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Surface versus incorporated residue effects on water-stable aggregates☆

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Abstract

Reduced tillage methods for field crop production result in less disruption of soil structure and often increased amounts of crop residue maintained on the soil surface. The combination of these two factors produces increased surface soil aggregation. This study was conducted in the field and within pots to determine whether surface residue by itself improves soil aggregation within a short period of time. The soil was a silt loam loess deposit in the Pacific Northwest, USA, where summers are hot and dry, and most precipitation (420 mm) is received during the mild winters. Two pot studies were conducted over winter, one under a shelter with controlled irrigations (183 mm), and the other outdoors receiving natural precipitation (77 mm). In both pot studies 640 g m^{-2} wheat (*Triticum aestivum* L.) residue was either placed on the surface of the soil or thoroughly mixed into the soil. The field study was conducted on plots where, for the past 7 years, wheat crop residues were either incorporated through chisel/disk tillage or removed before tillage and replaced on the surface after tillage. The field study included plots where wheat was grown with no tillage. In the pots, there was no significant effect due to residue treatment on aggregate mean weight diameter, measured monthly for 4 winter months. This was true despite dissolved organic carbon being leached from the surface residue. In the 7-year-old field plots, replacing residues on the surface resulted in slightly greater mean weight diameter of aggregates at 5–10 cm depth compared to the mixed residue treatment. The no-till plots had significantly greater mean weight diameter at 0–5 cm depth than either tilled treatment. Our conclusion is that surface residue by itself failed to increase aggregation of tilled surface soil within the first rainy season after tillage.

Keywords: Soil aggregation; Crop residue; Tillage; Water-stable aggregates; No-till

1. Introduction

Soil aggregation is an extremely important determinant of a soil's physical characteristics. Aggregation is impacted by changes in management because some of the major agents of aggregation are biological in origin and therefore sensitive to changes in plant and microbial activity.

Maintenance of a layer of crop residue over the soil surface helps to protect from raindrop impact and cycles of freezing–thawing and drying–wetting. Generally, increased surface residue amounts are achieved through reduction in intensity of tillage. Over time, reduction in tillage results in significant changes in organic matter distribution, with increased stratification of organic matter on or near the surface, and lower organic matter levels at deeper depths (Ball et al., 1996; Franzluebbers, 2002). Researchers have found increases in aggregation under surface residue when compared with areas

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without residue (Burch et al., 1986; Wright et al., 1999). This might be due to soluble carbohydrates leached from fresh residues (Ball et al., 1996), or to particulate organic matter (Gale et al., 2000), or to the activity of fungi (Wright et al., 1999; Bossuyt et al., 2001) or other microbes.

In agricultural settings, the effects of surface residue are almost always confounded with the effects of tillage, making it difficult to separate the immediate effect of surface residue cover from the longer-term effects of organic matter stratification and reduced soil disturbance.

The study we report here was inspired by observation of continuous annual winter wheat plots where intensively-tilled soil was being compared to no-till. In one of the tilled treatments, surface residues were removed before tillage and replaced after tillage. We observed several phenomena in this tilled, surface residue treatment that appeared to be intermediate in magnitude between the no-till and the tilled treatment where residues were incorporated. These phenomena included soil temperature, moisture, and increased water percolation through surface soil samples. The temperature and moisture differences were obviously a result of the insulating effect of the surface residue layer. Improved percolation of water through sieved soil samples, however, suggested that surface residue may have a significant immediate effect on the surface soil in addition to protection from the weather. The most likely effect would be increased soil aggregation or aggregate stability. Tillage operations and depths were identical except for removal and replacement of surface residues in one treatment and incorporation of residues in the other. Tillage depth was 20 cm, so surface effects would have likely been destroyed or diluted from 1 year to the next. Surface residue provided in situ protection from aggregate slaking, but this did not necessarily explain improved percolation through disturbed soil samples.

Since there are tillage tools that cause minimal burial of residue, it is important to understand the potential for improving soil aggregation in systems where surface residues are maintained rather than buried. This study was designed to test the hypothesis that surface residue has an immediate effect (first rainy season) on aggregation of soil directly below the residue.

2. Methods

2.1. General description

Three experiments were used to test the hypothesis: two pot experiments and a field plot experiment which had been in place for 7 years. The field plots were located near Pendleton, OR (45°43′N, 118°38′W, elevation 458 m). Annual precipitation averages 420 mm and falls mostly as rain during the winter. Temperature averages 1 °C in January. Summers are hot and dry, with an average temperature of 21 °C in July. The soil was Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll) containing about 10% clay, 69% silt and 21% fine to very fine sand, and 15 g organic C kg^{-1} soil in the top 10 cm.

One pot experiment was conducted outdoors, and simultaneously another pot experiment conducted under shelter in order to control precipitation and provide more robust conclusions than could be produced from a single location in 1 year. The pot experiments were designed to compare soil aggregation under a layer of surface residue versus aggregation when residue was mixed into the soil. Both the sheltered and outdoor pot experiments used identical pots, soil, and residue. The outdoor pots were subject to weather and moisture conditions experienced by the field plots. The sheltered pots were subject to temperatures similar to the outdoor pots and field plots but received manual applications of water. The 7-year-old field plot experiment contained very similar treatments in a more realistic wheat production environment using farm equipment. The experiment was timed to coincide with the critical erosion season in the Pacific Northwest, which is after planting winter wheat.

2.2. Pot setup

A quantity of 0 to 5 cm surface soil that had been under wheat/fallow rotation without tillage for several years was collected near the field plot site. Surface residue was removed before collecting the soil. The soil was passed through a 1.3 cm screen, carefully mixed, and then divided into two piles. Winter wheat residue chopped to approximately 3 cm maximum lengths was mixed into one pile at a rate equivalent to 640 g m^{-2} (5 g in a finished pot, 2.9 g straw kg^{-1} soil). This amount of residue was equal to that found in the field plot surface residue treatment. This was the mixed treatment. For the surface residue treatment, an equivalent amount of residue was placed on the soil surface after filling the pots from the second pile of soil. The residue was from the previous summer's harvest of winter wheat, cv. Stephens, and consisted mostly of wheat culms and leaf sheaths with a C:N ratio of 130.

Pots were 10 cm diameter, 20 cm tall PVC tubes. For the outdoor pots, the tubes were set in the ground in a fallow area with the top edge about 1 cm above the ground surface. The bottom was open so the soil mixture made contact with the natural subsoil and could drain naturally. Pots in the shelter were placed on beds of soil, which enabled the pots to drain and not become waterlogged after irrigation. All pots were filled to within 2 cm of the top, which resulted in about 1.4 kg soil in each pot and a soil bulk density of about 1.0 Mg m^{-3}.

Each pot experiment had 16 pots with mixed residue, and 16 with surface residue, which allowed four replicate pots to be destructively sampled four times in 120 days (13 December 2004 to 4 April 2005). In total, there were 32 pots in the shelter and 32 outdoors. The outdoor pots received only natural precipitation. The sheltered pots received an amount of water equal to the local 20-year average precipitation for the 4 months of the experiment, December through March. Irrigation was by sprinkling 24 mm of water at 2-week intervals. Deionized water was applied over a period of 8 h in four 6 mm applications. Precipitation, irrigation added to sheltered pots, and temperature at 5 cm soil depth are shown in Fig. 1. Unusually low natural precipitation during the experiment resulted in the sheltered pots receiving much more water than the outdoor pots or field plots.

In addition to the soil-filled pots, both the outdoor and sheltered locations had four samples of surface residue placed on screen rather than soil. Water collected under the screen after irrigation (shelter) or natural precipitation events (outdoor) was analyzed for dissolved organic carbon using a Formacs HT combustion TOC analyzer (Skalar Analytical B.V., The Netherlands).

The pot experiments started 13 December 2004 to coincide with the typical wet season. Pots were kept free of plant growth. Every 4 weeks over the next 4 months pots were chosen randomly for destructive sampling. Soil samples from 0 to 5 cm and 5 to 10 cm depth were weighed for soil moisture and then dried at 40 °C before storage.

2.3. Field plots

The field plots were located within an experiment in its seventh year and having three treatments: (1) no-till, (2) chisel/disk tillage, and (3) chisel/disk tillage where the surface residues were raked aside before tillage, and then spread evenly back over the plot after tillage. Tillage to about 20 cm depth was performed in late September of each year. All three treatments were

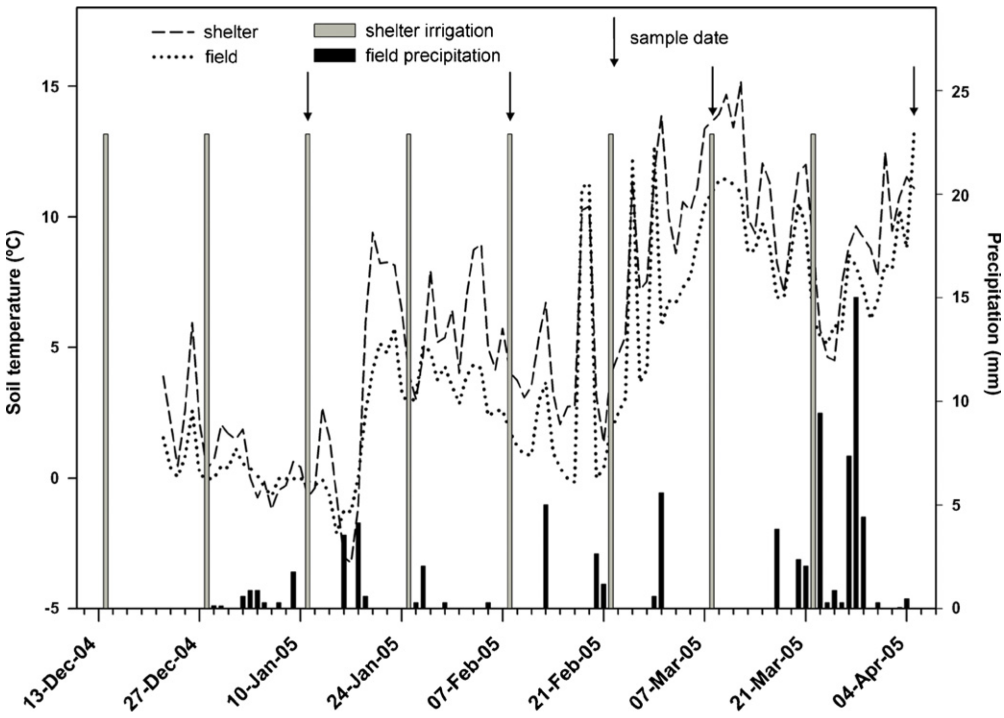

Fig. 1. Soil temperatures, field precipitation events, and irrigation of pots in the shelter. Also shown is the timing of the four soil samples. Soil temperatures were monitored at 5 cm. Total precipitation for the period was 77 mm for both the outdoor pots and field plots. Total irrigation of sheltered pots was 183 mm.

seeded to continuous winter wheat every fall (late October) using the same drill, seed, and fertilizer rates. No irrigation was applied. Average yield in the experiment was 3.7 Mg ha^{-1}, with no significant difference among treatments. The 3.7 m wide × 50 m long plots were arranged in four randomized, complete blocks. Soil samples were taken from each field plot on the same dates and at the same depths (0–5 and 5–10 cm) as the pot experiment. Three 4 cm diameter cores were combined per sample. Residue in the field plots was the same wheat variety as used in the pots but contained more leaf blades, glumes, and other fine materials. In addition, the no-till and surface residue field plots included a small amount of residue remaining from previous wheat harvests.

2.4. Aggregate measurements

Water-stable aggregates were measured by wet sieving on stacked sieves in a manner similar to that described by Angers and Mehuys (1993). First, the dried soil samples were passed though a 4 mm screen. Five grams were then placed on a 1000 μm sieve. Stacked under the 1000 μm sieve was a 250, a 125, and a 53 μm sieve, spaced about 1 cm apart vertically. The sieve set was immersed in deionized water until the soil sample was completely covered, then immediately sieved for 3 min at 20 cycles per minute. The length of stroke was 1.3 cm. This stroke and duration were sufficient to clear the screens of slaked soil, leaving only separated aggregates too large to pass through each sieve. The weight of soil retained on each sieve was determined after drying at 40 °C. This soil contained about 210 g kg^{-1} sand >53 μm, but only about 10 g kg^{-1} sand >125 μm, so aggregate fractions were not adjusted for sand content. Two subsamples were measured from each soil sample.

2.5. Statistical analysis

The mean weight diameter was computed for each water-stable aggregate measurement by summing the product of each fraction times its mean inter-sieve size (Angers and Mehuys, 1993). The mean weight diameters from the pot experiments were analyzed using a mixed model (SAS, 2003) with treatment (mixed residue, surface residue) and sample depth (0–5 cm, 5–10 cm) and their interaction set as fixed effects, and location (outdoor, sheltered), sample date, and replication set as random effects. A separate analysis was performed on the field plots using a mixed model with treatment (no-till, tillage with mixed residue, tillage with surface residue replaced after tillage) and sample depth (0–5 cm, 5–10 cm) and their interaction as fixed effects, and sample date and block as random effects. Effects were considered statistically significant at a maximum of $p = 0.05$.

3. Results

3.1. Surface versus mixed residue

A sample was taken every 4 weeks over a period of 4 months, so the data were tested for an effect of sample date. No significant effect existed, and there was no trend toward increasing aggregation with time.

In the pot experiments, there was no significant difference in aggregate mean weight diameter between the outdoor and sheltered location. Mean weight diameter in the pot experiments was also not different between surface residue and mixed residue treatments (average of means = 0.429 mm, standard error of means = 0.071 mm). There were no differences between depths and no significant interaction.

The surface residue and mixed residue treatments in the field plots were not significantly different, according to an individual t-test between these two main effects (Fig. 2). When considering all three field plot treatments, no-till had greater mean weight diameter than the two tilled treatments ($p < 0.001$, Fig. 2). This was due to much greater aggregation in the 0–5 cm depth of no-till, which also resulted in a significant main effect for depth ($p < 0.001$). The interaction between treatments and depths was significant ($p < 0.001$), with both depths of no-till and the 5–10 cm depth of the surface residue treatment having greater mean weight

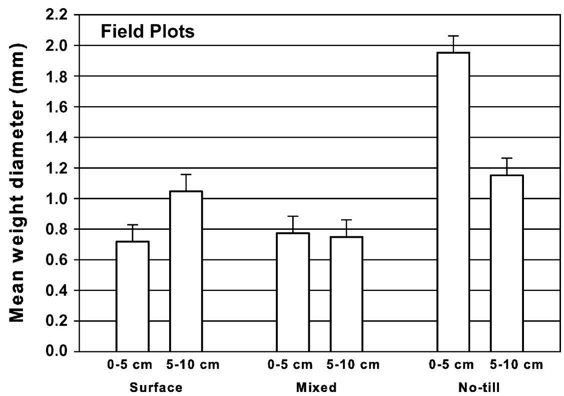

Fig. 2. Mean weight diameter of aggregates in the field plot experiment. Least-square means from mixed model with error bars showing the standard error of each mean. Main effect of treatment significant at $p < 0.001$, and of depth at $p < 0.001$. Interaction differences greater than 0.2 have $p > |t|$ less than 0.05.

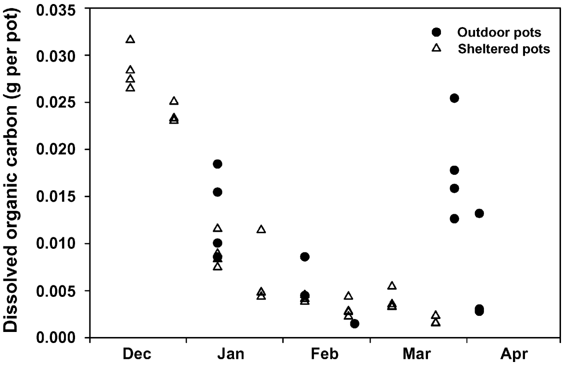

Fig. 3. Dissolved organic carbon collected below residue placed on screens in the sheltered and outdoor pot experiments. Samples were collected after irrigations in the sheltered pots and after precipitation events in the outdoor pots.

diameter than the 0–5 cm surface treatment and either depth of the mixed treatment (Fig. 2).

3.2. Dissolved organic carbon

Dissolved organic carbon collected below residue placed on screens in both the sheltered and outdoor pot experiments is shown in Fig. 3. The amount of carbon diminished with successive irrigations in the sheltered pots. The dissolved organic carbon from outdoor samples corresponded to rainfall. The early light rains were apparently not enough to extract much from the residue, but later rainfall yielded quantities of soluble carbon similar to the early irrigations of the sheltered pots. The average cumulative dissolved organic carbon was 0.08 g pot^{-1} for sheltered pots, and 0.04 g pot^{-1} for outdoor pots.

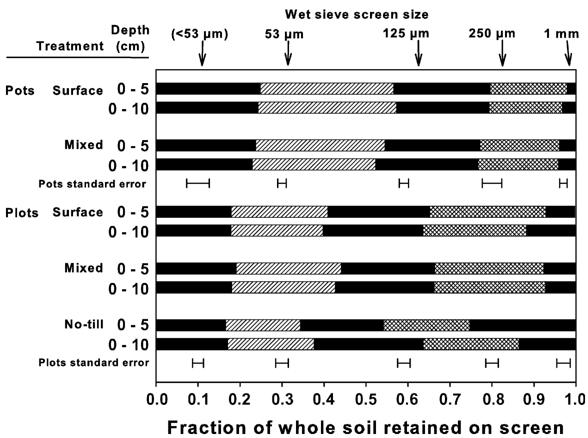

Fig. 4. Fraction of whole soil in each of five size classes after wet sieving with four screen sizes. Mean of replications, sample dates, and subsamples ($n = 32$). Standard error of the mean of each size class, calculated from the mixed model analysis, is shown for the pot experiments and the field plot experiment.

3.3. Relations among water-stable aggregate size classes

Mean weight diameter gives a single number weighted toward the larger aggregate sizes. The individual weights of aggregate fractions are shown in Fig. 4. It can be seen that the 125–250 μm size class changed little among management systems and depths. Mean weight diameter increased with no-till because of an increase in larger aggregates, particularly >1000 μm.

4. Discussion

A layer of surface residue did not promote aggregation in the pot experiment. Surface residue also did not increase aggregate mean weight diameter in the 0–5 cm layer of the tilled field plots. The hypothesis that surface residue would promote soil aggregation within the first winter season after tillage was not supported by the data. In fact, the average mean weight diameter tended to be greater in the pots where soil and residue were mixed, and mean weight diameter was greater at 5–10 cm than 0–5 cm in the tilled field plots with surface residue (Fig. 2).

Small increases in soil aggregation can lead to large increases in ponded infiltration. For example, in a study on this same soil, 17% greater water-stable aggregates >250 μm in the Ap horizon corresponded to 170% greater ponded infiltration rate (Wuest et al., 2005). The significant effects reported here represent increases in >250 μm aggregation ranging from 8 to 120%, and should be, therefore, large enough to have substantial effects on infiltration and runoff.

In our study, the no-till treatment had surface soil with more >1000 μm aggregates than any other treatment; this may indicate that, after 7 years of surface residue accumulation and relatively little soil disturbance, conditions were more favorable for fungal activity. Denef et al. (2001) used ground wheat residue and found that fungicide treatment prevented large aggregate formation. The field plots also had live and decaying roots, accumulated fine and coarse wheat residues from recent harvests, and partially decomposed residues from past harvests.

Residue mixtures, including leaf, leaf blade, culm, and chaff, have decomposition rates different than the rates for individual plant parts (Collins et al., 1990). The field plots received a natural mixture of crop residue components, while both pot studies received mostly culm and leaf sheath. Another difference between the pots and field plots was the length of time they were exposed to precipitation or irrigation. The field plots were seeded in late October, and received their first substantial rainfall on 1 November. The data do not indicate an increase in aggregation over the 4-month study period, but we could not measure with certainty the effect of time on the field plots exposed to surface residue.

Although this study was designed to test one fairly simple hypothesis, it might also provide information concerning aggregate formation. At first glance it may seem trivial to note that when the proportion of large aggregates increases the proportion of small aggregates decreases. There is, however, much discussion in the literature about the role of microaggregates and macroaggregates in aggregate genesis (Oades, 1984; Six et al., 1999). The interest is in identifying the division between classes that increase and those that decrease. It is apparent that, in all but the no-till plots, increases in aggregates >1000 μm did not reduce the proportion of 250–1000 μm aggregates; in fact, they increased together while the smaller classes decreased (Fig. 4). Treatments that increased the >1000 μm class aggregated some of the <53 μm and 53–125 μm fractions. It is more difficult to explain why the 125–250 μm size neither decreased or increased. It seems to indicate that the increased aggregation was not simply a general, random increase in size or stability accompanied by a decrease in the smallest aggregates and individual soil particles. Certain classes increased, while others stayed the same or decreased. This analysis was based on net changes and does not imply that the 125–250 μm class experienced no activity.

Another phenomenon can be seen in the no-till plots regarding proportions of aggregate size classes. The no-till treatment, 0–5 cm depth, had large aggregates of a somewhat different character than the other treatments.

It should be noted that the choice of screen size and sieving technique is likely to impact results. One demonstrated artifact of laboratory measurements includes differences in aggregate strength between wetting intact cores and disturbed cores (Bossuyt et al., 2001). Pre-wetting treatments and slaking methods also produce large differences in aggregate measurements (Cambardella and Elliott, 1993). Different techniques and soils have produced variable relationships among size classes. For example, Denef et al. (2001) imposed treatments that created aggregates >2000 μm, and <250 μm, but none in the 250–2000 μm range. In our experiment, a slaking method was chosen to measure aggregates because slaking is an important factor in local runoff and erosion.

From this study we conclude that a layer of surface residue, recently applied to tilled soil, does not by itself increase aggregation in the soil immediately below it. We now propose an alternative explanation for the pre-experiment observation that replacing surface residue instead of incorporating it during tillage increases aggregation. Perhaps surface residues produce long-lasting aggregation effects that are greater than buried residue because surface residue fosters fungal activity (Beare et al., 1993). If the aggregating agent is durable, the aggregation effect might accumulate despite tillage. In a previous, intensively tilled experiment, measures of aggregate stability were highly correlated to glomalin and Basidiomycete assays (Wuest et al., 2005). If the fungi-mediated effect is slow and operates under relatively dry conditions, this would explain our failure to find a surface residue effect in the pot experiments while finding greater aggregate stability at the 5–10 cm depth in the field plots that were tilled with surface residues replaced for 7 consecutive years (Fig. 2). Under no-till cropping systems, this fungal effect would add to any effect of reduced tillage and stratification of organic matter.

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