Do High Velocity Water Flow Paths Develop Over Time Under No-till?

Stewart B. Wuest, Tami Johlke, and Wes Matlock

Abstract

Water flow through soil is not uniform. Preferential flow paths, where water moves downward much faster than in the surrounding soil, are common in both tilled and untilled soil. We used a 10-min pulse of dye to mark preferential flow paths to learn more about the role of preferential flow in improving water infiltration under different tillage systems. Small cores were taken from dyed and undyed soil at 4- to 10-inch depth. Compared to bulk soil, preferential flow zones had fewer small aggregates, greater water content, and lower bulk density. Root mass and total soil carbon were not significantly different. The same relative differences were found in both tilled and untilled soil. This means 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 water flow in untilled soil is not due to better developed preferential flow pathways, but rather to more 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.

Keywords: no-till, preferential flow, soil bulk density, tillage, water infiltration

Introduction

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. A better understanding 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).

Several studies have provided insight into the nature of preferential flow. Dyed water is sometimes used to mark the flow of water. Different tillage methods have produced different dye patterns, both in the tilled zone and below it (Petersen et al. 2001). In a tilled soil, Omoti and Wild (1979) found dyed zones had low bulk density and sometimes very small fissures. They concluded from the soil they studied 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 day after applying water at low rates. The preferential flow zones also had greater concentrations of organic substrates and nutrients compared to bulk 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 carbon and water-stable aggregates in preferential flow zones. If preferential flow is related to roots in an untilled soil, it seems likely that preferential flow capacity might increase with time through the increase in root growth by perennial plants, establishment of new

roots, and perhaps even re-establishment of roots in former root channels in annual plant systems.

Preferential flow appears to be a major factor involved in high infiltration rates under long-term no-till cropping systems in silt loam loess of the Pacific Northwest (Wuest 2005). Another factor correlated to high infiltration is the degree of surface soil aggregation (Wuest et al. 2005). Water-stable aggregates in the uppermost surface soil are controlled by organic carbon levels and can be significantly increased in less than 7 years when converting from intensive tillage to no-till. Preferential flow associated with capacity for very high infiltration rates, however, appears to take decades to fully develop (Wuest et al. 2006).

In Pacific Northwest silt loam soils, preferential flow zones appear to be distinct areas of high water flow, which presumably are active repeatedly over 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 carbon substrates for soil aggregation and nutrient turnover, which further improves the environment for root growth.

This hypothesis could be tested by following flow zones over time, but it is difficult to make repeated measurements of flow paths over time because the most straightforward method to identify and measure them is marking with dyed water and destructive sampling. Another approach is to use destructive sampling to compare preferential flow zones in a tilled soil to those in an untilled soil. At the same time, the characteristics of preferential flow zones can be compared to 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 carbon, soil aggregation, and root mass. We also hypothesized that preferential flow zones in untilled soil would be more developed than in tilled soil.

Materials and Methods

The experimental plots were located near Pendleton, Oregon (45°43'N, 118°38'W, elevation 1,500 ft). Annual precipitation averages 17 inches and falls mostly between October 1 and May 1. Summers are hot and dry. The soil was Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll containing about 10 percent clay, 69 percent silt, and 21 percent 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 3 treatments: 1 untilled for 7 years and 2 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 for both spring pea and winter wheat, versus no-tillage 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 sodium iodide as a tracer so data could be obtained for organic carbon without contamination by carbon 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 8-inch-diameter cylinders. Row spacing of the wheat crop was 10 inches, and cylinders were always placed to include one crop row inside the cylinder. Cylinders were driven into the soil about 10 inches, and the soil around the inner circumference tamped with a thin plot stake to seal any gaps between the cylinder wall and the soil column. The water level was maintained at approximately 2 inches above the average soil surface for 2 hours.

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 potassium bromide. Following 2 hours of ponded infiltration, the dye solution was mixed with the water in the top of the cylinder and left to infiltrate for 10 min. At the end of the 10-min period, 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 a 0.7-inch-inner-diameter by 0.8-inch-long, sharpened, thin-wall metal cylinder (0.31 inch^3 measured volume). Two samples were taken from dyed soil, and two from un-dyed soil.

As previously mentioned, sodium iodide was used as a second tracer method in the untilled pea–winter wheat plots using the method of van Ommen et al. (1988). A total of 88 samples were taken using the iodine tracer. These samples were analyzed for root mass, water content, and total carbon, but not water-stable aggregates.

To process the core samples, sample wet weight was recorded before transferring to a 1,000-µm sieve (1,000 µm = 1 mm), under which were a 250-, a 125-, and a 53-µm sieve, all spaced about 1-cm apart vertically. The entire sieve set was immersed in 300 ml deionized water until the soil sample was completely covered, then immediately sieved for 3 min at 20 cycles per minute and 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. Roots were collected from the 1,000-µm screen after crushing and washing any aggregates remaining on the screen. Roots were then dried at 104°F and weighed.
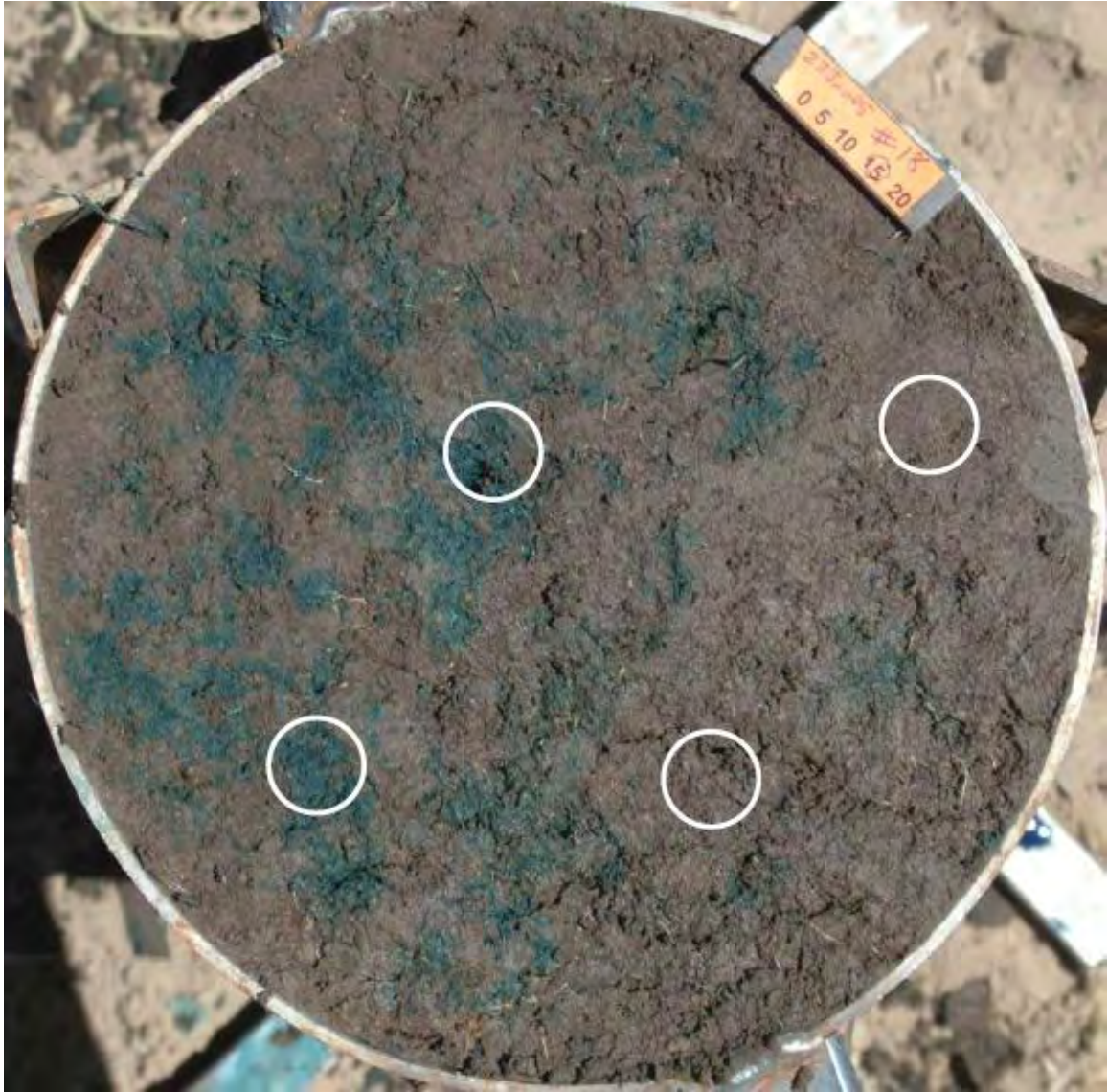
Figure 1. Example of an 8-inch-diameter infiltration cylinder cross-section at 6-inch depth from an untilled plot in the continuous winter wheat experiment. Blue areas (visible only in color reproduction) are preferential flow pathways stained by a 10-min pulse of dye after 2 hours of ponded infiltration. White circles show location of small core samples, two in dyed zones and two in undyed zones.

Results

Infiltration rates at the end of the 2-hour ponded infiltration averaged 1.6 inches per hour in tilled plots and 2.2 inches per hour in untilled plots. These are normal rates for these methods and tillage treatments on this soil (Wuest 2005, Wuest et al. 2006).

Analysis of the iodine-tracer samples collected in untilled plots resulted in 1.23 percent total soil carbon in preferential flow zones versus 1.20 percent in 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) 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 tilled soil. This probably influenced the root comparison between tilled and untilled soil, so the greater root mass measured in tilled soil should be considered a tentative result.

Within both tilled and untilled soils, preferential flow zones had lower bulk density than non-preferential 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 (= 1,000 μm) sieve ($P > F$, 0.0216). Compared to untilled soil, 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 to untilled soil. There were no statistically significant interactions at $P = 0.05$, although it can be seen in Figure 3 that the tilled, bulk soil had a major influence on the statistically significant factors.

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 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.
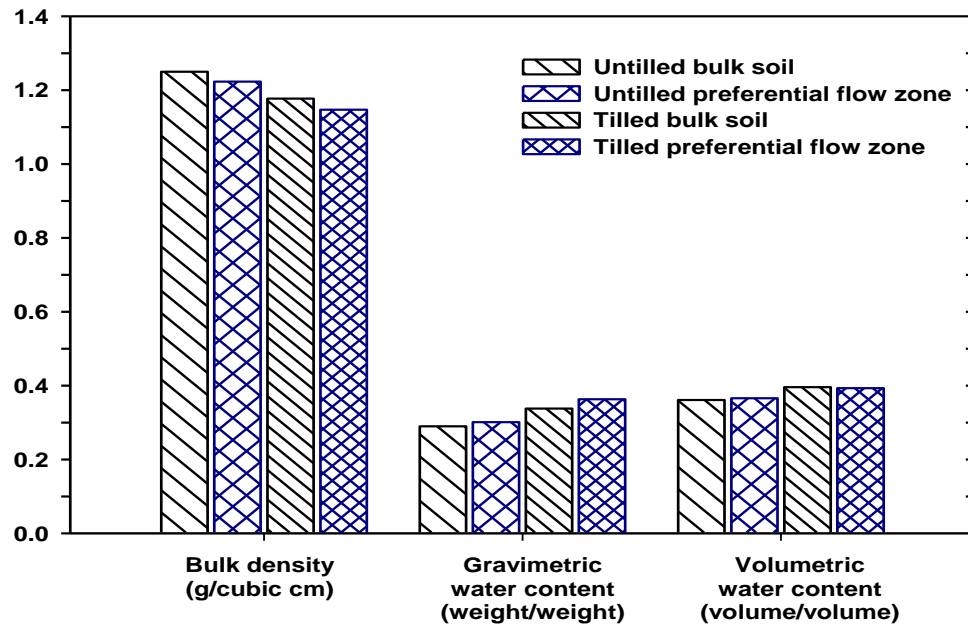
Figure 2. Soil bulk density, gravimetric, and volumetric water content of soil samples taken from preferential flow zones and undyed bulk soil of tilled and untilled plots. The difference between tilled and untilled plots is statistically significant for all three factors. The difference between preferential flow zones and bulk soil is statistically significant for bulk density and gravimetric water content.
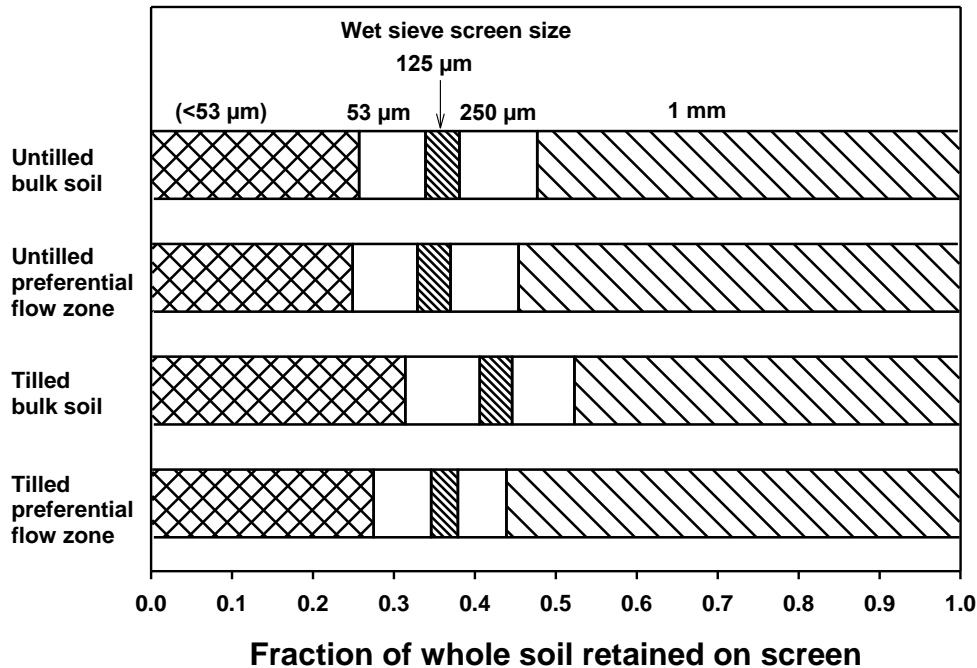
Figure 3. Proportion of water-stable aggregates in each of five size classes. Tilled and untilled plots are statistically different for < 53 µm and 250 µm. The difference between bulk soil and preferential flow zones are statistically significant for < 53 µm, 53 µm, and 1 mm.

Discussion

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 color reproduction of Figure 1. In our experience, if the cylinders were left unexcavated for 18 hours after removing the dye solution from the soil surface, the dye staining patterns still appear distinct and not noticeably different than when excavated immediately.

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 indicates that statistically significant differences are probably robust.

110

As discussed in the introduction, one possible cause for increased water infiltration rates over time after tillage ceases would be an increase in 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. We 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 dataset, however, root mass was not greater in preferential flow zones, and carbon differences were not 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 over time in untilled soil. These results do not support the hypothesis that there is increasing zone development over time after tillage stops.

The difference in soil density between preferential flow zones and bulk soil was similar for tilled and untilled plots. Infiltration rate was greater in untilled soil even though bulk density in flow zones of untilled soil was greater than either zone in 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 comprise a greater proportion of the soil, are more uniformly distributed, and create deeper dye penetration than in tilled soil (Wuest 2005). Greater gravimetric and volu-metric 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. So while the difference between bulk soil and preferential flow zones was not greater in soil untilled for 7 years, the lower water content (better drainage) of untilled soil indicates the flow zones may be more effective as well as more numerous.

Contrary to the original hypothesis, it is possible that preferential flow zones develop increased bulk density and smaller differences in aggregate stability over 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. 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 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 proportion of stable aggregates and in soil bulk density. Surprisingly, bulk density in preferential flow zones of the untilled soil were greater than either preferential or bulk soil of the tilled soil despite the untilled soil having greater total water 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.

These results focus attention on the top inch 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 soil at lower depths.

Note: More details on this research are published in Vadose Zone Journal, 2009.

References

Bertrand, A. R. 1965. Rate of water intake in the field. Pages 197-209 *in* C. A. Black (ed) Methods of soil analysis. Part 1. First ed. Agronomy Monographs 9. ASA and SSSA, Madison WI.

Bundt, M., F. Widmer, M. Pesaro, J. Zeyer, and P. Blaser. 2001. Preferential flow paths: biological 'hot spots' in soils. Soil Biology and Biochemistry. 33:729-738.

Flury, M., and H. Fluhler. 1995. Tracer characteristics of Brilliant Blue FCF. Soil Science Society of America Journal 59:22-27.

Flury, M., H. Fluhler, W. A. Jury, and J. Leuenberger. 1994. Susceptibility of soils to preferential flow of water: A field study. Water Resources Research 30:1945-1954.

Gish, T. J., and W. A. Jury. 1983. Effect of plant roots and root channels on solute transport. Transactions of the American Society Agricultural Engineering.   26:440-444, 451.

Omoti, U., and A. Wild. 1979. Use of fluorescent dyes to mark the pathways of solute movement through soils under leaching conditions: 2. Field experiments. Soil Science 128:98-104.

Petersen, C. T., H. E. Jensen, S. Hansen, and C. Bender Koch. 2001. Susceptibility of a sandy loam soil to preferential flow as affected by tillage. Soil and Tillage Research. 58:81-89.

Radulovich, R., P. Sollins, P. Baveye, and E. Solorzano. 1992. Bypass water flow through unsaturated microaggregated tropical soils. Soil Science Society of America Journal. 56:721-726.

Strudley, M. W., T. R. Green, and J. C. Ascough II. 2008. Tillage effects on soil hydraulic properties in space and time: State of the science. Soil and Tillage Research. 99:4-48.

van Ommen, H. C., L. W. Dekker, R. Dijksma, J. Hulshof, and W. H. van der Molen. 1988. A new technique for evaluating the presence of preferential flow paths in nonstructured soils. Soil Science Society of America Journal. 52:1192-1193.

Wuest, S. B. 2001. Earthworm, infiltration, and tillage relationships in a dryland pea-wheat rotation. Applied Soil Ecolology. 18:187-192.

Wuest, S. B. 2005. Bias in ponded infiltration estimates due to sample volume and shape. Vadose Zone Journal 4:1183-1190.

Wuest, S. B., T. C. Caesar-TonThat, S. F. Wright, and J. D. Williams. 2005. Organic matter addition, N, and residue burning effects on infiltration, biological, and physical properties of an intensively tilled silt-loam soil. Soil and Tillage Research. 84:154-167.

Wuest, S. B., J. D. Williams, and H. T. Gollany. 2006. Tillage and perennial grass effects on ponded infiltration for seven semi-arid loess soils. Journal of Soil and Water Conservation. 61:218-223.