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Technical Note

Comparison of Preferential Flow Paths to Bulk Soil in a Weakly Aggregated Silt Loam Soil

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Preferential flow paths are common in both tilled and untilled soil, but how or why soil in preferential paths differs from neighboring bulk soil is not well understood in either. We used a 10-min pulse of dye to mark preferential flow paths at the end of 2 h of ponded infiltration. Small cores were taken from dyed and undyed soil at the 10- to 25-cm depth. Compared with the bulk soil, preferential flow zones had more large and fewer small aggregates, greater water content, and lower bulk density (1.20 vs. 1.23 Mg m^{-3}). Root mass and total soil C were not significantly different. In comparison to untilled soil, tilled soil had more unaggregated soil, greater water content, and lower bulk density (1.16 vs. 1.24 Mg m^{-3}). Statistical analysis suggested no interactions between the preferential flow zone–bulk soil factor and the tilled–untilled factor. Infiltration rates in untilled soil were greater despite greater bulk density in both preferential flow zones and the non-preferential-flow matrix soil. These results suggest that greater saturated water conductivity in untilled soil is not due to better developed individual preferential flow pathways, but rather to a greater number of potential pathways being well connected to the surface water source. This could have more to do with better aggregation of surface soil than with specific properties of the preferential flow paths.

Preferential flow is recognized as a common feature of water movement in soil (Radulovich et al., 1992; Flury et al., 1994). Recommendations for soil management practices that minimize water runoff could be improved if preferential flow pathways were better understood. It would also allow more accurate modeling of water movement in soil by improving mechanistic descriptions of tillage effects (Strudley et al., 2008).

Indirect methods are often used to detect preferential flow, and specific measurements characterizing zones of preferential flow are commonly lacking (Strudley et al., 2008).

The use of dyes as tracers has allowed researchers to identify preferential flow pathways in comparison to undyed, nonpreferential zones. When a pulse of tracer is applied to soil already at steady infiltration, the tracer bypasses the bulk soil and is isolated in preferential pathways (Kung et al., 2006). It is therefore possible to measure soil properties associated with preferential flow zones in comparison to undyed bulk soil in an attempt to understand how they form and why they conduct water faster.

Several studies have provided insight into the nature of preferential flow. Different tillage methods have been shown to produce different dye patterns, both in the tilled zone and below it (Petersen et al., 2001). In a tilled soil, Omoti and Wild (1979) found that dyed zones had low bulk density and sometimes very small fissures. For the soil studied, they concluded that bulk density was more important than earthworm channels in relation to the presence of dye. In a forest soil, Bundt et al. (2001) found that water content was greater in preferential flow zones even 1 d after a sprinkling experiment. The preferential flow zones also had greater concentrations of organic substrates and nutrients than the bulk soil. In a study of unsaturated flow, Gaston and Locke (2002) found more biomass C but less total organic C in dyed soil.

Roots can create channels for preferential flow, and their effect may vary depending on whether they are alive or dead (Gish and Jury, 1983). Roots are a possible mechanism for increases in soil C and water-stable aggregates in preferential flow zones. If preferential flow is related to roots in an untilled soil, it seems probable that the preferential flow capacity might increase with time through the increase in root growth by perennial plants and perhaps even the reestablishment of roots in former root channels in annual plant systems.

Preferential flow appears to be a major factor involved in high ponded infiltration rates under long-term no-till cropping systems in silt loam loess of the Pacific Northwest (Wuest, 2005). The degree of surface soil aggregation is another factor (Wuest et al., 2005). Water-stable aggregates in the uppermost

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surface soil are correlated with organic C levels and can be significantly increased in <7 yr when converting from intensive tillage to no-till. Preferential flow associated with a capacity for very high infiltration rates, however, appears to take decades to fully develop (Wuest et al., 2006).

In this Pacific Northwest soil, preferential flow zones appear to be distinct areas of high water flow, which presumably are active repeatedly during a season or even years where the soil is not significantly disturbed. The number of zones encountered in a soil cross-section was greater in untilled soil, and this corresponded to greater ponded infiltration rates (Wuest, 2005; Wuest et al., 2006). This leads to the question of how preferential flow zones develop and what their most important characteristics are. It is possible that positive feedback mechanisms are involved, where improved water availability or lower bulk density improves root growth, which in turn increases C substrates for soil aggregation and nutrient turnover, which further improves the environment for root growth.

This theory could be tested by following flow zones with time, but it is difficult to make repeated measurements of flow paths with time because the most straightforward method to identify them is marking with dyed water and sampling destructively. Another approach is to use destructive sampling to compare preferential flow zones in a tilled soil with those in an untilled soil. At the same time, the characteristics of preferential flow zones can be compared with the bulk soil. This study was conducted to test the hypothesis that preferential flow zones in a silt loam soil would differ from the rest of the soil in measurements of bulk density, soil C, soil aggregation, and root mass. It was also hypothesized that preferential flow zones in untilled soil would have greater differences than in tilled soil.

Materials and Methods

The experimental 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. Temperatures average 0.6°C in January. Summers are hot and dry, with an average temperature of 21°C in July. The soil was a Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll containing about 10% clay, 69% silt, and 21% fine to very fine sand). Samples were taken from plots of two separate ongoing experiments. The first was a continuous winter wheat (*Triticum aestivum* L.) experiment with three treatments: one untilled for 7 yr and two using disk tillage. The second experiment was a pea (*Pisum sativum* L.)–winter wheat rotation established in 1941 (Wuest, 2001). Two tillage treatments sampled in this second experiment were plowing before planting both pea and winter wheat vs. no-till planting for both crops. Each experiment had four replications. Measurements were made in winter wheat plots in the spring, after winter rainfall had reconsolidated the effects of tillage.

Two sets of samples were collected using dye to identify preferential flow paths, one from each of the two experiments. Soil bulk density, water content, aggregates, and root mass were measured. A third set was collected using NaI as a tracer so that data could be obtained for organic C without contamination by C contained in the dye. This third set of samples was taken from the pea–winter wheat experiment.

We made single-ring infiltration measurements (Bertrand, 1965) using 20-cm-diameter cylinders. Row spacing of the wheat crop was 25 cm, and the cylinders were always placed to include one crop row inside the cylinder. Cylinders were driven into the soil about 25 cm and the soil around the inner circumference tamped with a 4-mm-thick plot stake to seal any gaps between the cylinder wall and the soil column. Previously collected rainwater was used to avoid the effects of salts. The water level was maintained at approximately 5 cm above the average soil surface for 2 h. In this soil, quasi-steady-state infiltration is reached before 30 min (Wuest, 2005).

Preferential flow zones were identified by adding a pulse of Brilliant Blue dye (C.I. Food Blue 2, C.I. 42090; for characteristics, see Flury and Fluhler, 1995) and KBr. This dye has relatively low retardation in the soil, and the KBr was added as a check to make sure that even small amounts of the tracer solution were not showing up in the bulk soil samples. Following 2 h of ponded infiltration, the dye solution was mixed with the water in the top of the cylinder and left to infiltrate for 10 min. The target concentrations were 5 g dye and 1.8 g KBr L^{-1} of ponded water. At the end of the 10-min period, the remaining water was suctioned off with a vacuum hose. We then immediately excavated the cylinder and took samples from specific depths (Fig. 1). Volumetric samples were taken with an 18-mm inner diameter by 20-mm-long, sharpened, thin-wall metal cylinder (5.13-cm^3 measured volume). Two samples were taken from the dyed soil and two from the undyed soil. Each sample was placed in an airtight can. If dye had not reached 15 cm, the cylinder was cross-sectioned at the 10-cm depth for sample collection.

In the continuous winter wheat experiment, we sampled one infiltration cylinder in each of the four replications of each treatment, resulting in 22 successful samples from dyed zones and 23 from undyed zones. We also took samples from about 22 to 25 cm, at the bottom of the excavated cylinder. All four untilled plots had dyed zones at the bottom, but only three of eight plots under

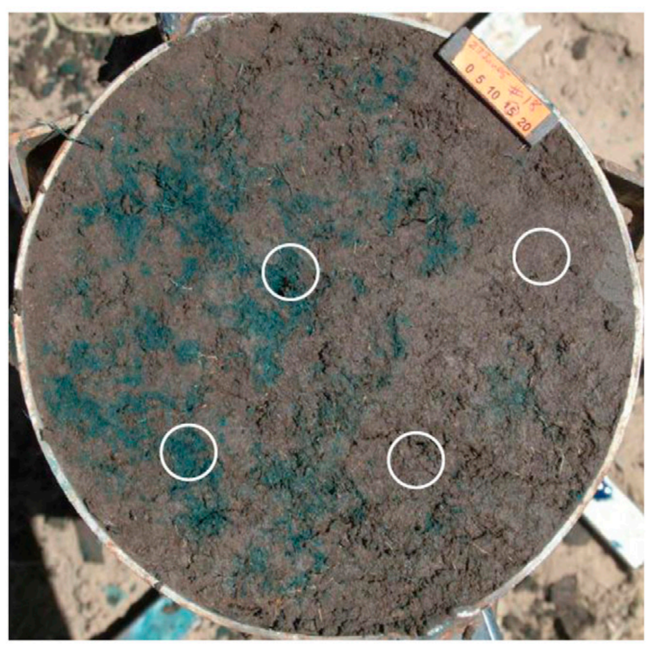

Fig. 1. Example of a 20-cm-diameter infiltration cylinder cross-section at 15-cm depth from an untilled plot in the continuous winter wheat experiment. Blue areas are preferential flow pathways stained by a 10-min pulse of dye after 2 h of ponded infiltration. White circles show location of small core samples, two in dyed zones and two in undyed zones.

tillage had dye at the bottom of the cylinder, and therefore only 14 dyed and 14 undyed samples were possible at the lower depth.

For the dye-based samples from the pea–winter wheat experiment, three of the untilled plot samples were taken from 15 cm, but in the fourth plot it was necessary to move up to 10 cm to find dye. In the tilled plots, one cylinder was lost when the water-saturated soil collapsed before a cross-section could be taken; in another, the dye had very little penetration so samples were taken from 3.5 cm. In the other two plots, samples were successfully taken at 10 cm. In total, the pea–winter wheat experiment produced 14 dyed and 14 undyed samples. No attempt was made to take samples from the bottom of the infiltration cylinders in the pea–winter wheat experiment.

As mentioned above, NaI was used as a second tracer method in the untilled pea–winter wheat plots using the method of van Ommen et al. (1988). After at least 2 h of ponded infiltration, a NaI solution was added to the ponded water to bring it to about 20 mmol L^{-1} I^{-}. Twenty minutes later the cylinder was excavated. Horizontal cross-sections were dusted with potato starch. After the starch was wetted by soil solution, it was sprayed with dilute NaOCl solution to create purple stains where iodine was in contact with the starch. Staining patterns were very similar to those produced using dye. Distinct purple areas were sampled as preferential flow zones and uncolored areas as bulk soil. Care was taken to trim all potato starch off the samples. Two cylinders were sampled in each of two plots, and four preferential flow zone and four bulk soil samples were taken from each cross-section. Eleven cross-sections were made at depths ranging from 7 to 23 cm, for a total of 88 samples using the iodine tracer. These samples were analyzed for root mass, water content, and total C but not water-stable aggregates.

To process the core samples, sample wet weight was recorded before transferring to a 1000-μm sieve, under which were 250-, 125-, and 53-μm sieves, all spaced about 1 cm apart vertically. The entire sieve set was immersed in 300 mL of deionized water until the soil sample was completely covered, then immediately sieved for 3 min at 20 cycles min^{-1} and a 1.3-cm stroke. This stroke and duration was 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 Walla Walla soil contains about 21% sand >53 μm, but <1% sand >125 μm, so aggregate fractions were not adjusted for sand content. Mean weight diameter was computed by summing the product of each fraction times its mean intersieve size (Angers and Mehuys, 1993). As mean weight diameter is mostly influenced by the largest diameter aggregates, for this study we used the 250-μm intersieve size (that is, 625) for a weighting factor of aggregates retained on the 1-mm sieve. Since about half of the aggregates were >1 mm, this still resulted in about 80% of the mean weight diameter value coming from >1-mm aggregates.

Roots were collected from the 1000-μm screen after crushing and washing any aggregates remaining on the screen. Roots were then dried at 40°C and weighed. Dye and Br^{-} concentrations were determined for the supernatant of the aggregate-washing water using a spectrophotometer and Br^{-} electrode. Total organic C was determined on the recombined dried soil by dry combustion. This soil contains insignificant amounts of inorganic C near the surface, so total C is a measure of total organic C. Dry soil weight was also used to calculate the original soil water content and bulk density.

Statistical Analysis

Our primary objective was to compare preferential flow zones to nonpreferential flow zones, and tilled and untilled soil. For statistical analysis, we used a mixed model with flow zone, tillage treatment, and their interaction as fixed effects. Block, experiment, and depth were designated as random effects since these were not intended to be investigated as specific factors of interest (SAS Institute, 1998). This statistical model treats cylinder cross-sections as an additional blocking factor, so depth effects are removed from the main effects. All samples were combined for analysis of root mass, bulk density, and water content. Iodine-traced samples were analyzed separately to determine the total C content. Differences were considered statistically significant if $P > F$ (probability of a greater F) was <0.05.

Results

Infiltration rates at the end of the 2-h ponded infiltration averaged 41 mm h^{-1} in tilled plots and 56 mm h^{-1} in untilled plots. These are normal rates for these methods and tillage treatments on this soil (Wuest, 2005; Wuest et al., 2006).

Bromide was added to the dye solution to determine if dye retardation (Perillo et al., 1998) would interfere with the ability to distinguish between preferential and nonpreferential flow zones. Bromide and dye content were highly correlated ($r = 0.92$), indicating that areas without dye were not conducting tracer solution.

Analysis of the iodine-tracer samples collected in untilled plots resulted in 12.25 g kg^{-1} total soil C in preferential flow zones vs. 12.04 g kg^{-1} in the bulk soil. The difference was not statistically significant ($P > F = 0.1898$).

Root mass differed only between tillage treatments ($P > F = 0.0003$). There were more roots in tilled plots (0.085 g $sample^{-1}$) than untilled plots (0.027 g). It should be noted, however, that while samples were balanced for dyed and undyed zones by taking sample cores from both in each cylinder cross-section, it was sometimes necessary to decrease the depth of sampling to find dyed zones in the tilled soil. This probably influenced the root comparison between tilled and untilled soils.

Within both tilled and untilled soils, preferential flow zones had lower bulk density than nonpreferential flow zones ($P > F = 0.0106$; Fig. 2). On average, however, tilled plots had lower bulk density than untilled plots ($P > F = 0.0001$). There was no interaction between zones and tillage.

Samples taken from preferential flow zones had greater aggregation (Fig. 3) and, therefore, less material <53 μm ($P > F = 0.0415$), less retained on top of the 53-μm sieve ($P > F = 0.0445$), and more retained on the 1-mm sieve ($P > F = 0.0216$). Compared with the untilled soil, the tilled soil had a lower proportion of water-stable aggregates. More soil passed through the 53-μm sieve ($P > F = 0.0001$) and less material was retained on the 250-μm sieve ($P > F = 0.0115$) compared with the untilled soil. There were no statistically significant interactions at $P = 0.05$, although it can be seen in Fig. 3 that the tilled, bulk soil had a major influence on the statistically significant factors.

Mean weight diameter differences were significant for preferential flow zones vs. the bulk soil ($P > F = 0.0415$; Fig. 3), and for tilled vs. untilled soils ($P > F = 0.0012$). The interaction was

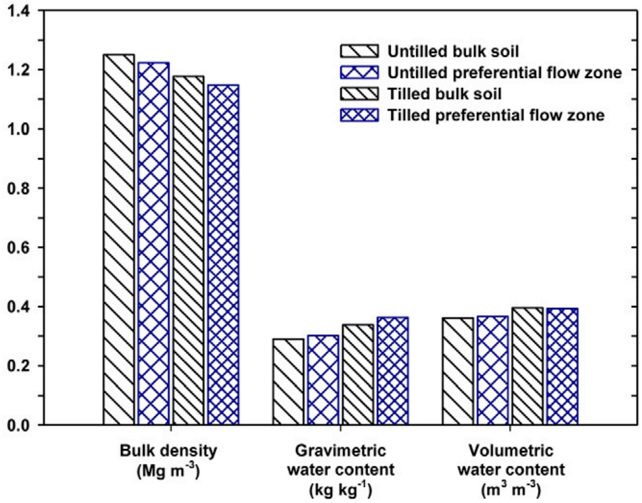

FIG. 2. Soil bulk density and gravimetric and volumetric water contents of soil samples taken from preferential flow zones and undyed bulk soil of tilled and untilled plots. The difference between tilled and untilled plots is statistically significant for all three factors. The difference between preferential flow zones and bulk soil is statistically significant for bulk density and gravimetric water content.

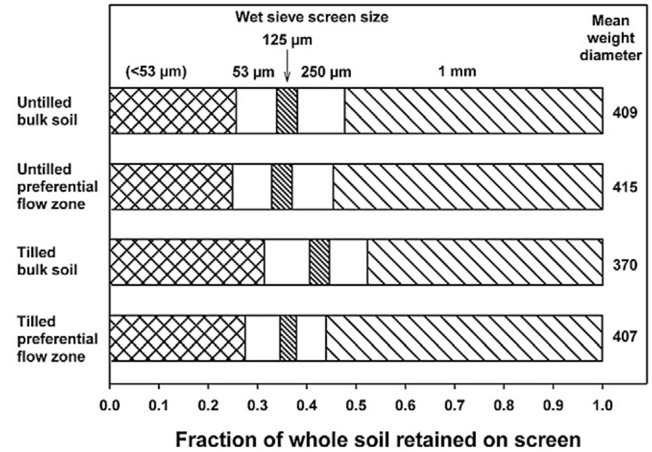

FIG. 3. Proportion of water-stable aggregates in each of five size classes. Tilled and untilled plots are statistically different for <53 and 250 µm and mean weight diameter. The difference between bulk soil and preferential flow zones are statistically significant for <53 and 53 µm, 1 mm, and mean weight diameter.

not statistically significant ($P > F = 0.0912$), but again the tilled bulk soil is clearly the most influential treatment.

As might be expected, preferential flow zones had greater water content (Fig. 2). This was statistically significant ($P > F = 0.0009$) when calculated as gravimetric water content. Tilled soil had a greater water content both as gravimetric ($P > F = 0.0001$) and volumetric ($P > F = 0.0003$) water contents. There was no interaction between zone and tillage.

Discussion

The use of dye to mark preferential flow paths for short periods of time created clearly demarcated dyed and undyed areas of soil in cylinder cross-sections, as shown in the color reproduction of Fig. 1. The fact that the dye was introduced after at least 2 h of ponded infiltration with plain water means that there should have been little tendency for the dye to migrate laterally into the bulk, non-preferential-flow soil. To minimize this tendency further, the samples were taken as soon as possible after the 10-min dye exposure period. In my experience, even if the cylinders were to be left unexcavated for 18 h after removing the dye solution from the soil surface, the dye staining patterns would appear distinct and not noticeably different than when excavated immediately.

There is a certain bias in taking the small, 18-mm-diam. samples, however. Because the dyed areas are only a small fraction of the total area and irregularly shaped, the small core sample usually included various amounts of undyed soil (Fig. 1). What this means for data interpretation is that the samples classified as preferential flow zones are actually mostly or partly preferential flow soil with varying amounts of bulk soil included. Any differences detected should therefore be considered conservative estimates of the true differences between pure preferential flow zone soil and bulk soil because the C, roots, etc. of the preferential flow zones were diluted with some bulk soil. Taking bulk density, for example, some very narrow fractures with bulk density near zero may be responsible for the preferential flow of water, but our sample necessarily included the soil around the fractures and resulted in a total bulk density much closer to the average for the bulk soil than to zero. In this experiment, we had sufficient numbers of carefully paired samples to overcome the dilution effect and produce statistically significant results, but in future experiments one could try taking even smaller samples, or perhaps vary the diameter of the sample in an attempt to include only dyed soil in the preferential flow zone samples.

The above discussion about the sample dilution effect is important for putting the results in the proper perspective relative to the magnitude of differences detected. There is an additional consideration that might prove valuable if the results of this study and others are extended into attempts to model water flow. Bulk soil was identified as any soil that did not contain dye. There is no reason to believe that the absence of dye indicates an incapacity for high rates of water flow. In other words, dye is proof of high-velocity water flow, but lack of dye might only indicate that soil was not sufficiently connected to high-flow soil both above and below to be part of a preferential flow path. This connectivity issue is not of great importance to the interpretation of the current results but, similar to the sample dilution effect, indicates that statistically significant differences are probably robust.

As discussed above, one possible cause for increased water infiltration rates with time after tillage ceased would be an increase in the preferential flow capacity of individual flow zones. If roots tend to grow into previous root channels, they might provide positive feedback for increased water availability, aeration, nutrient turnover, and soil aggregation. It was also anticipated that root mass might be greater in preferential flow zones because dye has been seen in association with roots, and roots can produce vertical pathways for water infiltration (Gish and Jury, 1983). In this data set, however, root mass was not greater in preferential flow zones, and C differences were not statistically significant. Aggregation was greater in preferential flow zones, but there was more of a difference in tilled soil than in untilled soil. This indicates that preferential flow zones were not developing better aggregation with time in the untilled soil. These results do not support a hypothesis of increasing zone development with time after stopping tillage.

The difference in soil density between preferential flow zones and the bulk soil was similar for tilled and untilled plots. Lower bulk density in preferential flow zones was also found by Omoti and Wild (1979). The infiltration rate was greater in the untilled soil even though the bulk density in flow zones of the untilled soil was greater than either zone in the tilled soil (Fig. 2). Greater bulk density in untilled soil often accompanies greater hydraulic conductivity, which is attributed to fewer but better connected pores (Strudley et al., 2008). Our personal observation, based on hundreds of cylinder cross-sections from this and other experiments, is that the dyed flow zones in untilled soil are a greater proportion of the soil, are more uniformly distributed, and create deeper dye penetration than in tilled soil (Wuest, 2005). Greater gravimetric and volumetric water contents in tilled soil (Fig. 2) might indicate a greater resistance to water flow below the soil surface. This agrees with our observation that tilled soil remains wetter than untilled soil when infiltration cylinders are left to drain in situ overnight.

Contrary to the original hypothesis, it is possible that preferential flow zones develop increased bulk density and smaller differences in aggregate stability with time, and that the increase in water infiltration rates is a result of more of the potential flow zones being sufficiently connected to the surface. Aggregate stability measurements are somewhat artificial in the context of the bulk soil matrix under undisturbed conditions, and should be considered only partial and indirect indications of undisturbed structure (Young et al., 2001). They are a more direct indication of the tendency for slaking and crusting of the soil surface, which often controls infiltration to a greater extent than macroporosity below the crust (Bouma, 1982; Golabi et al., 1995). If untilled soils develop a surface soil with greater resistance to slaking and sealing, the increased connectivity to greater numbers of potential flow zones might increase infiltration rates even if the overall bulk density increases with time after tillage stops.

Conclusions

Dyed soil zones known to be conducting water at high velocity differed from bulk soil in the proportion of stable aggregates and in soil bulk density. Surprisingly, bulk density in preferential flow zones of the untilled soil was greater than either the preferential flow zone or bulk soil of the tilled soil despite the untilled soil having greater total saturated conductivity. This may mean that the existence of an active preferential flow path is more dependent on its connection to a surface water source than on its own water transport characteristics. Untilled soils often accumulate surface organic matter and therefore have stronger surface soil aggregation, which may lead to less restriction of water flow to potential preferential flow zones below the surface. The control of infiltration by surface characteristics could be tested by applying aggregate stabilizing or destabilizing agents to determine the effects on hydraulic conductivity and preferential flow patterns.

These results focus attention on the top few centimeters of the soil surface. If this shallow zone is controlling water infiltration and preferential flow, then its careful characterization may be as important to accurate modeling and soil management as characterization of the soil at lower depths.

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