Nutrient export pathways in agricultural systems include overland and subsurface flow (Fuchs et al., 2009), with the latter comprising matrix and preferential flow. Preferential flow encompasses any rapid water movement through large pores that bypasses the unsaturated zone (Beven and Germann, 1982; Bouma, 1982). While earthworm burrows, root networks, cracks and anthropogenically induced voids make preferential flow the rule rather than the exception in most soils (Lin et al., 1996; Reichenberger et al., 2002; Alaoui and Helbling, 2006), matrix and preferential flow often occur concurrently (Weiler and Naef, 2003). Preferential flow has important agronomic and environmental consequences: it prevents surface-applied chemicals from remaining in the root zone and instead transports them to depths greater than expected via Darcian flow, increasing the risk of groundwater contamination (Jarvis, 2007).

Numerous studies have investigated preferential flow in grassland or forested (DeWalle et al., 1988; Dewalle and Swistock, 1994; Leaney et al., 1993; Weiler and Naef, 2003; Alaoui et al., 2011) and agricultural environments (Logsdon et al., 1990; Edwards et al., 1993; Gazis and Feng, 2004; Cullum, 2009; Wuest, 2009; Katuwal et al., 2015; Wang and Zhang, 2017). With no direct preferential flow measurement method available (Wuest, 2009), these studies relied on dye tracing experiments, tracer mass balances, dual-porosity models, and two- or three-component hydrograph separation equations. Past research highlighted the role of tillage (Kladivko et al., 1997; Cullum, 2009; Kemper et al., 2011), tile drainage (Shipitalo et al., 2004), and manure application (Martens and Frankenberger, 1992; Benbi et al., 1998; Araji et al., 2001; Miller et al., 2002) on preferential flow. Knowledge gaps, however, remain regarding preferential flow in Vertisols subject to organic amendments.

Vertisols or “cracking clays” have a clay content of at least 30% to a depth of 50 cm and a significant potential for preferential flow due to shrinking–swelling properties and desiccation cracks (Dinka et al., 2013; Kurtzman et al., 2016). They are often used to grow cotton (Gossypium hirsutum L.), corn

Core Ideas

- Matrix flow and macropore flow interact in Vertisols via lateral infiltration.
- Maximum water infiltration depths are greater in Vertisols with hog manure.
- Manure does not affect the mobilization of old soil water via macropore flow.

Abstract: Preferential flow has different agronomic and environmental effects in various soils. The objectives of this study were (i) to quantify matrix and preferential flow and (ii) to assess the effect of organic amendments on flow dynamics in agricultural Vertisols. Dye tracing and isotopic analysis were used to infer soil water infiltration and mixing on two plots: one treatment (with liquid hog manure) and one control. Results showed infiltration depths reaching 64 cm for the treatment plot and 45 cm for the control. For both plots, matrix flow was only observed in the top 10 cm, whereas preferential flow extended beyond the tillage depth. Dye traces provided evidence of lateral infiltration across macropore–matrix boundaries, while post-experiment soil water averaged δ2H = −15.1‰ and δ18O = −118.9‰, hinting at old water mobilization via macropore flow. The potential impacts of these results on chemical transport should be validated across different soils and environmental conditions.
(Zea mays L.), wheat (Triticum aestivum L.), and soybean [Glycine max (L.) Merr.] in subhumid climates, with or without supplemental irrigation. Kurtzman and Scanlon (2011) hypothesized matrix flow to be small in Vertisols, but this hypothesis needs to be tested in the presence of organic amendments—such as manure—that modify soil hydraulic properties. The objectives of this study were therefore (i) to quantify the relative importance and interaction of matrix and preferential flow in agricultural Vertisols and (ii) to assess the effect of organic amendments on soil water dynamics.

Materials and Methods

Research plots were established on a near-level (0–2% slope) canola field near Culross, MB, Canada. The region receives 580 mm of annual precipitation, with 21% as snow, and low air temperatures (−16°C) occur in January (ECCG, 2017). Annual evapotranspiration exceeds precipitation, and seasonal ground frost develops down to 75 to 100 cm depth. Soils are Gleyed Humic Vertisols of the Red River Series (Brierley et al., 2011; Gleyic Humicrgis in the US taxonomy), and nearby soil survey pits show evidence of historical cracking, that is, cracks filled with black, organic-rich topsoil down to 75 to 100 cm depth.

Two 1-m² plots—one treatment and one control—were selected: they were located 50 cm apart and have tillage depths of 10 to 12 cm. Following over 2 wk of warm, rain-free and irrigation-free conditions, canola (Brassica spp.) sprouts (20 cm or less) and desiccation cracks were visible on both plots in June 2015. Five liters of liquid hog manure was applied to the treatment plot to mimic typical application rates in the region. Shortly after, low-toxicity and high-visibility brilliant blue dye (Weiler and Fluhler, 2004) mixed with water from a local, on-farm retention pond was sprinkled onto both plots for soil staining. Thirty-two millimetre dye solution (“sprinkled water”) was applied to each plot over a 30-min period to simulate water inputs associated with convective rainstorms in this region (Raddatz and Hanesiak, 2008; Shook and Pomeroy, 2012). Three days after sprinkling, each plot was excavated to a depth of 100 cm, and five vertical profiles (or slices; see Fig. 1A) were photographed. Binary images (stained versus unstained soil) were created by manually delineating blue patches on each photograph as “fingerprints” of soil water flow. Following the procedures of Weiler and Fluhler (2004), each binary image was divided into 200 horizontal strips and each strip classified into one of five potential flow types: (i) homogeneous matrix flow, (ii) heterogeneous matrix flow and fingering, and macropore flow with (iii) low, (iv) mixed, or (v) high interaction with the surrounding soil matrix. Soil water was sampled from 30-cm-depth MicroRhizon (Soil Moisture Inc.) samplers located in the vicinity of a soil crack in each plot 1 wk before and 6 h after sprinkling. Water ponding on the plots after sprinkling was also sampled. All water samples were tested for δ¹⁸O and δ²H to infer soil water mixing (Kendall and Doctor, 2004).

Results

Stain patterns were highly variable (Fig. 1B), spanning depths of 0 to 45 cm and 0 to 64 cm for the control and treatment plots, respectively. Dye breakthrough was the shallowest for slices A and the deepest for slices B, C, and D, which is consistent with the micro-topography of the plots that dipped by 1 to 2 cm toward the middle: sprinkled water moved toward the middle of each plot before infiltrating. Matrix flow—homogeneous or heterogeneous with fingering—was never present past the tillage depth (~10 cm), with the exception of slice B in the treatment plot (Fig. 2A). Below 10 cm, macropore flow with low, mixed, or high interaction with the surrounding soil matrix dominated.

Isotopic analysis results are summarized in a δ–δ plot (Fig. 2B), with each square symbol showing a different water sample. The δ–δ plot also shows meteoric water lines (MWL), which relate δ¹⁸O and δ²H for precipitation samples collected globally (global meteoric water line) and locally (local meteoric water line) (Craig, 1961). All water samples associated with the experiment were located below the meteoric water lines (Fig. 2B), which signals evaporation (Kendall and Caldwell, 1998). The sprinkled water and pre-sprinkling soil water had similar δ¹⁸O signatures but distinct δ²H signatures—with a difference more than 40 times larger than the analytical precision. Post-sprinkling soil water plotted on a mixing line connecting pre-sprinkling soil water and sprinkled water (Fig. 2B), suggesting that it was a mixture of the two water sources forming the extremities of the mixing line (Kendall and Doctor, 2004), namely, old water and new water.

Discussion and Implications

Three main outcomes emerged from this study: (i) recently applied manure increased infiltration depths in the monitored Vertisols; (ii) fingering and macropore–matrix interactions were appreciable; and (iii) post-sprinkling soil water was a mixture of old and new water, even when macropore flow dominated. Regarding outcome (i), the introduction of new organic matter via manure to soil micropores and macropores (cracks) likely resulted in “greased” pathways that facilitated deeper infiltration and a co-occurrence of matrix and preferential flow. Previous studies documented similar changes after long-term manure applications (e.g., Miller et al., 2002), whereas the current study hints at short-term changes. The limited occurrence of matrix flow in the top 10 cm may signal the presence of perched sub-surface flow above a textural discontinuity created by tillage activities. Regarding outcome (ii), fingering was most likely heterogeneity driven rather than instability driven, as is often the case with clay and peat soils (Ritsema et al., 1998; Wang et al., 2000). The identification of macropore flow with high interaction on the stained images was evidence of water being transferred from macropores to the surrounding soil matrix, a process termed _lateral infiltration_ (Beven and Clarke, 1986). Outcome (iii) reinforces the idea of water exchanges at macropore–matrix boundaries. Indeed, macropore flow was shown to be composed of old water by many
researchers (DeWalle et al., 1988; McDonnell, 1990; Kienzler and Naef, 2008) and new water by others (Steenhuis et al., 1994; Stone and Wilson, 2006; Jarvis, 2007; Vidon et al., 2012). The current study rather suggests a mixture of old and new water, with or without organic amendments (Fig. 2B). Previous studies even showed that vertical macropores allow new water to be translocated from the surface to tile drains (e.g., Stamm et al., 1998; Smith et al., 2015; Williams et al., 2016). In the current study, however, dye stains did not extend to the 100-cm depth where tiles are typically installed in the region. Lateral infiltration followed by macropore flow of old water would make it possible for nutrients desorbed from bulk soil to be preferentially transported, although the specifics of sorption kinetics that would allow such to happen are unknown. Manure application therefore affected the maximum infiltration depths observed in the treatment plot but not the presence of lateral infiltration or soil water mixtures, which were observed across both plots.

While our results add to the growing knowledge on soil water movement in dual-porosity systems, they are not generalizable due to limited experimental replication. The in situ study had to take place during a short time window in early summer, when conditions were dry enough for cracks to establish but crops low enough for cracks to be visible and facilitate site selection. Also, only two plots were excavated so as not to impede farming. Notwithstanding, the current study hints at manure effects that were restricted to vertical infiltration depth and did not extend to lateral infiltration
dynamics. Laboratory-based experiments should therefore be performed, not only to improve replication but also examine the prevalence of lateral infiltration dynamics under changing manure origins and application methods, macropore origins, antecedent wetness conditions, and rainfall intensities.

References

Fig. 2. (A) Soil water flow profiles classified based on the scheme of Weiler and Fluhler (2004). (B) Isotopic signatures of the water samples collected before and after sprinkling across both plots.


