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Effects of tillage pan on soil water distribution in alfalfa-corn crop rotation systems using a dye tracer and geostatistical methods

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ABSTRACT

The present study was designed to assess the potential effects of tillage pan on the distribution and the movement of soil water. Two different tillage regimes of an alfalfa-corn crop rotation system were carefully selected. Plot 1 contained alfalfa without tillage for the past 10 years. Plot 2 contained alfalfa with no tillage for the first 5 years and corn with conventional tillage for the succeeding 5 years. A dye tracer was introduced to these plots and the different types of water flow were visualized using classified dye-stained patterns. In addition, the kriging maps of gravimetric soil water content were used to indicate potential distribution characteristics. Semivariance analysis was performed to determine spatial variability on a centimeter scale. The role of macropore flow was weaker in the alfalfa plot than in the corn plot because of the difference in flow path and distribution. A belt of high soil moisture content appeared in the vertical soil profile of the alfalfa plot, indicating that the macropore flow showed a deeper stained depth. Several scattered locations in the corn plot contained high amounts of water, suggesting that macropore flow also occurred. The soil water content in the corn plot demonstrated infiltration patterns with higher degrees of fragmentation than that in the alfalfa plot. Moreover, a lateral flow with a wider stained width was triggered by the compacted tillage pan in the corn plot. Thus, the role of lateral flow was more dominant in the corn plot than in the alfalfa plot. The spatial correlation distance of the soil water content of infiltration patterns was 23.08 cm in the alfalfa plot compared with 10.52 cm in the corn plot. This trend indicated a high spatial variation of moisture in water infiltration patterns of the alfalfa field. In addition, strong spatial autocorrelation was observed in soil water infiltration patterns in both plots (nugget percentages of <25%). Our results highlighted a significant change of soil water behaviors in crop rotation from alfalfa to corn. In particular, downward water flow was restricted by a compacted tillage pan; thus, water was stored in the loose soil structure of the corn plot.

1. Introduction

Long-term monoculture can influence soil structure. On the one hand, Gibbs and Reid (1988) reported that soil structure is improved by planting alfalfa; this conservation tillage system has shown advantages in the modification of many physical properties, such as aggregate stability (Angers and Mehuys, 1988) and soil infiltration rate (Meek et al., 1990). On the other hand, Jabro et al. (2009) reported that tillage is one of the most important practices in conventional tillage systems; this practice affects the physical and hydraulic properties of soil, including pore size, porosity, and infiltration (Cameira et al., 2003; Rasmussen, 1999). Therefore, modified cropping systems have been adopted to maintain soil quality. In crop rotation, forage crops, such as alfalfa, are initially planted and row crops, such as corn, are then introduced; this crop rotation is commonly practiced by many farmers in northwestern China. However, problems often occur when crop is changed from alfalfa to corn; for example, a plow pan may hinder soil water from permeating into soil. A few investigations have focused on the effect of a plow pan on soil water distribution (Kasteel et al., 2007). The underlying mechanisms may restrict agricultural management and limit simulations related to the influence of interventions on water quality.

The soil water infiltration process generally includes matrix flow and preferential flow. The former is a relatively slow and even movement of water and solutes through soil while passing through all pore spaces (Allaire et al., 2009). Two kinds of preferential flow were considered in the present study. Macropore flow is the flow of water and contaminants through naturally formed channels such as cracks, plant roots, worm holes, and voids between peds (Beven

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and Germann, 1982). Meanwhile, lateral flow occurs when infiltrating water moves laterally and locally along an inclined hydraulically restrictive layer such as the bedrock (Allaire et al., 2009). Interaction refers to the water drawn into the surrounding matrix by capillary forces, which was transferred through the macropore walls during infiltration (Beven and Clarke, 1986).

Water flow path in soil, even in plow pans, can be visualized using dye tracers (Flury and Wai, 2003). This technique provides direct information on path continuity, number, depth, and efficiency of different preferential flow processes. Ghodrati and Jury (1990) reported that image analysis of photographed dye profiles can enhance the interpretation of soil water flow. Additional complex steps have been performed during image analysis to improve the quantification of dye concentration and distribution. Weiler and Flühler (2004) and Cey and Rudolph (2009) demonstrated that further interpretation and calculations can be performed after dye concentration maps are completed by using classification techniques or image analysis software; with further interpretations and calculations, the types of water flow through macroporous soils can be identified and further insights into the interaction of water between macropores and soil matrix can be provided. However, these methods to obtain concentration categories are complicated and tedious. Moreover, German-Heins and Flury (2000) found that Brilliant Blue FCF dye undergoes sorption in soil to some extent. Therefore, dye-stained patterns inaccurately reflect the extent of water infiltration. These difficulties limit the complete understanding of the effects of plow pan on flow processes.

Conducting semivariogram analysis, Grevers and De Jong (1994) evaluated soil pore continuity. Droogers et al. (1998) described the spatial distribution of pores based exclusively on dye patterns. Geostatistics provides powerful analytical tools that can be used to capture horizontal and vertical variations of a specific property. Kriging and semivariogram analyses are two important components of geostatistics. Kriging is an interpolating technique in which spatial structure is considered to provide a map of the spatial distribution of a variable (e.g., soil water) across a study area. This spatial structure is explained by a semivariogram, which illustrates how the variability of a variable (e.g., soil water) increases with distance (Flipo et al., 2007). The power of this approach has been demonstrated in ecological structure studies (Ettema and Wardle, 2002) and spatial patterns of soil moisture (Anctil et al., 2002). Schume et al. (2003) conducted semivariogram analysis and verified that soil water content exhibits spatially correlated behaviors. Geostatistics is not a novel analytical tool. However, spatial distribution and variability of soil water content in infiltration patterns at a centimeter scale has not yet been interpreted with semivariogram analysis. Such information could improve current understanding of potential infiltration processes and distribution characteristics.

In this study, a traditional method involving a dye tracer was conducted on two soil plots with different tillage regimes. The study was divided into the following parts: (1) dye-stained patterns were interpreted and analyzed using classification techniques; (2) kriging technique was used to produce maps of soil water content; and (3) spatial variability of soil water content was explained using a semivariogram. This study aimed to assess the effect of tillage pan on the distribution and the flow processes of soil moisture based on a comparative analysis of water flow in the vertical soil profiles of an alfalfa-corn crop rotation system.

2. Materials and methods

2.1. Experimental site

The study area was located in MinQin county of Gansu province, Northwest China. Its specific geographic position is between 101°49′–104°12′E and 38°03′–39°28′N. The three sides of east, west, and north of MinQin county are surrounded by the Tengger Desert and Badain Jaran Desert. The area has an arid continental climate with an average annual temperature of 7.8 °C. Mean precipitation in the area is 110.5 mm yr^{-1}. Annual average evaporation is 2646.4 mm yr^{-1}. The soil under study was classified as “irrigated desert soil” in accordance with Chinese Soil Classification System (Gansu Provincial Soil Survey Office, 1992), similar to Anthropic Camborthids according to Soil Taxonomy (Soil Survey Staff, 1998).

2.2. Dye tracer

During the period of October 5th to 10th, 2013, dye tracer experiments were conducted on two sites, which were located 10.0 m away from each other, after the crops were harvested. The first plot was planted with alfalfa (*Medicago sativa* L.) without tillage from 2003 to 2013. The second plot was planted with alfalfa without tillage from 2003 to 2008 and then with maize (*Zea mays* L.) with conventional tillage from 2008 to 2013. Selected soil properties from the two field sites are provided in Table 1.

At each site, three plots were randomly selected as replicates, and each replicate plot was surrounded by a 0.30 m high quadrat made of PVC (diameter = 0.25 m). The dye-stained test sites were prepared by carefully removing the surface vegetation and a thin layer of the soil (less than 2.0 cm) in order to ensure a horizontal surface. The side walls and edges of the PVC quadrats were water-tight and the bottom edges were inserted 0.10 m into the soil. All the plots were irrigated with 5.4 L of the water dye solution, containing 3.0 g L^{-1} Brilliant Blue FCF (Flury and Flühler, 1995). When the ponding disappeared, the infiltration times were recorded. The infiltrated area was covered with a vinyl film to prevent evaporation and dilution by rainfall

Table 1
Soil properties (mean ± SE, $n = 3$) of the experimental sites.

Treatments	Soil depth (cm)	Initial gravimetric water content (%)	Bulk density ($g\,cm^{-3}$)	Particle size		
				Clay (%)	Silt (%)	Sand (%)
Corn plot	0–10.0	8.03 ± 0.01	1.38 ± 0.04	11.55 ± 0.01	40.33 ± 0.11	48.12 ± 0.04
	10.0–20.0	9.50 ± 0.02	1.42 ± 0.03	10.05 ± 0.03	39.75 ± 0.10	50.20 ± 0.02
	20.0–30.0	7.05 ± 0.01	1.63 ± 0.02	12.11 ± 0.10	38.56 ± 0.06	49.33 ± 0.09
	30.0–40.0	2.62 ± 0.02	1.69 ± 0.05	13.43 ± 0.06	39.25 ± 0.01	47.32 ± 0.05
	40.0–50.0	6.98 ± 0.03	1.50 ± 0.07	11.99 ± 0.02	39.45 ± 0.04	48.56 ± 0.08
Alfalfa plot	0–10.0	4.51 ± 0.32	1.40 ± 0.02	11.05 ± 0.01	40.75 ± 0.08	48.20 ± 0.11
	10.0–20.0	6.99 ± 0.02	1.39 ± 0.06	13.11 ± 0.04	39.56 ± 0.02	47.33 ± 0.09
	20.0–30.0	7.33 ± 0.09	1.41 ± 0.01	11.43 ± 0.10	39.25 ± 0.04	49.32 ± 0.05
	30.0–40.0	7.85 ± 0.18	1.41 ± 0.03	11.99 ± 0.11	40.45 ± 0.06	47.56 ± 0.14
	40.0–50.0	8.05 ± 0.07	1.40 ± 0.01	12.23 ± 0.03	39.65 ± 0.01	48.12 ± 0.02