

## INCORPORATED SOURCE CARBON AND NITROGEN FERTILIZATION EFFECTS ON CARBON STORAGE AND SOLUBLE SILICA IN A HAPLOXEROLL

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Long-term field experiments with repeated additions of incorporated carbon sources are ideal to examine soil organic carbon (SOC) storage and its interaction with soil constituents. The objectives were to (i) determine the effect of crop residue management, N fertilizer, and organic amendments on SOC storage and (ii) evaluate the influence of source C on fine organic matter interaction with soluble silica (Si). A long-term wheat (*Triticum aestivum* L.)-fallow experiment with several crop residue management practices (NB, no burn; SB, spring burn; and FB, fall burn), three N rates (0, 45, and 90 kg N ha<sup>-1</sup>), and organic amendments (NB<sub>M</sub>, 22.4 t ha<sup>-1</sup> manure; and NB<sub>PV</sub>, 2.24 t ha<sup>-1</sup> pea vines) was established in 1931 on a Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll). Soil cores (2-cm depth increments) to 50-cm depth were analyzed for coarse organic matter, fine organic matter, pH, bulk density ( $\rho_b$ ), water-soluble C ( $C_{ws}$ ), and water-soluble Si ( $Si_{ws}$ ). The SOC storage for the NB<sub>M</sub> (5.78 kg C m<sup>-2</sup>) was 25% higher than that for the FB<sub>0</sub> (4.62 kg C m<sup>-2</sup>) in the 0- to 50-cm depth. Nitrogen fertilizer application (45 or 90 kg N ha<sup>-1</sup>) decreased  $Si_{ws}$  by 17%, whereas applied manure or pea vines increased  $Si_{ws}$  by 10%. Silica solubilization and movement in response to reduced pH was greater in the absence of organic amendments or reduced crop residue returns. Increased SOC storage derived from amendments or N fertilization with a retention of crop residues prevented siliceous pan formation and associated impaired infiltration and internal drainage. Phytolith processes may enhance soil C sequestration and influence the chemistry of both Si and SOC. (Soil Science 2006;171:585-597)

**Key words:** Carbon sequestration, coarse organic matter, fine organic matter, water-soluble carbon, cemented siliceous pan.

SOIL organic C storage in a Walla Walla silt loam is sensitive to long-term crop residue management, N fertilization, and organic amendments (Rasmussen et al., 1980; Collins et al., 1992; Rasmussen and Parton, 1994) in the semiarid Pacific Northwest even when moldboard plowed. Rasmussen et al. (1980) reported that 18% to 20% of the added C remained in the soil as soil organic carbon (SOC). This rate

of SOC humification in a xeric Mollisol is somewhat lower than the 28% reported for an ustic Mollisol that was also moldboard plowed (Larson et al., 1972). Respective annual source C necessary to sustain SOC levels in these two Mollisols were 1.8 and 3.7 Mg C ha<sup>-1</sup>.

The Walla Walla silt loam is one of many Mollisols in the Pacific Northwest dryland cereal production area that contains a high concentration of potentially mobile Si ranging from 40 to 100 mg water-soluble SiO<sub>2</sub> kg<sup>-1</sup> soil in the form of H<sub>4</sub>SiO<sub>4</sub> (Douglas et al., 1984). A constant but limited supply of  $Si_{ws}$  in this soil can be expected because the less soluble siliceous minerals (e.g., amorphous silica and volcanic glass) can undergo slow dissolution in the presence of complex-forming ligands, such as

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carboxylic and phenolic acids (Bloom and Nater, 1991). Amorphous forms of Si can dissolve rapidly in an acidic soil environment (Beckwith and Reeve, 1963, 1964; Milnes and Twidale, 1983; Wilson et al., 1996). Dissolution may also be accelerated by release of  $H^+$  ions during the nitrification of the applied  $NH_4^+$ . Barak et al. (1997) showed the acidification impact of long-term N fertilizer use.

Siliceous pans induced by cropping practices have been observed in the Palouse and Columbia Plateau regions of the Pacific Northwest (Allmaras et al., 1982; Douglas et al., 1984; Brown and Mahler, 1987; Al-Ismaily, 1997; Gollany et al., 2005). These siliceous pans are not ordinary pressure pans because of the high concentrations of  $Si_{ws}$ , absence of a change in clay content, and inconsistent change in bulk density (Allmaras et al., 1982; Pikul and Allmaras, 1986). The bulk density of these pans ranges from 1.1 to 1.3  $Mg\ m^{-3}$  (Al-Ismaily, 1997), which is lower than the values (1.6–2.2  $Mg\ m^{-3}$ ) reported for fragipans (Lindbo and Veneman, 1993). Low penetrometer resistance in the Ap and BA horizons when wet and increasing as the soil dries (Douglas et al., 1984; Baham and Al-Ismaily, 1996; Wilkins et al., 2002) is characteristic of high  $Si_{ws}$  concentrations and its potential to reduce root penetration into the siliceous pan. Impaired infiltration and drainage has also been demonstrated (Zuzel et al., 1990; Pikul and Zuzel, 1994). Poor drainage through this siliceous pan was also responsible for reduced soil-water content in the BA horizon necessary for overwinter survival of *Fusarium solani* inoculum (Kraft and Allmaras, 1985). Soil management to reduce or prevent  $Si_{ws}$  movement into the lower Ap horizon is important to prevent impaired water drainage and to promote root penetration.

Douglas et al. (1984) were among the first to examine the impacts of both SOC and pH (results of the use of N fertilizer in wheat production) on the leaching of  $Si_{ws}$  from the Ap horizon. Gollany et al. (2005) compared the variation of  $Si_{ws}$ , pH, and SOM with depth in the moldboard and sweep systems after a long-term use of N fertilizers. Their results confirmed the  $Si_{ws}$  illuviation into the boundary between Ap and BA horizon as illustrated by the leaching experiment of Douglas et al. (1984). The objectives of this study were to (i) determine the effects of wheat residue management (other than tillage effects), organic amendment, or N fertilizer on SOC storage and (ii) evaluate the

influence of source C on the  $Si_{ws}$ , pH, and fine organic matter (FOM) in soil profiles. Profiles of  $p_b$ ,  $C_{ws}$ , and coarse organic matter (COM) were determined to confirm the  $Si_{ws}$  relation to pH and FOM produced by fertilization.

## MATERIALS AND METHODS

### *Site Description and Field Experiment*

A long-term crop residue management field experiment was initiated in 1931 at the Pendleton Agriculture Research Center in northeastern Oregon (45° 43' N, 118° 38' W, with 454-m elevation) (Rasmussen and Parton, 1994). This field experiment is located approximately 0.5 km from the tillage experiment of Gollany et al. (2005). The climate is semiarid with an annual mean temperature of 10.2°C and precipitation of 420 mm, 70% of which occurs mainly as winter rain during the period of November 1 to April 30 (Zuzel et al., 1993). The experimental plots were located on a Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll) with slopes of 2% to 3%.

Since the establishment of the experiment in 1931, some treatment changes were made, but most treatments sampled in 1983 had been in place since 1931. Several residue burn treatments had a minor change in 1978 (Rasmussen and Parton, 1994), but the pre-1978 treatments were not expected to exceed treatment effects since 1978. One set of the no-residue burning treatments was changed to spring residue burning. The spring residue burning (SB) with no N addition ( $SB_0$ ); fall burning with no N addition ( $FB_0$ ); manure application ( $NB_M$  at 22.4  $t\ ha^{-1}$  = 1482 kg C and 112 kg N  $ha^{-1}$ ); pea vine addition ( $NB_{PV}$  at 2.24  $t\ ha^{-1}$  = 794 kg C and 34 kg N  $ha^{-1}$ ); or no residue burning (NB) with 0 ( $NB_0$ ), 45 ( $NB_{45}$ ), and 90 kg N  $ha^{-1}$  ( $NB_{90}$ ) were all in place since 1967 (Table 1). The spring residue burning with 45 ( $SB_{45}$ ) and 90 kg N  $ha^{-1}$  ( $SB_{90}$ ) were in place since 1978. The FB and SB plots were not disturbed after harvest and before burning. Nitrogen was broadcast as  $(NH_4)_2SO_4$  from 1931 to 1961 and as  $NH_4NO_3$  from 1962 to 1982. Individual plots are 11.6 × 40.2 m. The experiment design is an ordered sequence (nonrandom selection) of treatments with two replications within each series (A- or B-series) that are offset by 1 year and not randomized. The A-series with winter wheat in 1983, after fallow in 1982, was sampled when wheat was actively tillering. Details of the experimental design, crop residue inputs, grain

TABLE 1

Total amount of coarse organic matter (COM), fine organic matter (FOM), water-soluble C ( $C_{ws}$ ), water-soluble Si ( $Si_{ws}$ ), and soil organic N ( $N_{Org}$ ) in Ap horizon (0–26 cm) and sampled BA horizon (26–50 cm) in the long-term crop residue management experiment

Treatment	N rate, kg ha <sup>-1</sup> ‡	Residue, kg ha <sup>-1</sup> §	Horizon	SOC components*		$C_{ws}$ , g C m <sup>-2</sup>	$Si_{ws}$ , g Si m <sup>-2</sup>	$N_{Org}$ , kg N m <sup>-2</sup>
				COM, kg C m <sup>-2</sup>	FOM, kg C m <sup>-2</sup>			
FB <sub>0</sub>	0	5110	Ap	0.15	3.42	40.6	23.9	0.262
			BA	—	1.20	11.9	11.4	—
SB <sub>0</sub>	0	5290	Ap	0.27	3.78	45.7	24.4	0.283
			BA	—	1.41	25.5	13.2	—
SB <sub>45</sub>	45	7040	Ap	0.31	3.78	40.8	18.6	0.315
			BA	—	1.30	20.6	11.7	—
SB <sub>90</sub>	90	7590	Ap	0.16	3.46	50.0	21.0	0.295
			BA	—	1.27	23.3	12.6	—
NB <sub>0</sub>	0	5210	Ap	0.20	3.50	53.5	23.8	0.309
			BA	—	1.13	24.5	11.9	—
NB <sub>45</sub>	45	7030	Ap	0.32	3.85	51.1	20.4	0.337
			BA	—	1.36	20.3	12.6	—
NB <sub>90</sub>	90	7460	Ap	0.35	3.84	52.4	19.8	0.315
			BA	—	1.27	21.8	12.7	—
NB <sub>M</sub>	manure	7940	Ap	0.33	4.46	69.3	26.1	0.402
			BA	—	1.32	22.5	12.7	—
NB <sub>PV</sub>	pea vines	6950	Ap	0.19	4.04	55.6	26.3	0.354
			BA	—	1.08	25.3	11.6	—
	S.E. <sup>  </sup>	230		0.12	0.20	9.5	1.2	0.014

\*COM >0.5 mm expressed as C; FOM <0.5 mm expressed as C; COM C in the BA horizon ranged from 2 to 10 g C m<sup>-2</sup> but not shown.

†NB, crop residue incorporated without residue burning; FB, fall burn of crop residue, estimated 67% C loss; SB, spring burn of crop residue, estimated 55% C loss (Rasmussen and Parton, 1994).

‡Before MP tillage in April of summer fallow year, manure was added at a rate of 22.4 Mg ha<sup>-1</sup> (1.480 Mg C ha<sup>-1</sup>) and pea vines were added at 2.4 Mg ha<sup>-1</sup> (0.790 Mg C ha<sup>-1</sup>); these rates are used when applied in the wheat-fallow system; no N was applied.

§Estimated crop residue available at harvest from 1977 to 1983; estimate when measured in the wheat year—not annualized, root residue not included.

||The S.E. with 12 *df* were estimated originally in Gollany et al. (2005).

yields, SOM changes, and management were given earlier (Rasmussen and Parton, 1994). Briefly, all plots sampled in 1983 were mold-board plowed 22 cm deep in April 1982, followed by secondary tillage (field cultivator, tine harrow, and three rod weeder passes during summer fallow). Fertilizer and organic amendments were applied in April 1982 before tillage. The cropping system is alternating winter wheat and summer fallow (15 months). Crop residues returned were measured since 1978 to 1983 (Rasmussen and Parton, 1994).

#### Soil Sampling

Soil samples were taken midway between winter wheat rows on April 5, 1983. Cores were selected randomly within the inner 2/3 of the plot area to avoid plot-to-plot contamination. Samples were processed and analyzed with those

of Gollany et al. (2005) within 6 months of collection. All soil used in this study was sampled using equipment and a soil sampling procedure described previously by Allmaras et al. (1988) and Gollany et al. (2005). Briefly, a tube sampler was used to remove a soil core (inner diameter = 18 mm and *l* = 30 cm) from the 0- to 30-cm depth. Each soil core was pushed out of the tube sampler onto a half-round tray, cut into 2-cm soil sections with a spatula, separated, and placed into plastic lined bags for storage. A second soil core (*l* = 20 cm) was removed from the 30- to 50-cm depth and sectioned as above. Soil samples from 18 cores were composited for each of the nine treatments. Samples were taken from all nine different treatments in replication II of series A because the soil depth in an adjacent replication was substantially shallower with considerable variation in soil depth to

bedrock. Replication errors from Gollany et al. (2005) were applied to measurements in this study and were nearly the same as those from an earlier sampling (Rasmussen and Parton, 1994). Core count and quantitative soil transfer were utilized for accurate bulk density determination. Soil cores were gently broken, air-dried, and stored in plastic lined bags at room temperature until analyzed. The air-dried mass was converted to an oven dry base, and sample volume (number of cores, 2-cm increments) was used to calculate soil bulk density ( $\rho_b$ ). Soil sampling and soil analysis procedures were the same as described previously (Gollany et al., 2005).

#### *COM and FOM Separation*

Air-dried soil samples were gently sieved through a 0.5-mm sieve (35 mesh) to avoid breaking up fresh and partially decomposed crop residue and to separate out the coarse and visible crop residue (Allmaras et al., 1988). A coarse crop residue fraction (plant residue contaminant with adhered soil particles) retained on the 0.5-mm sieve was further processed to determine COM, the crop residue free of contaminant soil. This >0.5-mm fraction containing some contaminant mineral soil was air-dried. The term FOM is used for soil material with organic matter that passed through the sieve (<0.5 mm) to distinguish this fraction from the COM fraction containing predominantly particulate material. Gentle sieving minimized particulate organic matter contamination of FOM. The air-dried crop residue fraction containing contaminant soil (>0.5 mm) and a subsample of the FOM fraction (<0.5 mm) were each then ball milled with SPEX/Mixer/Miller (Model 8000, SPEX Industries, Inc., Scotch Plains, NJ).<sup>1</sup> Total C was determined for both fractions with a Leco carbon analyzer (Leco Corp., St. Joseph, MI). Selected analysis showed that none of these soil samples contained inorganic C. A conservation of C procedure (Allmaras et al., 1988) was then used to estimate the weights of contaminating mineral soil in the fraction >0.5 mm. This separation of COM and FOM was made only in the top 26 cm, which corresponds to the deepest depth of residue incorporation by the moldboard plow. Total C

determined by combustion is SOC derived from various SOC pools ranging from labile to occluded C. This SOC is the C component of SOM as defined by Stevenson (1994).

#### *Soil pH, Water-Soluble Carbon ( $C_{ws}$ ), and Water-Soluble Silica ( $Si_{ws}$ ) Measurements*

Part of the air-dried soil fraction (<0.5 mm) used for FOM determination was also used for additional soil measurements. Soil pH was measured in duplicate for each soil sample using a 1:2 (w/w) soil to 0.01 M CaCl<sub>2</sub> mixture.

Water-soluble C was determined in a filtrate of 1:5 (soil/water) suspension as described in Gollany et al. (2005). Briefly, the soil suspension was then shaken for 30 min, allowed to settle overnight, centrifuged (12,000×g) for 10 min, and filtered (Whatman No. 40). Filtrate aliquots were used for soluble C and Si determination. The  $C_{ws}$  present in the aqueous filtrate was analyzed as oxidizable C (Technicon Industrial Systems, 1976; Douglas et al., 1984).

Silicic acid in the aqueous filtrate was determined using a modified heteropoly blue method (Rand et al., 1975; Douglas et al., 1984) adapted for use with the Technicon Industrial Systems. Ammonium molybdate at pH 1.2 was reacted with silica and any phosphate contaminant to produce heteropoly acids. First, a 0.03 M HCl solution was introduced into the auto analyzer sample stream to dilute the aliquot, and oxalic acid was added to eliminate interference from phosphates before ascorbic acid addition. Silicomolybdate in acidic solution formed molybdenum blue and was assayed colorimetrically. Silicic acid determined by this procedure is referred to in the following discussion as  $Si_{ws}$ .

#### *SOC Storage Index*

A SOC storage index was calculated as a ratio of the final FOM divided by the sum of source C added over the 52-year period (Table 2). The measured final FOM in the 50-cm profile was reduced to account for the biologically inactive charcoal (chemically occluded C). The biologically inactive charcoal for the Walla Walla silt loam used in this study is 35% of FOM (Skjemstad et al., 2002). Source C includes crop residue C, estimated C from root contribution, and amendment C contribution. The source C for the NB<sub>0</sub>, NB<sub>45</sub>, and NB<sub>90</sub> was estimated from measured incorporated straw plus estimated root C. Root C was estimated as 30% of total shoot C at harvest including grain (Buyanovsky and Wagner, 1997). Grain

<sup>1</sup> Mention of trade names or commercial products in this manuscript is solely for the purpose of providing specific information and does not imply recommendation or endorsement by USDA.

TABLE 2

Calculations of soil organic carbon (SOC) storage index per source C input since 1931 for the 50-cm soil profile in the long-term crop residue management experiment

Treatment*	Amendment or burning effect <sup>†</sup>	Total FOM <sup>‡</sup>	Straw yield, Mg ha <sup>-1</sup>	Grain yield, Mg ha <sup>-1</sup>	Straw C <sup>§</sup> source	Root C source	Total C <sup>  </sup> source	SOC storage index <sup>¶</sup>
FB <sub>0</sub>	0.33	46.2	5.11	2.58	0.71	0.97	1.67	0.69
SB <sub>0</sub>	0.45	51.9	5.29	2.67	1.00	1.00	2.00	0.65
SB <sub>45</sub>	0.45	50.8	7.04	3.92	1.33	1.38	2.71	0.47
SB <sub>90</sub>	0.45	47.3	7.59	4.50	1.43	1.52	2.95	0.40
NB <sub>0</sub>	1.0	46.3	5.21	2.78	2.19	1.01	3.19	0.36
NB <sub>45</sub>	1.0	52.1	7.03	4.10	2.95	1.40	4.36	0.30
NB <sub>90</sub>	1.0	51.1	7.46	4.64	3.13	1.52	4.66	0.27
NB <sub>M</sub>	1.48	57.8	7.94	4.87	3.33	1.61	6.43	0.22
NB <sub>PV</sub>	0.79	51.2	6.95	3.81	2.92	1.36	5.06	0.25

\*NB, crop residue incorporated without residue burning; FB, fall burn of crop residue, estimated 67% C loss; SB, spring burn of crop residue, estimated 55% C loss (Rasmussen and Parton, 1994).

<sup>†</sup>Before MP tillage in April of summer fallow year, manure was added at a rate of 22.4 Mg ha<sup>-1</sup> (1.480 Mg C ha<sup>-1</sup>) and pea vines were added at 2.4 Mg ha<sup>-1</sup> (0.790 Mg C ha<sup>-1</sup>); these rates are used when applied in the wheat-fallow system; no was N applied (Rasmussen and Parton, 1994).

<sup>‡</sup>Sum of fine organic matter (FOM) in Ap and BA horizon to the 50-cm soil depth.

<sup>§</sup>Estimated straw available at harvest from 1977 to 1983; estimate when measured in the wheat year—not annualized; straw biomass contained 42% C; straw return reduced by burn treatment.

<sup>||</sup>Total C return from root plus C from the straw; C from straws were adjusted for burning and amendments when applied as estimated by Rasmussen and Parton (1994); root biomass assumed to be 30% of the straw biomass including grain; root biomass contained 42% C; carbon return from grain and straw estimated from grain and straw as measured by Rasmussen and Parton (1994).

<sup>¶</sup>SOC storage index; SOC storage per source C input since 1931 was calculated as a ratio of the final FOM divided by the sum of source C added over the 52-year period excluding fallow years. The measured final FOM was reduced to account for the charcoal. The charcoal contained in the Walla Walla silt loam used in this study is 35% of FOM (Skjemstad et al., 2002); source C includes crop residue C, estimated C from root contribution, and amendment C contribution.

yield at harvest was measured by Rasmussen and Parton (1994). The C storage index (0.36) for NB<sub>0</sub> was calculated as follows: [FOM; 46.3 Mg ha<sup>-1</sup> (0.65)/{Straw C; (0.42) 5.21 Mg ha<sup>-1</sup> + Root C; (0.42)(0.30)(Grain; 2.78 Mg ha<sup>-1</sup> + Straw; 5.21 Mg ha<sup>-1</sup>)}]/[26]. Straw loss due to stubble burn was estimated as 67% for fall burn (FB) and 55% for spring burn (SB) of the straw yield at harvest as measured by Rasmussen and Parton (1994); straw production was in the same proportion among treatments as in 1978. The C storage index (0.69) for FB<sub>0</sub> was calculated by multiplying straw C contribution by 0.33 (burning loss of 67%) as follows: [FOM; 46.2 Mg ha<sup>-1</sup> (0.65)/{Straw C; (0.42) 5.11 Mg ha<sup>-1</sup> + Root C; (0.42)(0.30)(Grain; 2.58 Mg ha<sup>-1</sup> + Straw; 5.11 Mg ha<sup>-1</sup>)}]/[26]. Amendment contribution for the NB<sub>M</sub> (1.480 Mg ha<sup>-1</sup>) and NB<sub>PV</sub> (0.790 Mg ha<sup>-1</sup>) was added to the denominator to calculate the C storage index for these treatments. The manure and pea vine amendments were obtained from the same source year after year and had a high dry matter content (Rasmussen and Parton, 1994).

#### Soil Organic Nitrogen Estimation

Organic N (N<sub>Org</sub>) data sets from 1984 to 1986 (Rasmussen and Parton, 1994) were used in the current study to estimate N<sub>Org</sub> in the top 26 cm. The N<sub>Org</sub> (g N kg<sup>-1</sup>) was converted to mg cm<sup>-3</sup> using bulk density profiles measured as described above. Any change in N<sub>Org</sub> between 1983 and 1984/1986 (when Rasmussen and Parton sampled in 1984) was assumed to be negligible.

#### Statistical Procedures

Nested ANOVA and Generalized Linear Model procedures (SAS Institute, 1988) were used for statistical analysis as detailed in Gollany et al. (2005). The nested ANOVA was used to compute a standard error of the mean in each treatment × soil property × depth. Significant differences among treatment means ( $P < 0.05$  or  $P < 0.01$ ) were tested using "t" tests. Multiple linear regression and ANOVA in Generalized Linear Model were used to estimate parameters and statistical significance.

## RESULTS AND DISCUSSION

*Effect of Crop Residue Management and Organic Amendment*

The results of N rate and residue at harvest for the nine treatments are presented in Table 1. Four treatments were selected to illustrate the extremes of soil constituents in the profiles: NB<sub>0</sub>, NB<sub>90</sub>, NB<sub>M</sub>, and FB<sub>0</sub> (Figs. 1 and 2). Bulk density profiles were characteristic of MP system (Fig. 1a). Gollany et al. (2005) showed similar profiles for MP system where it was compared with sweep tillage system. The maximum  $\rho_b$  occurred at 10-cm depth, as expected from the secondary tillage operation, with a minimum  $\rho_b$  at the 10- to 18-cm depth. The  $\rho_b$  was highest in the FB<sub>0</sub> and lowest in the NB<sub>M</sub> treatment, whereas NB<sub>0</sub> and NB<sub>90</sub> were between the two extremes. However, the differences within each depth are not significantly different. Profiles of other treatments (not shown in the figures) were similar to those of NB<sub>0</sub> and NB<sub>90</sub>.

Coarse organic matter profiles were also characteristic of MP system with the FB<sub>0</sub>, and NB<sub>M</sub> as the extremes. The COM profiles of MP in this study also were similar to MP reported earlier and different from sweep tillage system (Gollany et al., 2005). The NB<sub>0</sub> and NB<sub>90</sub>

treatments had a profile similar to the NB<sub>M</sub> treatment (Fig. 1b). The COM and  $\rho_b$  profiles were inversely correlated, which corresponded well with earlier results for MP (Gollany et al., 2005). The overall average COM was approximately 7% of FOM in the Ap horizon (shown for all treatments in Table 1).

Mean pH values for the Ap horizon were at least one unit significantly ( $P < 0.01$ ) higher in the NB<sub>M</sub> treatment than in the NB<sub>90</sub> treatment (Fig. 1c) because of different Ca and Mg inputs in the materials added (Rasmussen and Rohde, 1988). The pH values of the NB<sub>0</sub> and FB<sub>0</sub> treatments were between these extremes but significantly ( $P < 0.05$ ) higher than those in the NB<sub>90</sub> treatment. General shapes of the soil pH profiles in the BA horizon were similar to those for MP system shown by Gollany et al. (2005). The profiles for NB<sub>45</sub> were between NB<sub>0</sub> and NB<sub>90</sub> treatments. However, pH profiles of the treatments converged in the BA horizon, unlike in Gollany et al. (2005), where soil pH was one-half unit lower in the MP compared to sweep tillage system.

Fine organic matter profiles illustrated the characteristic deposition of residues in the long-term MP system (Fig. 2a). However, FOM profiles show an accumulation in the NB<sub>M</sub> and

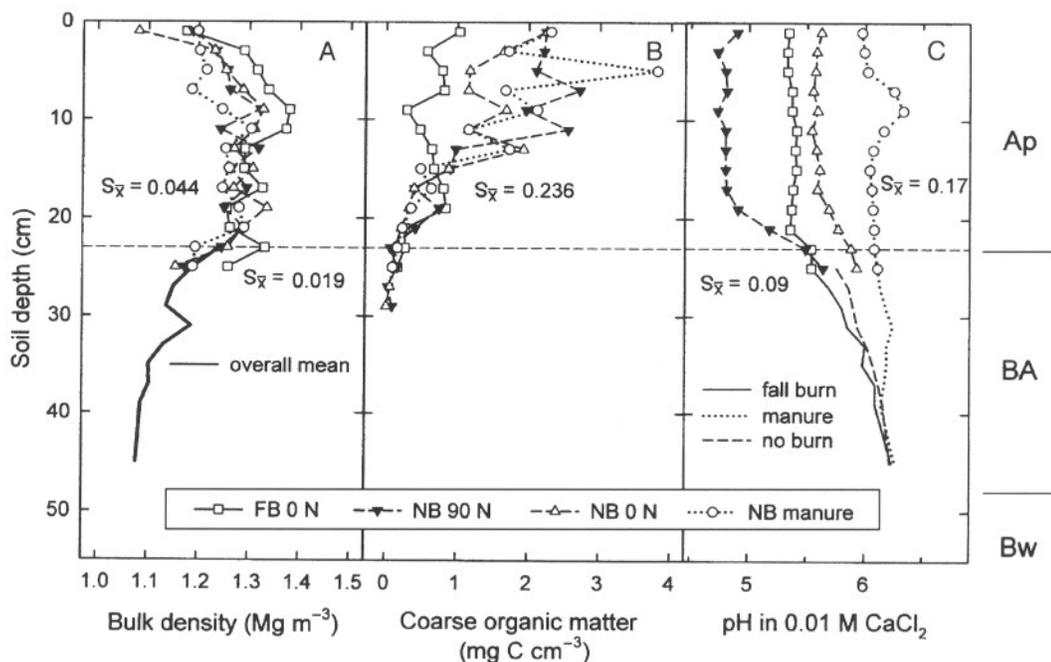


Fig. 1. Profiles of (A) soil bulk density ( $\rho_b$ ), (B) coarse organic matter (COM), and (C) soil pH in four selected treatments, as related to residue management, organic amendment, and N fertilizer rate.

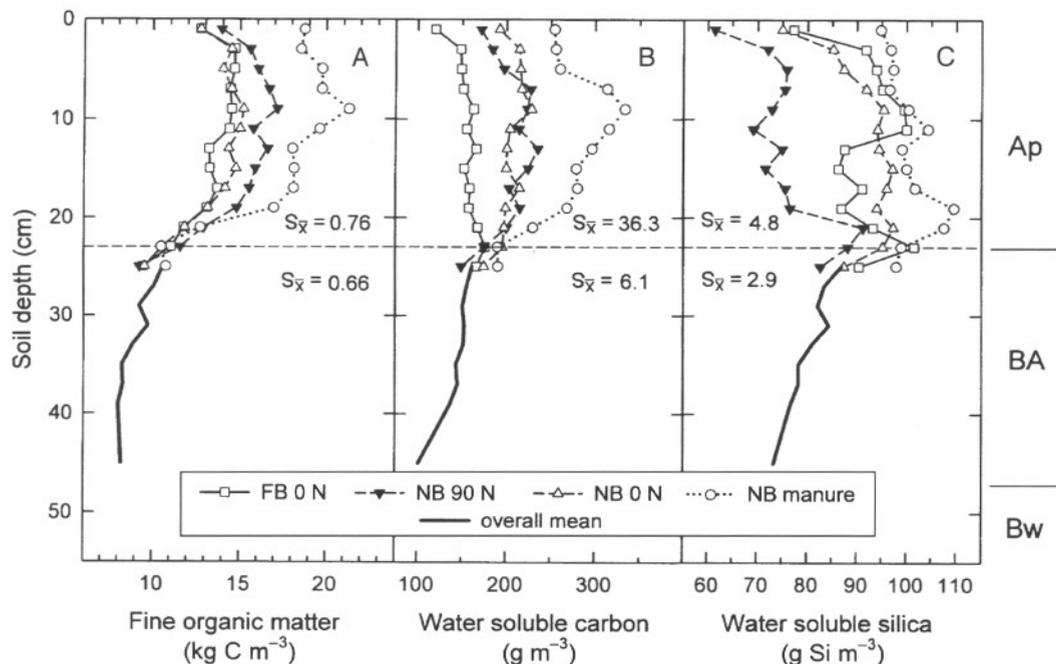


Fig. 2. Profiles of (A) fine organic matter (FOM), (B) water-soluble carbon ( $C_{ws}$ ), and (C) water-soluble silica ( $Si_{ws}$ ) in four selected treatments, as related to residue management, organic amendment, and N fertilizer rate.

the  $NB_{90}$  treatments that are distinct from those developed in the absence of N fertilizer ( $NB_0$  and  $FB_0$ ). The FOM storage (Table 1) for the  $NB_M$  ( $5.78 \text{ kg C m}^{-2}$ ) was 25% higher than that for the  $FB_0$  ( $4.62 \text{ kg C m}^{-2}$ ) in the 0- to 50-cm depth, and the difference was significant ( $P < 0.05$ ). A highly significant ( $P < 0.01$ ) FOM storage ( $4.25 \text{ kg C m}^{-2}$ ) for the mean of  $NB_M$  and  $NB_{PV}$  treatments was found in the 0- to 26-cm depth compared to the lowest FOM accumulation in the  $FB_0$  ( $3.42 \text{ kg C m}^{-2}$ ) treatment (Table 1). Although not statistically significant, the burning influenced FOM accumulation more than the N application. The FOM accumulations in the Ap horizon were in the order:  $NB_M > NB_{PV} > NB_{45} > NB_{90} > SB_{45} = SB_0 > NB_0 > SB_{90} > FB_0$  (Table 1). Although there were significantly ( $P < 0.05$ ) different FOM profiles in the Ap horizon, there were no significant differences among the selected treatments in the BA horizon (Table 1). This is different from the sustained tillage effects (MP vs. sweep) in the BA horizon reported by Gollany et al. (2005).

Water-soluble C profiles in the Ap horizon followed a pattern similar to FOM, with a significant ( $P < 0.05$ ) difference between  $FB_0$  and  $NB_M$  treatments, whereas both  $NB_0$  and

$NB_{90}$  were between the extremes (Fig. 2b). Concentrations of  $C_{ws}$  in the Ap horizon increased with the addition of organic amendments ( $NB_M$  and  $NB_{PV}$ ) and crop residue returns (not burning) (Table 1). Overall, the mean ratio of  $C_{ws}$  to FOM within the Ap horizon was 0.010, and the F ratio for this simple linear regression (not shown) was significant ( $P < 0.01$ ). The  $NB_{PV}$  treatment had the highest  $C_{ws}$  to FOM ratio (0.023) in the BA horizon. The high  $C_{ws}$  to FOM ratio is probably related to the nutrient quality of the amendments added and associated changes in soil biological and biochemical properties. The  $C_{ws}$  values were likely at a maximum because soils were sampled during April when soil moisture and temperature in winter wheat plots were suitable for residue decomposition (Douglas et al., 1980). These ratios are lower than  $C_{ws}$  ratios (0.025) observed previously due to a tillage effect (Gollany et al., 2005). There were no significant differences in  $C_{ws}$  in the BA horizon (Fig. 2b and Table 1) and profile values were always less than  $150 \text{ g C m}^{-3}$  (Fig. 2b). Overall mean  $C_{ws}$ , as a percentage of SOC (1.3%) in the 0- to 26-cm depth, was nearly four times greater than the  $C_{ws}$ , as a percentage of SOC (0.3%) in the 0- to 30-cm depth of an

udic Mollisol in Wisconsin (Brye et al., 2001). This suggests higher C solubilization in these xeric Mollisols under the cropping systems and climate of eastern Oregon than those under udic Mollisols. Air-drying may have mobilized C and increased the  $C_{ws}$  fraction in the current study.

Water-soluble Si generally increased with depth in the upper 11-cm soil depth but was nearly constant throughout the 11- to 20-cm soil depth (Fig. 2c). A sharp increase occurred near the interface of the Ap and BA horizons at approximately 20 cm in depth. Application of N fertilizer (45 and 90 kg N ha<sup>-1</sup>) significantly ( $P < 0.01$ ) decreased the mean  $Si_{ws}$  in the Ap horizon by 17% compared to treatments without N application (Table 1), whereas application of manure or pea vines significantly ( $P < 0.05$ ) increased the mean  $Si_{ws}$  by 10% above the zero N application. The increase in  $Si_{ws}$  with organic amendments may have resulted from the additions of contaminant Si from phytoliths addition. Silica in the soil solution is taken up by plant roots in the form of silicic acid (H<sub>4</sub>SiO<sub>4</sub>) and subsequently deposited throughout the intracellular and extracellular structures of their leaf, stem, and root systems (Parr and Sullivan, 2005) to form phytoliths. Deposits of Si in plants have become known as opal phytoliths (Jones and Milne, 1963). Gramineae (e.g., wheat) species have a silica content of approximately 1% to 3%, expressed as SiO<sub>2</sub> per dry weight in the shoot (Parr and Sullivan, 2005). Such silicification results in physically occluded C within the phytoliths.

Soil organic N increased with the addition of residue, N fertilizer, and amendments (Table 1). Fall burn produced significantly ( $P < 0.05$ ) less  $N_{Org}$  than NB<sub>0</sub>. Levels of  $N_{Org}$  in the soil were FB<sub>0</sub> < SB<sub>0</sub> < NB<sub>0</sub>. The  $N_{Org}$  content was significantly ( $P < 0.01$ ) higher with organic amendment addition (0.402 kg N m<sup>2</sup>) than when only wheat residue (0.309 kg N m<sup>2</sup>) was added. The  $N_{Org}$  order was NB<sub>M</sub> (0.402) > NB<sub>PV</sub> (0.354) > NB (0.320) > SB (0.297) > FB (0.262). When averaged over SB and NB,  $N_{Org}$  levels were 0.30, 0.33, and 0.31 kg N m<sup>-2</sup> with N application rates of 0, 45, and 90 kg N ha<sup>-1</sup>, respectively. The effects of organic amendment addition on  $N_{Org}$  were greater than N rate.

#### SOC Storage

Soil organic C storage in the FOM fraction varied with the amount and type of residue (burning of wheat residue, addition of manure or pea vines) incorporated into the Ap horizon

(Table 1). However, only minor treatment differences in FOM were observed in the BA horizon. The FOM in the 0- to 26-cm depth ranged from 3.42 to 4.46 kg C m<sup>-2</sup> for FB<sub>0</sub> and NB<sub>M</sub>, respectively. The FOM in the 26- to 50-cm depth ranged from 1.13 to 1.41 kg C m<sup>-2</sup> for NB<sub>0</sub> and SB<sub>0</sub>, respectively, with no significant difference between treatments.

Estimated SOC storage index (Table 2) ranged from 0.22 for NB<sub>M</sub> to 0.69 for FB<sub>0</sub> and showed the largest differences between the mean of organic amendments (0.23) and the mean of wheat residue return-only treatments (0.45). The SOC storage index decreased from 0.36 to 0.27 with the 90 kg N ha<sup>-1</sup> fertilizer application. The larger ratio for the FB<sub>0</sub> (0.69) and SB<sub>0</sub> (0.65) compared to NB<sub>0</sub> (0.36) and the difference in the index between wheat residue and organic amendment both suggest that root tissue is more recalcitrant than shoot tissue. Campbell et al. (1991) found that wheat root tissue decomposed 9% slower than shoot tissue over a 30-year period. Gale and Cambardella (2000) observed a similar recalcitrance of root relative to shoot tissue. The ratio for the burn treatments may be positively biased because the SOC may contain an unknown amount of biologically inactive chars from the burned straw residue.

Increasing sequestered SOC as source C increased is evidence of soil quality improvement (Rasmussen and Albrecht, 1998). In the same location, Pikul and Zuzel (1994) found an increase in soil porosity as SOC increased. However, a decreasing SOC storage index is a more direct index of microbial activity than the amount of SOC remaining after the most labile forms have provided the energy for microbial activity. Biederbeck et al. (1984) have shown a positive microbial biomass response to N fertilization and increased source C from wheat straw. Furthermore, Buyanovsky et al. (1994) have shown that larger water stable aggregates contained fragments of SOC with a shorter turnover time than in microaggregates. Williams (2004) reported that the FB<sub>0</sub> and SB<sub>0</sub> soil glistened, whereas the NB<sub>M</sub> soil was darker and rough when wetted after a light rain. This soil matrix response to wetting and reduced overland flow for NB<sub>M</sub> compared to burned treatments in relation to precipitation (Williams, 2004) suggests that the SOC storage index may be more closely related to improved soil physical properties (i.e., soil structure and infiltration) than do the SOC concentration.

*Source C and N Fertilizer Induced Changes in FOM, pH, and Si<sub>ws</sub> Responses*

Soil management that changes SOC storage and soil pH can impact Si<sub>ws</sub>. Profiles of Si<sub>ws</sub> in the Ap horizon were sensitive to residue management (imported organic material and source C from wheat) and N rate (Fig. 2c and Table 1). A multiple linear regression was used to examine the influence of soil constituents on Si<sub>ws</sub>. The equation developed to depict the effect of FOM, pH, and  $\rho_b$  on Si<sub>ws</sub> was:

$$\text{Si}_{ws} = \alpha' + \beta'_1(\text{pH}) + \beta'_2(\text{FOM}) + \beta'_3(\rho_b) + \beta'_4(D) \quad R^2 = 0.86 \quad (1)$$

where Si<sub>ws</sub> is water-soluble Si (g Si m<sup>-3</sup>);  $\alpha' = -193.31$ ;  $\beta'_1 = 25.19$ ;  $\beta'_2 = -0.64$ ; FOM is fine organic matter (kg C m<sup>-3</sup>);  $\beta'_3 = 123.55$ ;  $\rho_b$  is bulk density (Mg m<sup>-3</sup>);  $\beta'_4 = -0.10$ ; and *D* is depth (cm).

This equation accounted for 86% of the variability in Si<sub>ws</sub> (F ratio;  $P < 0.01$ ). All regression coefficients were significantly ( $P < 0.01$ ) different from zero except that for *D* ( $P < 0.20$ ). The simple correlations (Table 3) were small except for the correlation between pH and Si<sub>ws</sub> (0.74),  $\rho_b$  with Si<sub>ws</sub> (0.47), and FOM with *D* (-0.38). Fine organic matter and pH were only weakly correlated.

Acidification of soil due to the use of N fertilizer, solubilization of amorphous Si, and leaching from the Ap horizon is consistent with the positive coefficient (Eq. (1)) for pH. Addition of fertilizer when crop residue was not burned decreased pH and Si<sub>ws</sub> in the upper part (0- to 20-cm depth) of the Ap horizon (Figs. 1c and 2c). The decrease in Si<sub>ws</sub> is either a result of Si uptake by plant or leaching. Increased Si<sub>ws</sub> leaching with a decrease in pH was reported by Douglas et al. (1984). Measurements of Si<sub>ws</sub>, amorphous Si, soil pH, and total acidity in a profile of the same Walla Walla silt loam (Baham and Al-Ismaily, 1996) indicated

that Si had leached from the upper layer of the Ap horizon and illuviated into the boundary between the Ap and BA horizons. Brown and Mahler (1987, 1988) hypothesized that acidification from long-term use of NH<sub>4</sub><sup>+</sup>-based N fertilizers solubilized Si, which then illuviated until cementing in the plow (siliceous) pan of Mollisols in Idaho. Barak et al. (1997) showed the acidification impact of long-term N fertilizer use. Brown and Mahler (1988) concluded that Si concentrations in the plow (siliceous) pan were apparently controlled by polymerized Si deposit. Evaporation during the summer months and utilization of water by plants promote precipitation of amorphous Si (Chadwick et al., 1987a,b). Amorphous Si precipitates when Si concentration in solution reaches the range of 50 to 60 mg L<sup>-1</sup> (Elgawhary and Lindsay, 1972). The precipitated Si forms bridges between adsorbing soil components that bond the particles near the points of grain contact without filling the pore space to a significant extent (Chadwick et al., 1987a,b). Silica bridging between soil particles is responsible for the hardness and brittleness of these siliceous pans.

The general shape of the Si<sub>ws</sub> profile (Fig. 2c) was similar to those observed by Baham and Al-Ismaily (1996) in the same field and those found earlier by Brown and Mahler (1987, 1988) for soils in Idaho. Higher Si<sub>ws</sub> concentrations were found in the Ap horizon than in the BA horizon, with a highest concentration at the base of Ap horizons. The Si<sub>ws</sub> profile similarities among the cited studies suggest that Mollisols of the Pacific Northwest under cropland management are generally similar.

The significant ( $P < 0.01$ ) negative coefficient (Eq. (1)) for the FOM is consistent with decreased Si<sub>ws</sub> leaching as the organic matter increased. Addition of fertilizer without crop residue burning increased FOM (Table 1 and Fig. 2a) and decreased pH and Si<sub>ws</sub> (Figs. 1c and 2c), whereas added organic amendments increased both FOM and Si<sub>ws</sub> in the upper part (0- to 20-cm depth) of the Ap horizon (Figs. 1c and 2c). In a leaching study using soil samples from this long-term field experiment, Douglas et al. (1984) showed that H<sub>4</sub>SiO<sub>4</sub> leaching decreased as SOC increased. A relatively higher Si<sub>ws</sub> in the NB<sub>M</sub> and NB<sub>PV</sub> treatments compared to the treatment without organic amendments could be a response to either decreased leaching or the presence of moderately soluble amorphous Si forms such as opal phytoliths. Norgren (1973) estimated that opal phytoliths

TABLE 3

Simple correlation between soil pH, fine organic matter (FOM) C, soil bulk density ( $\rho_b$ ), soil depth (*D*), and water-soluble silica (Si<sub>ws</sub>) in the Ap horizon

	pH	FOM	$\rho_b$	<i>D</i>	Si <sub>ws</sub>
pH	1.00				
FOM	-0.01	1.00			
$\rho_b$	-0.07	0.26	1.00		
<i>D</i>	0.31	-0.38	0.14	1.00	
Si <sub>ws</sub>	0.74	-0.01	0.47	0.33	1.00

were formed at a rate of  $112 \text{ kg ha}^{-1} \text{ year}^{-1}$  in the Walla Walla silt loam soils. This high formation rate was attributed to the large amount of readily weatherable volcanic silica parent material from which these soils developed (Al-Ismaily, 1997). The weathering rate of opal phytoliths is intermediate between amorphous Si and quartz (Tan, 1993). Solubility of opal phytoliths ranges from 0.5 to  $10 \text{ mg Si L}^{-1}$ , which is approximately 3 to 5 times lower than amorphous Si and 3 to 10 times higher than quartz (Bartoli and Wilding, 1980). Chemical and physical factors such as water content, temperature, Al content, surface area, and density influence the dissolution of opal phytoliths. Increasing temperature was reported to accelerate Si dissolution from phytoliths by reducing the protective effect of organic coatings such as humic acids, amides, and amines (Wilding et al., 1967; Bartoli and Wilding, 1980).

The soil chemistry of Si in intensively managed agricultural systems has received little attention except in volcanic soils of the tropics. Hydrolysis weathering of primary minerals such as feldspars can release monosilicic acids under acidic condition (Elgawhary and Lindsay, 1972). A constant but limited supply of  $\text{Si}_{\text{ws}}$  in this soil can be expected. The more soluble siliceous minerals (volcanic glass and other amorphous minerals) can also undergo dissolution in the presence of organic ligands (Beckwith and Reeve, 1964). Citrate anion produced higher concentrations of soluble  $\text{H}_4\text{SiO}_4$  from soil than when extracted with either acetate or chloride anion. Adsorption-desorption of  $\text{H}_4\text{SiO}_4$  is also pH dependent, and adsorption increases as pH value increases (Beckwith and Reeve, 1964). The citrate anion also sorbed to soil stronger than did the acetate anion (Beckwith and Reeve, 1964). The response of soluble  $\text{H}_4\text{SiO}_4$  to different acid concentrations also indicated a sorbed Si source rather than from a stoichiometric dissolution of a silicon compound.

Hayes and Swift (1978) and Hayes and Himes (1986) suggest that  $\text{Si}_{\text{ws}}$  could be a part of an admixture with water-soluble fulvic acid and polysaccharides. A dry solid phase may remain amorphous (Hayes and Himes, 1986), and silica may be partially covered or otherwise deactivated by the carbonaceous materials. Silica complexes with carbonaceous materials in volcanic soils (Griffith and Schnitzer, 1975) have been shown to reduce C biodegradation (Martin and Haider, 1986). Therefore, Si surface com-

plexes or sorption reactions with carbonaceous substances also may protect SOC from microbial decomposition.

#### SUMMARY AND CONCLUSIONS

Organic amendments, N fertilizer, and crop residue management effects on total SOC sequestered and  $\text{Si}_{\text{ws}}$  interaction were examined in a wheat-fallow cropping system on a Walla Walla silt loam. Organic amendments had a greater impact on SOC storage in both the Ap and BA horizons than did the crop residue management or N fertilization. Storage of SOC in the FOM fraction for 0- to 26-cm depth ranged from 3.42 to  $4.46 \text{ kg C m}^{-2}$  for  $\text{FB}_0$  and  $\text{NB}_M$ , respectively. Within the Ap horizon, FOM concentrations were in the order:  $\text{NB}_M > \text{NB}_{\text{PV}} > \text{NB}_{45} > \text{NB}_{90} > \text{SB}_{45} = \text{SB}_0 > \text{NB}_0 > \text{SB}_{90} > \text{FB}_0$ . At the 26- to 50-cm depth, FOM storage ranged from 1.13 to  $1.41 \text{ kg C m}^{-2}$  for the  $\text{NB}_0$  and  $\text{SB}_0$ , respectively. The overall average COM was approximately 7% of FOM in the Ap horizon. Mean pH values for the Ap horizon were at least one unit higher for the  $\text{NB}_M$  treatment than the  $\text{NB}_{90}$  treatment. The highest  $\text{Si}_{\text{ws}}$  concentrations were found at the lower depths of Ap horizons, particularly for  $\text{NB}_M$ , whereas nitrogen fertilizer application ( $45$  and  $90 \text{ kg N ha}^{-1}$ ) compared to no-N application decreased  $\text{Si}_{\text{ws}}$  by 17% due to  $\text{Si}_{\text{ws}}$  leaching. Organic amendments ( $\text{NB}_M$  or  $\text{NB}_{\text{PV}}$ ) including larger quantities of crop residue increased the SOC concentration enough to increase  $\text{Si}_{\text{ws}}$  by 10%. Sequestered SOC is suggested to counteract silica solubilization effect of the residual acidic N fertilizer. Carbon storage index ranged from 0.23 for organic amendments to 0.69 for the fall burn treatment, and the index decreased as N rate increased. The SOC storage index suggested that root-derived source C is more resistant to decomposition than the shoot-derived source C. A smaller index indicates higher value for the denominator; hence, more source C is available for microbial activity. This index may have more value for source C relation to soil physical properties because improved biological activity has a direct relation to soil physical properties (e.g., soil aggregate stability).

High SOC, particularly FOM, reduced Si dissolution, illuviation, and deposition at the base of the Ap horizon. Although the form of this  $\text{Si}_{\text{ws}}$  and FOM association was not determined, it is likely that the FOM reduced the

siliceous surface available for dissolution. The potential C management of these naturally high  $H_4SiO_4$  Mollisols requires an understanding of the association of FOM with  $Si_{ws}$ . We suggest that the additions of sufficient organic matter, especially organic amendments, may increase FOM and  $Si_{ws}$  interaction by forming phytoliths or amorphous Si (Hayes and Himes, 1986), or Si complexes (Griffith and Schnitzer, 1975). Either one of these processes can account for reduced SOC biodegradation and reduced siliceous surface area available for dissolution. Determination of SOC by high-temperature furnace method did not detect any possible variations of labile SOC pools. The fate of organic C occluded within phytoliths should be examined because this passive C pool component of SOC is highly resistant to oxidation compared to other SOC components. Extending our knowledge of phytolith behaviors in soils should improve an understanding of the biogeochemical cycling of Si and C in cropland.

#### ABBREVIATIONS

COM: coarse organic matter;  
 $C_{ws}$ : water-soluble carbon;  
 FOM: fine organic matter;  
 MN: manure;  
 MP: moldboard plow tillage;  
 $N_{Org}$ : soil organic nitrogen;  
 FB: fall residue burning;  
 NB: no-residue burning;  
 SB: spring residue burning;  
 PV: pea vines;  
 $H_4SiO_4$ : silicic acid;  
 $Si_{ws}$ : water-soluble silica;  
 SOC: soil organic carbon;  
 SOM: soil organic matter.

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#### REFERENCES

- Al-Ismaily, S. S. 1997. Genesis of silica-enriched agricultural pans in soils managed under wheat-fallow cropping systems. Master Thesis. Oregon State Univ., Corvallis.
- Allmaras, R. R., K. Ward, C. L. Douglas, Jr., and L. G. Ekin. 1982. Long-term cultivation effects on hydraulic properties of a Walla Walla silt loam. *Soil Tillage Res.* 2:265-279.
- Allmaras, R. R., J. L. Pikul, Jr., J. M. Kraft, and D. E. Wilkins. 1988. A method for measuring incorporated crop residue and associated soil properties. *Soil Sci. Soc. Am. J.* 52:1128-1133.
- Baham, J., and S. S. Al-Ismaily. 1996. Formation of weakly cemented siliceous pans induced by long term agricultural management. *In: S. Albrecht (ed.). Columbia Basin Agricultural Management. Ann. Rept. SR961: 68-70. Oregon State Univ., Corvallis, OR.*
- Barak, P., B. O. Jobe, A. R. Kreuger, L. A. Peterson, and D. A. Laird. 1997. Effects of long-term soil acidification due to nitrogen fertilizer inputs in Wisconsin. *Plant Soil* 197:61-69.
- Bartoli, F., and L. P. Wilding. 1980. Dissolution of biogenic opal as a function of its physical and chemical properties. *Soil Sci. Soc. Am. J.* 44:873-878.
- Beckwith, R. S., and R. Reeve. 1963. Studies on soluble silica in soils: I. The sorption of silicic acid by soils and minerals. *Aust. J. Soil Res.* 1:157-168.
- Beckwith, R. S., and R. Reeve. 1964. Studies on soluble silica in soils: II. The release of monosilicic acid from soils. *Aust. J. Soil Res.* 2:33-45.
- Biederbeck, V. O., C. A. Campbell, and R. P. Zentner. 1984. Effect of crop rotation and fertilization on some biological properties of a loam in southwestern Saskatchewan. *Can. J. Soil Sci.* 64:355-367.
- Bloom, P. R., and E. A. Nater. 1991. Kinetics of dissolution of oxide and primary silicate minerals. *In: Rates of Soil Chemical Processes. D. L. Sparks and D. L. Suarez (ed.). SSSA Spec. Publ. 27. Soil Science Society America, Madison, WI, pp. 151-189.*
- Brown, T. H., and R. L. Mahler. 1987. Sorption of silica in a northern Idaho Palouse silt loam. *Soil Sci.* 144:181-189.
- Brown, T. H., and R. L. Mahler. 1988. Relationships between soluble silica and plow pans in Palouse silt loam soils. *Soil Sci.* 145:359-364.
- Brye, K. R., J. M. Norman, L. G. Bundy, and S. T. Gower. 2001. Nitrogen and carbon leaching in agroecosystems and their role in denitrification potential. *J. Environ. Qual.* 30:58-70.
- Buyanovsky, G. A., and G. H. Wagner. 1997. Crop residue input to soil organic matter in the Sanborn field. *In: Soil Organic Matter in Temperate Ecosystems: Long-term Experiments in North America. E. Paul, K. Paustian, E. T. Elliot, and C. V. Cole (eds.). CRC Press, Boca Raton, FL, pp. 73-83.*
- Buyanovsky, G. A., M. Aslam, and G. H. Wagner. 1994. Carbon turnover in soil physical fractions. *Soil Sci. Soc. Am. J.* 58:1167-1173.
- Campbell, C. A., L. G. LaFond, R. P. Zentner, and V. O. Biederbeck. 1991. Influences of fertilizer and straw baling on soil organic matter in a thin black Chernozem of western Canada. *Soil Biol. Biochem.* 23:443-446.

- Chadwick, O. A., D. M. Hendricks, and W. D. Nettleton. 1987a. Silica in duric soils.: I. A depositional model. *Soil Sci. Soc. Am. J.* 51:975-982.
- Chadwick, O. A., D. M. Hendricks, and W. D. Nettleton. 1987b. Silica in duric soils.: II. Mineralogy. *Soil Sci. Soc. Am. J.* 51:982-985.
- Collins, H. P., P. E. Rasmussen, and C. L. Douglas, Jr. 1992. Crop rotation and residue management on soil carbon and microbial dynamics. *Soil Sci. Soc. Am. J.* 56:783-788.
- Douglas, C. L., Jr., R. R. Allmaras, P. R. Rasmussen, R. E. Ramig, and N. C. Roager, Jr. 1980. Wheat straw decomposition and placement effects on decomposition in dryland agriculture of the Pacific Northwest. *Soil Sci. Soc. Am. J.* 44:833-837.
- Douglas, C. L., Jr., R. R. Allmaras, and N. C. Roager, Jr. 1984. Silicic acid and oxidizable carbon movement in a Walla Walla silt loam as related to long-term management. *Soil Sci. Soc. Am. J.* 48:156-162.
- Elgawhary, S. M., and W. L. Lindsay. 1972. Solubility of silica. *Soil Sci. Soc. Am. Proc.* 36:439-442.
- Gale, W. J., and C. A. Cambardella. 2000. Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till. *Soil Sci. Soc. Am. J.* 64:190-195.
- Gollany, H. T., R. R. Allmaras, S. M. Copeland, S. L. Albrecht, and C. L. Douglas, Jr. 2005. Tillage and nitrogen fertilizer influence on carbon and soluble silica relation in a Pacific Northwest Mollisol. *Soil Sci. Soc. Am. J.* 69:1102-1109.
- Griffith, S. M., and M. Schnitzer. 1975. The isolation and characterization of stable metal-organic complexes from tropical volcanic soils. *Soil Sci.* 120:126-131.
- Hayes, M. H. B., and F. L. Himes. 1986. Nature and properties of humus-mineral complexes. *In: Interactions of Soil Minerals With Natural Organics and Microbes.* P. M. Huang and M. Schnitzer (eds.). SSSA Spec. Publ. 17. Soil Science Society of America, Madison, WI, pp. 103-158.
- Hayes, M. H. B., and R. S. Swift. 1978. The chemistry of soil organic colloids. *In: The Chemistry of Soil Constituents.* D. J. Greenland and M. H. B. Hayes (eds.). John Wiley and Sons, Birmingham, UK, pp. 179-320.
- Jones, L. H. P., and A. A. Milne. 1963. Studies of silica in the oat plant: I. Chemical and physical properties of the silica. *Plant Soil.* 18:207-220.
- Kraft, J. M., and R. R. Allmaras. 1985. Pea root pathogens in relation to soil structure, compaction and water content. *In: Ecology and Management of Soil-Borne Plant Pathogens.* C. A. Parker and J. F. Kollmorgen. (eds.). Academic Publishers, New York, pp. 203-205.
- Larson, W. E., C. E. Clapp, W. H. Pierre, and Y. B. Morachan. 1972. Effects of increasing amounts of organic residue in continuous corn: II. Organic carbon, nitrogen, phosphorus, and sulfur. *Agron. J.* 64:204-208.
- Lindbo, D. L., and L. N. Veneman. 1993. Morphological and physical properties of selected fragipan soils in Massachusetts. *Soil Sci. Soc. Am. J.* 57:429-436.
- Martin, J. P., and K. Haider. 1986. Influence of mineral colloids on turnover of soil organic carbon. *In: Interactions of Soil Minerals With Natural Organics and Microbes.* P. M. Huang and M. Schnitzer (eds.). SSSA Spec. Publ. 17. Soil Science Society of America, Madison WI, pp. 283-304.
- Milnes, A. R., and C. R. Twidale. 1983. An overview of silicification in Cainozoic landscapes of arid central and southern Australia. *Aust. J. Soil Res.* 21:387-410.
- Norgren, J. A. 1973. Distribution, form and significance of plant opal in Oregon soils. Ph.D. diss. Oregon State Univ., Corvallis.
- Parr, J. F., and L. A. Sullivan. 2005. Soil carbon sequestration in phytoliths. *Soil Biol. Biochem.* 37:117-124.
- Pikul, J. L., Jr., and R. R. Allmaras. 1986. Physical and chemical properties of a Haploxeroll after fifty years of residue management. *Soil Sci. Soc. Am. J.* 50:214-219.
- Pikul, J. L., Jr., and J. F. Zuzel. 1994. Soil crusting and water infiltration affected by long-term tillage and residue management. *Soil Sci. Soc. Am. J.* 58:1524-1530.
- Rand, M. C., A. E. Greenberg, and M. J. Taras. 1975. Heteropoly blue method. *In: Standard methods for the examination of water and wastewater, 14th ed.* M. C. Rand, A. E. Greenberg, and M. J. Taras (eds.). Am. Public Health Association and Water Pollution Control Federation, Washington, DC, pp. 490-492.
- Rasmussen, P. E., and S. L. Albrecht. 1998. Crop management effects on organic carbon in semi-arid Pacific Northwest soils. *In: Management of Carbon Sequestration in Soil.* R. Lal, J. M. Kimble, R. F. Follet, and B. A. Stewart (eds.). CRC Press, Boca Raton, FL, pp. 209-219.
- Rasmussen, P. E., and W. J. Parton. 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. *Soil Sci. Soc. Am. J.* 58:523-530.
- Rasmussen, P. E., and C. R. Rohde. 1988. Long-term tillage and nitrogen fertilization effects on organic nitrogen and carbon in a semi-arid soil. *Soil Sci. Soc. Am. J.* 52:1114-1117.
- Rasmussen, P. E., R. R. Allmaras, C. R. Rohde, and N. C. Roager, Jr. 1980. Crop residue influences on soil carbon and nitrogen in a wheat-fallow system. *Soil Sci. Soc. Am. J.* 44:596-600.
- SAS Institute. 1988. SAS/STAT user's guide. Version 6.03. SAS Int., Cary, NC.
- Skjemstad, J. O., D. C. Reicosky, A. R. Wilts, and J. A. McGowan. 2002. Charcoal carbon in U.S. agricultural soils. *Soil Sci. Soc. Am. J.* 66:1249-1255.
- Stevenson, F. J. 1994. Humic chemistry: Genesis,

- composition, reactions. 2nd ed. John Wiley and Sons, New York.
- Tan, K. H. 1993. Principles of soil chemistry. 2nd ed. Marcel Dekker, New York, NY.
- Technicon Industrial Systems. 1976. Dissolved organic carbon in water and wastewater. Industrial method number 451-76W. Technicon Industrial Systems, Tarrytown, NY.
- Williams, J. D. 2004. Effects of long-term winter wheat, summer fallow residue and nutrient management on field hydrology for a silt loam in north-central Oregon. *Soil Tillage Res.* 75: 109-119.
- Wilkins, D. E., M. C. Siemens, and S. L. Albrecht. 2002. Changes in soil physical characteristics during transition from intensive tillage to direct seeding. *Trans. ASAE.* 45:877-880.
- Wilding, L. P., R. E. Brown, and N. Holowaychuk. 1967. Accessibility and properties of occluded carbon in biogenetic opal. *Soil Sci.* 103:56-61.
- Wilson, M. A., R. Burt, T. M. Sobecki, R. J. Engel, and K. Hipple. 1996. Soil properties and genesis of pans in till-derived Andisols, Olympic Peninsula, Washington. *Soil Sci. Soc. Am. J.* 60:206-2218.
- Zuzel, J. F., J. L. Pikul, Jr., and P. E. Rasmussen. 1990. Tillage and fertilizer effects on water infiltration. *Soil Sci. Soc. Am J.* 54:205-208.
- Zuzel, J. F., R. R. Allmaras, and R. N. Greenwalt. 1993. Temporal distribution of runoff and soil erosion at a site in northeastern Oregon. *J. Soil Water Conserv.* 48:373-378.