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COMMUN. SOIL SCI. PLANT ANAL., 26(15&16), 2655-2666 (1995)

EFFECT OF ROOT SYSTEMS ON PREFERENTIAL FLOW IN SWELLING SOIL

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ABSTRACT: Permeability problems on irrigated soils may be alleviated by root systems that increase water flow by creating macropores. Infiltration rates have been shown to increase where plant roots decay and serve as preferential flow paths. For low-organic-matter swelling soil, there is a question whether macropores are able to resist the lateral swelling forces of the soil. The objective of this study was to observe preferential water flow paths in a swelling soil under two cropping systems. A Holtville silty clay (clayey-over-loamy, montmorillonitic Typic Torrifluvent) was observed *in situ*. Two crops, alfalfa (*Medicago sativa, L.*) and wheat (*Triticum turgidum*, L.) provided sharply contrasting root systems, with wheat possessing fine, fibrous roots; alfalfa on the other hand, has a taproot system. Macropores were observed after applying soil-adsorbing methylene blue dye to irrigation water. Shrinkage cracks failed to conduct dye after 10 minutes into a flood irrigation. Earthworm (*Lubricus terrestris*) channels were also not stable. However, decaying roots of alfalfa produced stable macropores, while wheat produced no such macropores. The influence of alfalfa-root-induced macropores was demonstrated by

the increase in final infiltration rate during alfalfa cropping which agreed with Meek et al.'s (1989, 1990) findings on sandy loam soils.

INTRODUCTION

Many irrigated soils in the desert Southwest USA have poor permeability to air and water that result in substantial economic consequences (Oster and Singer, 1984). Problems include inadequate soil moisture, inefficient water use, plant injury due to water ponding, and salinity. Low permeability can restrict leaching and cause salt accumulation, as much of the region is irrigated with water having a high salt content. Plant water stress is a problem during summer months with high evaporative demand. The smectite mineralogy of these soils allow them to intake water initially through cracks, but then swelling reduces the final infiltration rate to nearly the 1.0 mm h^{-1} lower threshold for irrigability (Salinity Laboratory Staff 1954, p.22), as shown in several field studies (Perrier et al., 1974; Mitchell and Donovan, 1991). The water flow is dominated by shrinkage cracks (Mitchell and van Genuchten, 1993), rather than surface crusts (Mitchell, 1986).

On non-swelling, sandy soils, the infiltration problems can be alleviated by the formation of macropores by decaying roots. Vertically oriented macropores can greatly increase water flow, as shown by Edwards et al. (1979) and Davidson (1985). Field transport phenomena may be a direct consequence of root systems, even if the soil is not cropped at the time of the study (e.g., Ellsworth et al., 1991). Barley (1954) observed that root systems increased infiltration rate. Mannering and Johnson (1969) compared infiltration rates under soybean (*Glycine max*, L.) and corn (*Zea mays*, L.) cropping systems, and found greater infiltration under the soybean crop during the late season and following harvest. Kidder et al. (1943) also observed greater infiltration under soybeans than under corn at the end of the growing season, when the prior crop history was the same. Gish and Jury (1983) found that when plants were actively growing, the infiltration rate was reduced because root growth blocked channels. Later in the season, when the roots decayed, channels were open for water flow. In general, decaying roots may leave long, continuous pores in the soil that enhance the transport of water and influence solute movement. Furthermore, infiltration rates have been observed to increase with greater root mass density when rates were measured after decomposition (Disparte, 1987).

Not all roots have the same effect on preferential flow, with alfalfa being exceptionally good at increasing water flow in field conditions. This ability to enhance flow is attributable to its morphology and the practice of not tilling alfalfa during a 3- to 5-year production cycle. The root system of alfalfa is characterized by a large-diameter, long, almost-straight taproot. The mature taproot is joined to a fleshy crown at the soil surface from which multiple stems originate. When the plant dies and decays, it creates an extended flow path with access to the soil surface. Barley (1954) observed that alfalfa may initially decrease infiltration rates, but later the root decomposition leaves channels which result in increased infiltration rates. Meek and his co-workers (Meek et al., 1989; 1990), in studies of cropping and tillage systems on a sandy loam, observed yearly increases in infiltration rate which corresponded to decreases in alfalfa stand density over a 4-year alfalfa trial. Their dye studies showed that the decayed-root macropores extended to the soil surface and increased infiltration even on plots that were frequently trafficked during multiple harvests.

Addressing the problem of poor permeability of swelling soils, Meek et al. (1990) raised the question of whether decaying root systems were effective in producing stable macropores in spite of lateral swelling forces. An alfalfa traffic study on a swelling soil in the Imperial Valley of California (Mitchell and Swain, 1987) provided a good setting for examining root-induced macropore flow under trafficked and non-trafficked alfalfa.

The objective was to compare macropore distribution (preferential water flow paths) in a swelling soil under alfalfa and wheat crops. These two root systems provided a sharp contrast with respect to morphology, with wheat providing a system of shallow, fine, fibrous roots, and alfalfa possessing a taproot system.

METHODS

Dye Studies

Dying techniques have been previously used to identify micromorphological properties that determine the locations of preferential flow in swelling soils (Ritchie et al., 1972; Bouma and Wosten, 1979). A 1.0 g L^{-1} solution of methylene blue was applied during flood irrigation of wheat-stubble and alfalfa at the USDA-ARS Irrigated Desert Research Station, Brawley, CA in September, 1989. The soil was a Holtville silty clay, classified as a clayey-over-loamy, montmorillonitic (calcareous) typic Torrifluvent, which possessed an abrupt lower boundary at approximately 50 cm below the surface. The organic matter content was 0.9% in the top 0.5 m of the soil profile (Perrier et al., 1974). Wheat had been harvested in June 1989 and the field was left undisturbed until the aforementioned September irrigation. Dye solution was applied to three 1-m diameter single-ring infiltrometers that were surrounded by ponded water. Dye application occurred to six infiltrometers at one of two times: when the irrigation water stream first arrived (t=0), or 30 min later. The dye application at the time of water arrival was designed to identify the depth of the soil cracks prior to irrigation. The later application was to determine macropore persistence at t=30 min. The total quantity of dye solution applied to the infiltrometer was 10 cm. Water was ponded around the infiltrometer and care was taken to prevent the dye solution from escaping laterally.

Seven days later, on September 21, the infiltrometer ring was removed and the soil was excavated by first carefully removing the dye from the soil surface. Then a pit was dug adjacent to the plot surface to study the vertical continuity and horizontal distribution of the macropores. Lastly, the soil was excavated from the top downward in 5-cm increments. Dye-colored areas were observed and photographs taken of each layer.

Next, a dye solution was applied in a similar manner to a nearby alfalfa field at t=10 and t=30 minutes after ponding. The alfalfa field contained an experiment that tested the effect of machinery traffic on soil physical parameters, including infiltration rate (Mitchell and Swain, 1987). Dye application occurred during an irrigation on

September 22. The t=10 application was used to determine whether cracks persisted 10 min after the occurrence of ponding. Sampling took place six days later on September 28.

The infiltration rate of the alfalfa-cropped soil was measured *in situ* several times between 1986 and 1989. Three infiltrometers (1-m diameter) were measured on each of four replications on a machine-trafficked treatment (simulating grower practice) and a no-traffic treatment. Water was ponded around the infiltrometers to minimize divergent flow. The final infiltration rate was taken at the point in time when changes were less than 10% per hour.

RESULTS AND DISCUSSION

Dye Applied to Wheat Stubble Field

The t=0 dye application resulted in dye-stained cracks that, when observed by looking directly down at the soil surface, appeared distributed in the horizonal plane. The exposed, vertical face from the adjacent pit revealed that the dyed soil at 6-cm depth contained short stained vertical lines of less than 3-cm length. The stained lines were wide in several places, which gave the impression of cracks that had filled with dye. Several of these dyed soil cracks were found at a depth of 12 cm, but none were found below the 15-cm depth. The maximum depth of the cracks was quite uniform, ranging between 12 and 15 cm (Fig. 1). The cracks were not as deep as was initially expected, perhaps because of an earlier irrigation of the maturing wheat, which gave insufficient time for the soil to dry.

The t=30 dye application did not generate dyed soil below the surface except in 3-cm deep cracks which had formed in the time between the irrigation and sampling events. These cracks received dry, dye-stained soil particles blown in by the wind. We were able to verify that the dye was a consequence of wind, rather than of water flow, by carefully peeling the soil peds and noting the lack of adsorbed dye. A less concentrated dye solution might reduced the excess dye that accumulated as dry particles at the soil surface. The high concentration of the dye at the soil surface was unexpected.

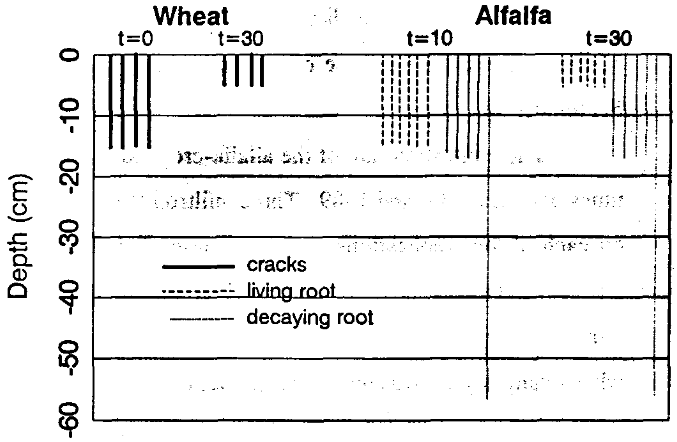

FIGURE 1. Type and extent of dye-stained macropores per 0.1 m^2 as the average of three replicates.

There was no evidence of dye-stained macropores resulting from decayed root channels in the wheat-stubble soil. The small wheat roots were ineffective in producing macropores in swelling soil that persisted after a 3-month fallow period. The wheat-stubble had preferential flow cracks 15-cm deep that closed within 30 min of flooding. No root-induced preferential flow was found in the wheat.

Dye Applied to Alfalfa Field

In contrast to the single mechanism of dye transport in the wheat-cropped soil (i.e. cracks), the alfalfa-cropped soil had two additional mechanisms of transport. Three types of soil staining were found in the alfalfa soil, which were associated to their respective transport mechanisms as follows: dye-stained soil from *cracks* that eventually swelled shut, stained soil in *earthworm tunnels*, and stained soil along *root channels*. Because no dye stains were found in cracks within 5 cm of the surface for both the t=10 and t=30 min applications, we concluded that any antecedent cracks were either closed shut with 10 min of ponding or were isolated from water flow during irrigation.

Live earthworms were observed during sampling of the alfalfa soil, unlike the wheat stubble soil. Dye was found coating small aggregates inside the earthworm tunnels, but the tunnel walls were not stained. Rather, the dye was found only on the aggregates, which were identified as earthworm casts. Evidently, earthworms swallowed the dye, then excreted it as they tunnelled through the soil. None of the tunnels had an abundance of dye that might have indicated a persistence of the channel during irrigation. We concluded that earthworm channels were not stable macropores for water flow for this soil, and that the observed dye in earthworm tunnels was from excrement. The dye is not known to be toxic to earthworms.

Macropores near living roots were involved in preferential water flow near the soil surface (Fig. 1). Dye residues were found in the soil bordering the bulky root top, or crown, to a depth of 16 cm. More dye residues were observed on sides of the peds that were bordered by the root crowns and lateral roots. The stained ped faces were less than 5-cm long on a side. Below the 16-cm depth, no dye residue was found near any living alfalfa roots. For the t=30 application, no dye was found below 5 cm (Fig. 1), which demonstrated the temporary state of cracks adjacent to living roots. Water flow adjacent to living roots may be attributed to either (i) the presence of a saturated film of water on the outside of roots, or (ii) preferential flow in stable pores caused by the soil-aggregating influence of the roots, or (iii) the soil and root shrinkage prior to irrigation that produced an adjacent void. Because Meek et al. (1989) found no dye transport along living roots in a non-swelling soil (using the same dye), we deduce that the third explanation--shrinkage was responsible for dye transport around the tap roots. Also supporting this theory is the reduced length of living-root cracks at t=30 (Fig. 1). Having established soil shrinkage to be the mechanism of dye transport around living alfalfa roots, we now turn to decaying roots.

The decaying roots of alfalfa, unlike those of senescent wheat, provided effective channels for the flow of water to lower depths during ponded soil conditions on a swelling soil. Dye-stained, decaying alfalfa roots were found in all of the infiltrometer plots. The dye appeared both within the epidermis of the decaying root and on the root exterior (Fig. 2). Occasionally, the dye would also cover an adjacent

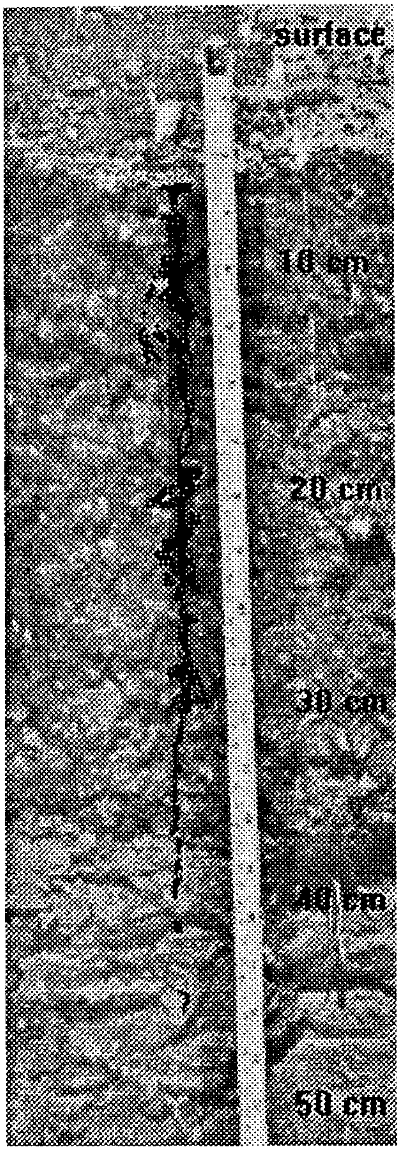

FIGURE 2. Horizontal view of alfalfa root with enhanced, blackened, images of the dye stains marking the macropore faces. The tape measure indicates the depth below the soil surface in inches and centimeters.

ped face, indicating that water flowed outward from the decaying taproot into soil cracks. Transport of dye along decaying root channels was observed to depths in excess of 55 cm, which was below the clay soil horizon into the silt layers of the Holtville silty clay. The decaying alfalfa roots acted as stable macropores and effectively transmitted both water and dye after 30 min of ponding.

Late summer root decay has been identified as the macropores involved in preferential flow in other alfalfa cropping situations (Barley, 1954). Meek et al. (1989) showed increased infiltration rates in late summer to correspond with the presence of decaying roots. There is a major distinction between the soil properties of this and the earlier studies cited. Whereas the decayed root holes persisted into the next cropping cycle (Meek et al., 1990) for a non-swelling soil, this study's swelling, labile, soil closed the cracks and worm holes during irrigation. Dye was only found in root holes with woody decaying organic matter that stabilized them against the pressures of the expanding soil. No pores devoid of root remains were found. Hence, we deduce that the enhanced macropore flow caused by decaying roots is only transitory in the Holtville silty clay, that is, until the root tensile strength is to weak to resist swelling forces. This soil's instability results from low organic matter content combined with a silty clay texture and the smectite mineralogy which induces swelling.

In Situ Infiltration Rates under Alfalfa

The temporary decaying-root macropores can, however, have a large impact on the soil final infiltration rate. Table 1 shows the October 1989 infiltration rate, measured after dye sampling, compared to earlier infiltration rate measurements taken under similar initial water content conditions. The final infiltration rate was not significantly different between treatments. However, the infiltration rate for both treatments was more than twice as high in October 1989 than for the previous measurements. The increase in infiltration rate can be attributed to the decaying-root macropores. Meek et al. (1989) found similar infiltration increases as alfalfa matured, although the sandy loam soil in their study had much greater infiltration rates than the Holtville silty clay.

TABLE 1. Final infiltration rates for grower and no traffic alfalfa treatments. Row and column values followed by the same letter are not significantly different at the α=0.05 probability level.

Date	Treatment	
	Grower	No Traffic
	--mm h^{-1} --	--mm h^{-1} --
May 1986	1.52a	1.36a
Oct 1986	1.32a	1.43a
May 1987	1.33a	1.58a
Oct 1989	3.23b	3.52b

CONCLUSIONS

The dissection of a dye-stained pores in swelling soil showed that cracks enable macropore flow, but only with 10 min of the start of flood irrigation. Alfalfa produced stable macropores along living roots and decaying root channels, while wheat did not. Decaying alfalfa roots provided a temporary channel for macropore flow. Cracks and earthworm channels did not remain open during irrigation because of the lateral pressure of the swelling in the Holtville silty clay. To conclude, alfalfa can influence water flow properties in both rigid and swelling soil, although the magnitude of the effect will be greater for rigid soils, where swelling forces do not close the macropores.

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