 30- to 40-cm soil depth profiles (zones). Loose crop residues were cleared from the surface before sampling. Four plots (locations in GP) in each experiment were sampled. Samples from each zone were oven-dried at 40°C for 48 h before being sent for soil organic matter (SOM) analysis at a commercial laboratory which uses the modified Walkley–Black method (Page et al., 1982). Soil samples were ground to pass a 2-mm sieve. Roots were not separated from the samples. Soil organic C was estimated by dividing SOM by 1.724.

Table 1. Current cropping systems and cropping history of long-term experiments at the Columbia Basin Agricultural Research Center, Pendleton, Oregon.†

Current cropping system		Cropping history			
Cropping system	Years since initiation	Cropping system	Years	Cropping system	Years
GP	73				
CTWF	73				
CTWWN	73				
CTSWN	28	CTWW	45		
CTSBN	24	CTWW	45	CTSW	4
NTWWN	6	CTSW	45	CTWF	22
NTSWN	6	CTSW	45	CTWF	22
NTSBN	6	CTSW	45	CTWF	22
CTWW0N	13	CTWW	60		
CTSW0N	13	CTWW	45	CTSW	15
CTSB0N	13	CTWW	45	CTSW, CTSB	4, 11
NTWW0N	6	CTSW	45	CTWF	22
NTSW0N	6	CTSW	45	CTWF	22
NTSB0N	6	CTSW	45	CTWF	22

† GP, grass pasture; CTWF, conventional tillage winter wheat–fallow; CTWWN, fertilized conventional tillage continuous winter wheat; CTWW0N, unfertilized conventional tillage continuous winter wheat; NTWWN, fertilized no-tillage continuous winter wheat; NTWW0N, unfertilized no-tillage continuous winter wheat; CTSWN, fertilized conventional tillage continuous spring wheat; CTWW0N, unfertilized conventional tillage continuous spring wheat; NTSWN, fertilized no-tillage continuous spring wheat; NTWW0N, unfertilized no-tillage continuous spring wheat; CTSBN, fertilized conventional tillage continuous spring barley; CTSB0N, unfertilized conventional tillage continuous spring barley; NTSBN, fertilized no-tillage continuous spring barley; NTSB0N, unfertilized no-tillage continuous spring barley.

1931

Data on SOM levels, obtained in 1931 at 8- and 23-cm soil depths, were also included in this study for comparisons. Details on sampling are not available. Soil organic matter of samples obtained in 1931 was determined using the "loss-on-ignition method" (Page et al., 1982).

Bulk Density Determination

Bulk density (D_b) values that were used to convert SOC percentages to weight per area were obtained following the method used by Gollany et al. (2005). A hand probe (40-cm length and 18-cm i.d.) was used to collect samples from the 0- to 40-cm depth in proximity to locations sampled for SOC. Each core was sectioned into 10-cm increments. Soil cores were oven-dried (105°C) and weighed. The oven-dry soil mass and sample volume (10-cm section and 18-mm diameter) were used for D_b determinations.

Grain Yield and Straw Determinations

Grain yield and straw weights reported in this study were obtained from 1997–1998 to 2002–2003 crop-years. At harvest, four bundle samples were obtained from each plot. Each bundle consisted of four drill rows, 1 m long; the bundles were hand cut and threshed, then analyzed for straw and grain weight. A Hege plot combine (Wintersteiger AG, Eging am See, Germany) was used to harvest the remaining crop. Bundle yields were highly correlated to combine yields ($r = 0.94$, $P < 0.001$).

Data Analysis

The oldest of the experiments (CTWW) was established in 1931 and the experimental design does not conform to the currently accepted experimental designs. The other experiments (CTSW, CTSB, NTWW, NTSW, and NTSB) were established following the design of CTWW. The fertilized and unfertilized treatments in each experiment have four subplots but the treatments are not replicated. However, the experiments were situated on uniformly deep soil; therefore, long-term data obtained from this experiment are likely to be influenced more by treatments than soil factors. Based on a soil survey conducted in 1931, the soil where the experiments are situated is 1.2 m deep to caliche (clay layer) and about 2.4 m to bedrock. Because of the nature of the design, it was impossible to compute tillage and fertilizer interactions. Therefore, to simplify the analysis, each tillage and fertilizer combination was considered a treatment, making a total of 14 treatments (Table 1).

Statistical methods suitable for analyzing unreplicated experiments were used to analyze these data (Perrett, 2004). The data were analyzed as a split plot design. The whole plot was a strip of field assigned to one of 14 treatments. The blocking factor for the whole plot is the field. Each whole plot is divided into four subplots. Four repeated measurements (samples at four depths) were taken from each subplot. It was assumed that the measures taken in each subplot of the whole plot are spatially independent. It is likely that there is some correlation among the measures taken from the sections of the same strip of field. However, such correlation is likely minimal. Also, the procedure used should be robust to small amounts of correlation. There is some limitation to this method, though. Because only one block (or field) was observed, there is no measure of what will happen on fields that are very dissimilar from this field. Therefore the results are generalizable to fields of the same nature as this field.

The whole plot was analyzed as an unreplicated randomized complete block design (RCBD) with subsampling according to Perrett (2004). The test statistic is:

$$t = \frac{\bar{y}_{i\bullet\bullet} - \bar{y}_{i'\bullet\bullet}}{\sqrt{\frac{2\hat{\sigma}_s^2}{b}\left(\frac{\rho_0}{1-\rho_0} + \frac{1}{s}\right)}} \quad [1]$$

where $\hat{\sigma}_s^2$ is a pooled estimate of the variability among sections within a strip of plot, ρ_0 is the plug-in value of the intraclass correlation coefficient (ICC), s is the number of subplots (4), and b is the number of fields (1). The ICC was estimated from the following equation:

$$\rho_0 = \frac{\sigma_W^2}{\sigma_W^2 + \sigma_S^2} \quad [2]$$

where σ_W^2 is whole plot variability and σ_S^2 is between subplot variability within whole plot. The value of ρ_0 used in this experiment was 0.2. The analysis compared average organic C in the 0- to 40-cm soil profile and organic C at each individual depth for all treatments. The p values for these comparisons are shown in Table 2.

RESULTS AND DISCUSSION

Tillage Effects on Carbon Sequestration

The long-term effects of different cropping systems on SOC under different cropping systems are shown in Fig. 1 through 4. The p values for treatment comparisons shown in these figures are shown in Table 2. No direct comparisons were made on SOC between CT and NT plots because of the different ages of the experiments. The NT plots were only 6 yr old compared to the GP and CT plots that were between 13 and 73 yr old at the time of the sampling in 2003 (Table 1). The SOC values in CT and NT treatments were each compared to SOC in GP and CTWF. So the same values of SOC from GP and CTWF were used in Fig. 1 through 4 for comparisons with other cropping systems values.

In GP, SOC was highest (31 Mg ha^{-1}) in the 0- to 10-cm zone and decreased with depth to 11 Mg ha^{-1} in the 30- to 40-cm zone. Because no tillage was practiced in GP, high SOC levels in GP in the 0- to 10-cm zone could be attributed to the large quantity of grass residues on the surface and high root biomass in topsoil. The reduction in SOC at lower depths indicated that the grasses grown were probably shallow rooted or produced less root biomass at greater depths. Compared to SOC levels in 1931, SOC under GP was 6 Mg ha^{-1} more in the 0- to 10-cm zone and 3 Mg ha^{-1} lower in the 20- to 30-cm zone.

The CTWF system had the lowest SOC at all depths, ranging from 16 Mg ha^{-1} in the 0- to 10-cm zone down to 9 Mg ha^{-1} in the 30- to 40-cm zone clearly indicating that fallowing depleted SOC compared to annual cropping. Growing one crop in 2 yr coupled with CT exacerbated the reduction in SOC. Relative to the SOC levels in 1931, fallowing decreased SOC by 9 and 12 Mg ha^{-1} in the 0- to 10- and 20- to 30-cm zone, respectively. Many other studies have shown that continuous cropping sequesters more SOC than the fallow system (Halvorson et al., 2002a, 2002b; Sherrod et al., 2003; Collins et al., 1992; Campbell et al., 2005).

Table 2. Comparisons (p values) of soil organic carbon between different tillage treatments.

Treatment†		Soil depth profile				
		0–40	0–10	10–20	20–30	30–40
Conventional tillage, fertilized (Fig. 1)						
1-CTWF	2-GP	<0.0001	<0.0001	0.0001	0.0689	0.1374
1-CTWF	3-CTWW	0.0001	0.7481	0.0002	0.0001	0.0077
1-CTWF	7-CTSW	0.0122	0.0550	0.0074	0.2682	0.8947
1-CTWF	11-CTSB	0.0001	0.0188	<0.0001	0.0349	0.1483
2-GP	3-CTWW	0.2390	<0.0001	0.7569	0.0202	0.2064
2-GP	7-CTSW	0.0055	0.0031	0.1259	0.4603	0.1745
2-GP	11-CTSB	0.2643	0.0106	0.7176	0.7562	0.9668
3-CTWW	7-CTSW	0.0910	0.1063	0.2183	0.0029	0.0109
3-CTWW	11-CTSB	0.9500	0.0399	0.5030	0.0416	0.1922
7-CTSW	11-CTSB	0.0801	0.6410	0.0510	0.2962	0.1876
Conventional tillage, unfertilized (Fig. 2)						
1-CTWF	2-GP	<0.0001	<0.0001	0.0001	0.0689	0.1374
1-CTWF	4-CTWW	0.0471	0.6388	0.0370	0.0474	0.7788
1-CTWF	8-CTSW	0.0121	0.0962	0.0113	0.2551	0.3897
1-CTWF	12-CTSB	0.0031	0.0801	0.0020	0.1486	0.2372
2-GP	4-CTWW	0.0011	<0.0001	0.0319	0.8613	0.2249
2-GP	8-CTSW	0.0056	0.0014	0.0918	0.4796	0.5222
2-GP	12-CTSB	0.0209	0.0018	0.2879	0.6943	0.7541
4-CTWW	8-CTSW	0.5668	0.2286	0.6238	0.3790	0.5607
4-CTWW	12-CTSB	0.2786	0.1961	0.2597	0.5707	0.3646
8-CTSW	12-CTSB	0.6056	0.9272	0.5202	0.7524	0.7430
No-tillage, fertilized (Fig. 3)						
1-CTWF	2-GP	<0.0001	<0.0001	0.0001	0.0689	0.1374
1-CTWF	5-NTWW	0.0185	0.0451	0.0380	0.2210	0.9527
1-CTWF	9-NTSW	0.1130	0.1872	0.4188	0.1877	0.9597
1-CTWF	13-NTSB	0.7154	0.5890	0.9268	0.8149	0.8319
2-GP	5-NTWW	0.0035	0.0039	0.0311	0.5355	0.1532
2-GP	9-NTSW	0.0003	0.0005	0.0009	0.6003	0.1507
2-GP	13-NTSB	<0.0001	<0.0001	0.0001	0.1102	0.0913
5-NTWW	9-NTSW	0.4103	0.4726	0.1920	0.9233	0.9929
5-NTWW	13-NTSB	0.0434	0.1357	0.0466	0.3198	0.7859
9-NTSW	13-NTSB	0.2177	0.4303	0.4731	0.2760	0.7927
No-tillage, unfertilized (Fig. 4)						
1-CTWF	2-GP	<0.0001	<0.0001	0.0001	0.0689	0.1374
1-CTWF	6-NTWW	0.0020	0.0109	0.0295	0.0348	0.7341
1-CTWF	10-NTSW	0.0490	0.2635	0.1051	0.0731	0.9791
1-CTWF	14-NTSB	0.9927	0.9757	0.7731	0.8914	0.5895
2-GP	6-NTWW	0.0303	0.0184	0.0399	0.7552	0.2476
2-GP	10-NTSW	0.0011	0.0003	0.0095	0.9772	0.1309
2-GP	14-NTSB	<0.0001	<0.0001	0.0002	0.0910	0.0458
6-NTWW	10-NTSW	0.2099	0.1332	0.5536	0.7336	0.7145
6-NTWW	14-NTSB	0.0020	0.0101	0.0563	0.0473	0.3808
10-NTSW	14-NTSB	0.0500	0.2510	0.1792	0.0963	0.6076

† CT, conventional tillage; GP, grass pasture; NT, no-tillage; SB, spring barley; SW, spring wheat; WF, winter wheat–fallow; WW, winter wheat.

Tillage influenced the amount and distribution of SOC in the soil profile. In both fertilized and unfertilized plots under continuous cropping (Fig. 1 and 2), CT depleted SOC in the 0- to 10- and 20- to 40-cm zones, but increased SOC levels in the 10- to 20-cm zone relative to 1931 SOC levels. The SOC was low in the 0- to 10-cm zone because residues were constantly removed by soil inversion. The reduction in SOC in the 0- to 10-cm zone could also be attributed to faster decomposition than at deeper zones. Franzluebbers (2004) revealed that SOC decomposed faster in topsoil than at greater depths. The 10- to 20-cm zone coincided with the depth of plow (20 cm) where most of the residues were buried, resulting in high levels of SOC in this zone. These conclusions are supported by Allmaras et al. (1996) who showed that 70% of oat residues were buried to a depth of 12 to 24 cm by moldboard plowing to a depth of 25 cm. In the 10- to 20-cm zone, SOC levels under fertilized plots of CTWW and CTSBN were not different

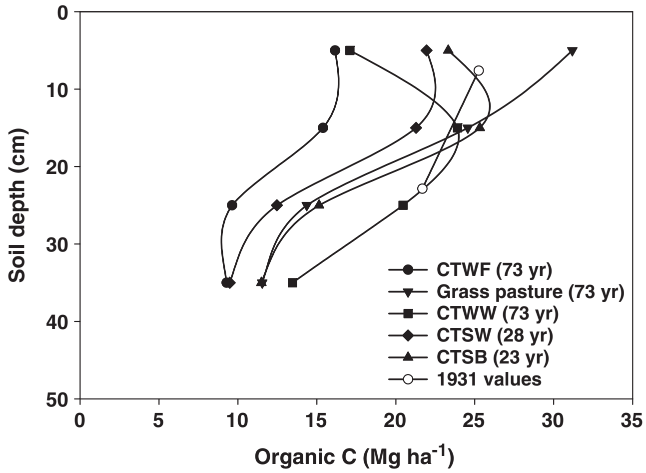

Fig. 1. Long-term effects of conventional tillage (CT) winter wheat–fallow (CTWF), grass pasture (GP), fertilized CT continuous winter wheat (CTWW), fertilized CT continuous spring wheat (CTSW), and fertilized CT continuous spring barley (CTSB) on soil organic carbon at the Columbia Basin Agricultural Research Center, Pendleton, Oregon.

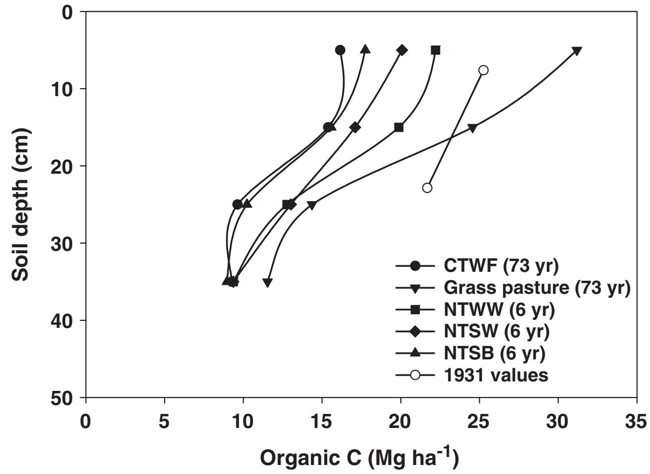

Fig. 3. Long-term effects of conventional tillage (CT) winter wheat–fallow (CTWF), grass pasture (GP), fertilized no-tillage (NT) continuous winter wheat (NTWW), fertilized NT continuous spring wheat (NTSW), and fertilized NT continuous spring barley (NTSB) on soil organic carbon at the Columbia Basin Agricultural Research Center, Pendleton, Oregon.

from 1931 SOC levels, indicating that annual cropping of these crops was able to maintain SOC in this zone even under CT conditions. There were significant correlations between SOC in the 10- to 20-cm zone and straw weight ($r = 0.56$; $P < 0.01$), indicating that SOC sequestration under CT can be enhanced by growing of crops that produce high biomass. Straw weight was highly correlated with grain yield ($r = 0.86$, $P < 0.0001$; Table 3). The SOC in the 20- to 40-cm zone that was below the plow zone could be attributed to roots. The decrease in SOC in this zone could, therefore, indicate that root biomass decreased with depth.

Under NT, SOC in both fertilized and unfertilized plots followed trends in GP, where SOC was highest in the 0- to 10-cm zone and decreased with depth (Fig. 3 and 4). There were no correlations between SOC and straw weight ($r = -0.06$) under NT, indicating that aboveground biomass did not directly influence SOC in the soil profile. Because residues were not incorporated into the soil, levels of SOC observed in the soil profile could be attributed mostly to roots. Qin et al. (2004) showed that root length density under NT was higher in the topsoil and lower at greater depths than under CT.

Total SOC values in the 0- to 40-cm zone are shown in Table 3. Accumulation of SOC was influenced by tillage and cropping frequency, with less tillage and high cropping intensity favoring C sequestration. The opposite was true for more tillage and less intensive cropping. Total SOC was highest in GP, a treatment that mimics the natural grassland. No-tillage was practiced in GP and grass residue was infrequently harvested or burnt only for management purposes. Total SOC was lowest in

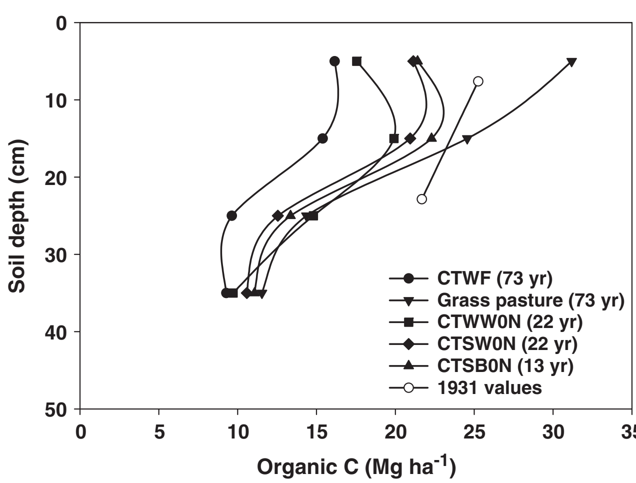

Fig. 2. Long-term effects of conventional tillage (CT) winter wheat–fallow (CTWF), grass pasture (GP), unfertilized CT continuous winter wheat (CTWW0N), unfertilized CT continuous spring wheat (CTSW0N), and unfertilized CT continuous spring barley (CTSB0N) on soil organic carbon at the Columbia Basin Agricultural Research Center, Pendleton, Oregon.

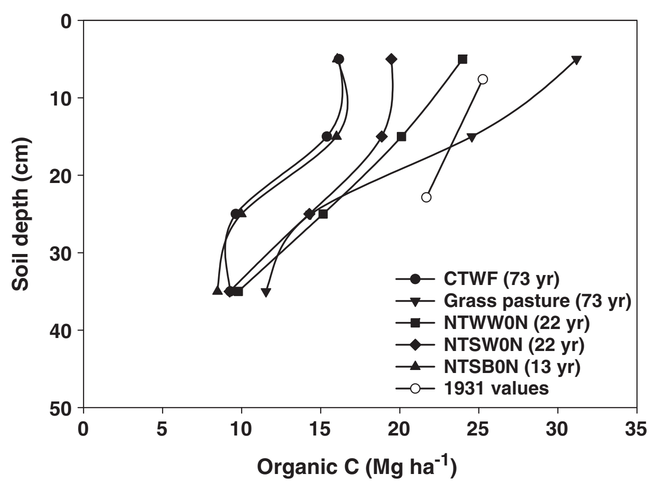

Fig. 4. Long-term effects of conventional tillage (CT) winter wheat–fallow (CTWF), grass pasture (GP), unfertilized no-tillage (NT) continuous winter wheat (NTWW0N), unfertilized NT continuous spring wheat (NTSW0N), and unfertilized NT continuous spring barley (NTSB0N) on soil organic carbon at the Columbia Basin Agricultural Research Center, Pendleton, Oregon.

Table 3. Effect of different long-term cropping systems on grain yield (6-yr average), straw dry weight (6-yr average), and total soil organic carbon (from start of each experiment to 2003) at the Columbia Basin Agricultural Research Center, Pendleton, Oregon.

Treatment†	Grain yield	Straw dry weight	Total soil organic C (0- to 40-cm zone)
	Mg ha^{-1}		
GP	–	–	81.63a‡
CTWF	2.53e	3.43e	50.44d
CTWWN	3.53bc	6.19a	74.92ab
CTWW0N	2.57e	3.17e	61.96c
NTWWN	3.58bc	5.68b	64.23bc
NTWW0N	2.18f	2.65f	69.02bc
CTSWN	3.29d	5.74ab	65.18bc
CTSW0N	2.20f	2.64f	65.21bc
NTSWN	2.59e	5.07e	59.55cd
NTSW0N	1.64g	2.23f	61.86c
CTSBN	4.42a	5.82ab	75.27ab
CTSB0N	3.37cd	4.00d	68.14bc
NTSBN	3.75b	5.40bc	52.51bcd
NTSB0N	1.70g	2.41f	50.50d

† GP, grass pasture; CTWF, conventional tillage winter wheat fallow; CTWWN, fertilized conventional tillage continuous winter wheat; CTWW0N, unfertilized conventional tillage continuous winter wheat; NTWWN, fertilized no-tillage continuous winter wheat; NTWW0N, unfertilized no-tillage continuous winter wheat; CTSWN, fertilized conventional tillage continuous spring wheat; CTWW0N, unfertilized conventional tillage continuous spring wheat; NTSWN, fertilized no-tillage continuous spring wheat; NTWW0N, unfertilized no-tillage continuous spring wheat; CTSBN, fertilized conventional tillage continuous spring barley; CTSB0N, unfertilized conventional tillage continuous spring barley; NTSBN, fertilized no-tillage continuous spring barley; NTSB0N, unfertilized no-tillage continuous spring barley.

‡ Means with similar letters are not significantly different from each other.

CTWF, where tillage was most intensive and cropping least intensive. The CT and NT treatments involving WW, SW, and SB had SOC levels that were in-between GP and CTWF levels. Being older, CT treatments had more SOC than NT treatments. However, considering that NT plots were only 6 yr old, it appears that NT treatments were accumulating SOC at a faster rate than CT. The SOC content was correlated with straw biomass production ($r = 0.56$, $P < 0.01$) only under CT treatments.

Factors Influencing Carbon Sequestration under Conventional Tillage

The timing of tillage, crop species, and fertilization influenced SOC distribution in the soil profile under CT. In both fertilized and unfertilized crops, CTWW had lower SOC in the 0- to 10-cm zone than CTSB and CTSW, and this was significantly so when compared to CTSB. Residues under CTWW were plowed down soon after harvest (in August) in preparation for seeding in the fall (October) and any residues in the 0- to 10-cm zone began decomposing six to seven months before spring crop residues were plowed down. The average temperature at CBARC, Pendleton, OR, is about 11°C and some SOC mineralization was expected to occur even during winter months. Beare et al. (2002) showed that 33% of the weight of autumn-incorporated barley straw was lost to decomposition compared to 18% of spring-incorporated. The SOC in the 10- to 20-cm zone was greatly influenced by the amount of biomass produced and was highest under fertilized plots of CTSB and CTWW, which produced about 5.8 and 6.2 Mg ha^{-1} yr^{-1} of straw, respectively (Table 3). Plowing to a depth of 20 cm buried most crop residues in the 10- to 20-cm zone. Below the plow layer (20- to 40-cm zone), SOC levels could be attributed largely to root biomass. Related work on corn (*Zea mays* L.) showed that root-derived C contributed about 1.6 to 1.8 times more C to SOC than stover-derived C (Balesdent and Balabane, 1996; Wilts et al., 2004). Campbell et al. (1991) also suggested that roots may be more important than aboveground biomass in contributing to maintenance of SOC. The SOC in 20- to 40-cm zone was highest under CTWW than under spring crops, indicating that winter wheat produced more root biomass than spring crops in this zone.

Soil organic carbon concentrations were also influenced by fertilization under CT. Fertilization increased total SOC (0- to 40-cm zone) by 13 and 7 Mg ha^{-1} in CTWW and CTSB, respectively, in 13 yr but had no effect on SOC in CTSW (Fig. 1 and 2; Table 3). The increase in SOC was largely due to increased shoot biomass that was subsequently incorporated into soil (Table 3).

Factors Influencing Carbon Sequestration under No-Tillage

Under NT, the amount and distribution of SOC in the soil profiles was largely influenced by the crop grown. There was no correlation between the aboveground biomass and SOC levels ($r = -0.06$; Table 3), indicating that SOC levels were largely influenced by belowground biomass. In similar studies, Hooker et al. (2005) showed that residue return did not increase SOC relative to residue removal under NT. In both fertilized and unfertilized plots, the highest amount of SOC was observed under NTWW (Table 3, Fig. 3 and 4). The amount of SOC in both fertilized and unfertilized NTSB plots was the lowest and was not significantly different from SOC under CTWF. This indicated that SB was not accumulating SOC through its roots as fast as the WW and SW under NT conditions. This may indicate that either barley produced less root biomass than WW and SW or its root growth was inhibited by other factors under NT. No-tillage has the tendency to increase D_b of the soil (Martino and Shakewich, 1994). Under our experimental conditions, D_b values of 1.45 and 1.00 g cm^{-3} were observed in the 10- to 20-cm zone under NT and CT, respectively. High D_b values under NT have the potential to impede root growth (Goss, 1977), resulting in lower root biomass in some crop species at greater soil depths. Barley has been shown to be more sensitive to mechanical stress than wheat (Goss, 1977) and the high D_b under NT probably impeded the growth of SB more than WW and SW root growth.

There were no significant differences in SOC levels between fertilized and unfertilized plots of all the crops under NT at all depths. This was unexpected since fertilized NT crops produced significantly higher grain yield and straw biomass than unfertilized NT crops (Table 3). This result strengthens the assumption that under NT, SOC was largely influenced by belowground biomass. A number of studies have shown that nitrogen fertilization increased SOC under dryland NT annual cropping (Halvorson et al., 1999; Campbell et al., 2005). Our NT experiment was in its sixth year at the time of the study and probably more time is required for differences between fertilized and unfertilized SOC levels to show. However, within this short period, NTWW and NTSW began to reverse the effects of 73 yr of CTWF on SOC. The NT plots were established on ground that was originally under CTWF since 1931. At the time of sampling in 2003, NTWW and NTSW had on average 16 and 10 Mg more SOC per hectare in the 0- to 40-cm zone than CTWF. This was equivalent to a sequestration rate of 2.6 and 1.7 Mg SOC ha^{-1} yr^{-1}, respectively. Much smaller gains (0.25 Mg ha^{-1} yr^{-1}) in SOC were reported in Canada (Campbell et al., 2005). This was probably due to different soils and lower temperatures in Canada than in Oregon.

CONCLUSIONS

The results show that tillage and cropping intensity influenced C sequestration. There was more potential to sequester C with less tillage and more intensive cropping than with more tillage and less intensive cropping. The SOC content was highest in GP where there was no tillage and where large amounts of grass residue accumulated on the soil surface. The CTWF system, which involved intensive tillage and less intensive cropping, depleted SOC the most. Therefore, to maintain or improve SOC levels in agricultural soils, the current popular CTWF cropping system should be replaced by continuous cropping and NT wherever possible. The results indicated that continuous cropping, even under CT, increased the amount of SOC in the soil. However, although continuous CT increased SOC in the plow layer, CT lost SOC near the surface, making the soil more susceptible to wind and water erosion. Annual cropping using crops producing high amounts of biomass such as WW and SB was necessary to maintain SOC in the plow layer under CT. Fertilizer indirectly influenced SOC accumulation through its influence on biomass production. Practicing NT for only 6 yr was beginning to reverse the destructive effects of 73 yr of CTWF on SOC. The increase in SOC at lower soil depths under NT appears to be influenced by root biomass. Crop species that have massive rooting systems have the potential to increase SOC in soils under NT. Winter wheat and spring wheat increased SOC more than SB under NT. This study demonstrated that increasing cropping frequency and eliminating tillage increased the potential for C sequestration.

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