Journal of Hydrology 398 (2011) 191–201

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Effect of antecedent soil moisture on preferential flow in a texture-contrast soil

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ARTICLE INFO

Article history:
Received 20 July 2009
Received in revised form 8 December 2010
Accepted 10 December 2010
Available online 24 December 2010

This manuscript was handled by P. Baveye, Editor-in-Chief

Keywords:
Duplex
Dye tracer
Finger flow
Funnel flow
Macropore flow
Shrinkage crack

SUMMARY

The effect of soil moisture status on preferential flow in a texture-contrast soil was investigated by applying 25 mm Brilliant Blue dye tracer to soil profiles at high and low antecedent soil moisture. Differences in soil morphology and chemistry between soil profiles had little effect on the depth of dye infiltration and dye distribution down the profile. Antecedent soil moisture strongly influenced the type, depth and rate of dye tracer movement. In the wet treatment, the dye tracer infiltrated to depths between 0.24 and 0.40 m, at an average rate of 120 mm h^{-1}. Whilst in the dry treatment, the same volume of dye tracer infiltrated to between 0.85 and 1.19 m depth at an average rate of 1160 mm h^{-1}. In dry antecedent conditions, finger flow developed in the A1 horizon as a result of water repellency. In the wet treatment, the wetting front developed permutations but did not break into fingers. Despite similar particle size distributions, flow in the $A2_e$ was slower than the A1 horizon, due to the absence of macropores. In the dry treatment, the dye tracer ponded on the upper surface of the B21 horizon, which then spilled down the sides of the large clay columns as rivulets, at rates of between 2000 and 3000 mm h^{-1}. The dye tracer accumulated at the base of the columns resulting in backfilling of the inter column shrinkage cracks, at an estimated rate of 750 mm h^{-1}. In the subsoil, water movement occurred via shrinkage cracks which resulted in flow by-passing 99% of the soil matrix in the B21 horizon and 94% of the soil matrix in the B22 horizon. Evidence of rapid and deep infiltration in ‘dry’ texture-contrast soils has implications for water and solute management. This knowledge could be used to: (i) improve irrigation and fertilizer efficiency (ii) explain variations in crop yield (iii) reduce salinity through improved leaching practices, (iv) reduce the risk of agrochemicals contaminating shallow groundwater.

1. Introduction

Preferential flow refers to all phenomena where water moves along preferred pathways through the soil profile allowing water to bypass part of the soil matrix. It allows water and solutes to move to greater depths, at faster rates, than predicted by the Richards equation for uniform flow (Hendrickx and Flury, 2001; Simunek and van Genuchten, 2007). Preferential flow is considered to be both common and widespread (Flury et al., 1994) resulting in either enhanced, or reduced capacity of the soil to buffer and filter potential contaminants (Clothier et al., 2008). Although the term preferential flow does not imply any particular mechanism, it usually refers to one or more of three physically distinct processes: macropore flow, finger flow, or funnel flow (Kung, 1993; Ogawa et al., 1999). Finger flow or fingering, results from air entrapment or water repellence causing an instability in the wetting front leading to the formation of thin fingers beneath a more uniformly wetted distribution zone (Glass et al., 1988). Finger flow is distinct from other forms of preferential flow in that it is a fluid phenomenon, resulting from spatial heterogeneity in water repellence or soil moisture content rather than soil structure (Jury and Horton, 2004; Lemmnitz et al., 2008). Funnel flow, results from lateral redirection of infiltrating water resulting from changes in soil texture or lithographic boundaries (Kung, 1990). Macropore flow or bypass flow results from infiltrating water moving through void spaces in the soil. Macropores are formed in various ways including soil shrinkage, root growth, chemical weathering, cycles of freezing and thawing, or bioturbation (Beven and Germann, 1982). In texture-contrast soils, two classes of macropores are observed: (i) biopores, which are created by soil fauna or flora, resulting in cylindrical, semi-stable voids, and (ii) shrinkage cracks, formed by drying of swelling clays (McCoy et al., 1994).

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doi:10.1016/j.jhydrol.2010.12.008

Dye tracers have been extensively used to characterise preferential flow paths in soils and to study the interaction between soil morphology and water movement (Flury et al., 1994; Weiler and Fluhler, 2004). Brilliant Blue FCF (C.I. Food Blue 42090) has become the most popular dye for studies of preferential pathways as it provides the best combination of mobility, high visibility and low toxicity (Flury et al., 1994). The use of dyes to measure flow rates is however limited by the sorption of dyes to soil particles, which cause the dyes to move at a slower velocity than the water in which they are dissolved, such that the wetting front and maximum extent of infiltration may be underestimated (Lipsius and Mooney, 2006; Mon and Flury, 2005). Quantitative procedures have been developed to determine dye concentration from digital images (Forrer et al., 2000), however in soils with multiple background colors or mottled subsoils, each background color requires its own calibration limiting quantitative analysis to binary images of dye presence and absence (Bogner et al., 2008).

Researchers are in disagreement about the extent to which antecedent soil moisture influences preferential flow in soils (Merdun et al., 2008). In macroporous soils, higher antecedent soil moisture generally increases the depth to which macropore flow penetrates as well as increasing total percolate volume, as increased moisture reduces lateral flow into the soil matrix (Beven and Germann, 1982; Jarvis, 2007; McCoy et al., 1994). Granovsky et al. (1994) found that in a drier soil only the more rapid flow pathways contributed to the flow, while the slower pathways having greater interaction with the soil matrix were mostly truncated. Jaynes et al. (2001) and Kung et al. (2000) also found that pesticide transport increased during irrigation events, due to larger pores becoming hydraulically active as the soil became progressively wetter. In contrast, Shipitalo and Edwards (1996) found the relative contribution of macropores to pesticide transport was be greatest when the soil was dry and decreased as the soil became wetter. Merdun et al. (2008) also reported that preferential flow was more evident when soil was initially dry compared to two wetter treatments. In water repellant soils infiltration into dry soil below the critical water content has been shown to result in the breakdown of the wetting front and formation of preferential finger flow (Dekker and Ritsema, 2000; Ritsema and Dekker, 1994). Wang et al. (2003) demonstrated that finger width ranged from 0.045 m in dry soil, to 0.17 m when soil was very wet. While in shrink-swell (vertic) soils preferential flow via shrinkage cracks is dynamically related to soil moisture content, in which maximum aperture occurs when soils are very dry (Greco, 2002). For example, Lin et al. (1998) demonstrated that increasing soil moisture from 0.1 to 0.45 (kg kg^{-1}) in a series of shrink-swell soils (Vertosols), decreased steady-state infiltration from 360 to 7.2 mm h^{-1}.

The effect of antecedent moisture on preferential flow in field texture-contrast soils is not well understood. Texture-contrast soils (including duplex soils) have a subsoil which is at least one and a half texture groups finer than the surface soil (Northcote, 1979). Texture of the surface horizon can range from coarse sand to clay loam, and that of the subsoil from light to heavy clay (Tennant et al., 1992). Texture-contrast soils cover approximately 20% of the Australian land mass (Fitzpatrick et al., 1994) and around 80% of agricultural regions in southern Australia (Chittleborough et al., 1994). They are associated with a range of management problems including; waterlogging, poor crop establishment, crusting, poor root penetration, (Cotching et al., 2001; Edwards, 1992; Morrell, 1992) and low yield resulting from slow infiltration and poor internal drainage through the B horizon (Cotching et al., 2004; Jayawardane and Prathapar, 1992). The dominant hydraulic characteristic of the texture-contrast soils is the abrupt reduction in hydraulic conductivity between the topsoil and the subsoil, which results in the formation of seasonal perched watertables. In locations with sufficient slope, perched water then moves downslope within the soil profile as subsurface lateral flow (Cox et al., 2002; Eastham et al., 2000; Ticehurst et al., 2007).

Studies by Smettem et al. (1991) and Brouwer and Fitzpatrick (2002) found bypass flow through macropores and old root channels in the subsoil of texture-contrast soils may prevent development of subsurface lateral flow. These findings conflict with evidence from hillslope studies, which demonstrate that macropores assist the development of subsurface flow by allowing rainfall to rapidly infiltrate to the impermeable layer. As antecedent soil moisture increases, these pore networks become more connected resulting in greater and more rapid subsurface flow (McDonnell, 1990; Sidle et al., 1995; Tsuboyama et al., 1994).

The extent to which antecedent soil moisture influences development of preferential and subsurface flow in texture-contrast soils is largely unknown. Although not commonly cited as a management constraint, water repellence and vertic subsoils have been reported in texture-contrast soils (Chittleborough et al., 1992; Crabtree and Gilkes, 1999; Gardner et al., 1992; Hall et al., 2010). While the effects of water repellence on wetting front stability and finger flow have not been investigated in texture-contrast soils, numerous studies have reported an inverse relationship between soil moisture and water repellency (Dekker and Ritsema, 1996, 2000; King, 1981; Wessolek et al., 2008) in which a critical soil moisture threshold demarcates the moisture content at which soil changes from being non-wettable to wettable (Dekker and Ritsema, 1994; Ritsema and Dekker, 1994). Similarly presence of shrink-swell clays and slickensides in the subsoil of texture-contrast soils indicates potential for seasonal changes in antecedent soil moisture to influence subsoil porosity and preferential flow through the development of shrinkage cracks at low antecedent soil moisture (Greve et al., 2010; McCoy et al., 1994).

This study sought to investigate the effect of antecedent soil moisture on the occurrence, type and depth of preferential flow in a series of texture-contrast soil profiles, in which the topsoil was known to be hydrophobic, and the subsoil was known to undergo volume change with moisture content. Quantitative understanding of the effects of antecedent moisture on preferential flow is required to understand the potential processes responsible for mobilization of agrochemicals to shallow groundwater and surface water bodies in these soils. A combination of dye tracers, image analysis and soil moisture monitoring have been used to investigate the relationships between antecedent moisture, and the occurrence, type and proportion of preferential flow in four texture-contrast soil profiles.

2. Methods

2.1. Site location and soil analysis

Dye infiltration studies were conducted at four locations at the University of Tasmania farm, Cambridge, Tasmania, Australia, (42°47′S, 147°26′E). The mean annual rainfall of the site is 478 mm and mean annual evaporation 1324 mm. Sites A (lower slope), B (mid slope) and C (upper slope), were located on soils developed on Pleistocene alluvial fan deposits, while site D was located on soils derived from Tertiary sediments. At all sites the A horizon contains aeolian sands (Holz, 1993). Sites A, B and C were managed as long term pasture, while site D was used for irrigated cropping two in every 5 years. Site A was classified as a Bleached Sodic, Natric, Brown, Sodosol (Isbell, 2002), Mollic Natrustalf (Soil Survey Staff, 2006), and Solodic Planosol (FAO-UNESCO, 1987), while sites B, C and D were classified as bleached Sodic, Natric, Brown, Kurosols (Isbell, 2002), Mollic Natrustalfs (Soil Survey Staff, 2006), and Solodic Planosols (FAO-UNESCO, 1987). Soils profiles consisted of sandy loam A1 horizon, which overlayed a bleached,