Field method for separating the contribution of surface-connected preferential flow pathways from flow through the soil matrix

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[1] Liquid latex was used as a method to seal visible surface-connected preferential flow pathways (PFPs) in the field in an effort to block large surface-connected preferential flow and force water to move through the soil matrix. The proposed approach allows for the quantification of the contribution of large surface-connected cracks and biological pores to infiltration at various soil moisture states. Experiments were conducted in a silty clay loam soil in a field under a no-till corn-soybean rotation planted to corn. Surface intake rates under ponding were measured using a simplified falling head technique under two scenarios: (1) natural soil conditions with unaltered PFPs and (2) similar soil conditions with latex-sealed large macropores at the surface. Results indicated that the contribution of flow from large surface-connected macropores to overall surface intake rates varied from approximately 34% to 99% depending on the initial moisture content and macroporosity present. However, evidence of preferential flow continued to appear in latex-sealed plots, suggesting significant contributions to preferential flow from smaller structural macropores, particularly in two out of four tests where no significant differences were observed between control and latex-sealed plots.

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1. Introduction

[2] Traditional field methods to observe effects of preferential flow on solute transport have often combined tracer studies with lysimeter and tile drainage systems to measure breakthrough curves [*Bogner et al.*, 2008; *Jury*, 1982; *Kung et al.*, 2000; *Shipitalo and Edwards*, 1996; *Williams et al.*, 2003]. The results of such studies indicate that PFPs, particularly surface-connected ones [*Allaire et al.*, 2002; *Kung et al.*, 2000; *Noguchi et al.*, 1999], allow solutes to bypass the soil matrix and reach deep into the soil profile under various field management regimes. Preferential flow has contributed to rapid and deep chemical leaching of adsorbing and nonadsorbing (conservative) substances such as pesticides and nitrogen [*Germann and Beven*, 1981; *Kladivko et al.*, 1999; *Luxmoore*, 1991]. In situ field methods have utilized staining and image analysis techniques to reveal the flow path of surface applied dyes [*Forrer et al.*, 2000; *Ghodrati and Jury*, 1990]. Other field methods developed to capture preferential flow path effect, behavior and morphology include color change spray techniques [*Lu and Wu*, 2003; *Tamm and Troedsson*, 1957], ground penetrating radar [*Freeland et al.*, 1998; *Vellidis et al.*, 1990], time domain reflectometry (TDR) [*Germann et al.*, 2007; *Nissen et al.*, 1999; *Vanclooster et al.*, 1995], and radio scanning [*Brown et al.*, 1999].

[3] Recently, application of liquid latex was evaluated as a field scale method for visualizing surface-connected PFP volume and geometry in fine textured soils [*Abou Najm et al.*, 2010]. The objective of this research is to examine the use of liquid latex to hydraulically inactivate surface-connected large PFPs during an infiltration event, in an attempt to estimate their contribution to overall flow at different field conditions. This becomes significant given the variation and dependency of this contribution (of surface-connected PFPs to overall flow) on local field conditions including rainfall intensity, water content, crack openings and connectivity.

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2. Materials and Methods

2.1. Field Site Information

[4] The experimental procedure was conducted on a Drummer silty clay loam soil at the Purdue Agronomy Center for Research and Education (ACRE), West Lafayette, Indiana. The Drummer soil series is a poorly drained

Table 1. Soil Properties

Horizon	Soil Texture[a]	Textural Class	Water Holding Capacity[b]	Bulk Density[c] (g cm^{-3})
Surface (0–30 cm)	21% sand, 46% silt, 33% clay,	clay loam	field capacity, 1/3 bar: 31.3%; wilting point, 15 bars: 10.9%	1.60
Subsurface (30–60 cm)	17% sand, 46% silt, 37% clay,	silty clay loam	field capacity, 1/3 bar: 36.9%; wilting point, 15 bars: 14.9%	1.56

[a]U.S. Department of Agriculture Classification.
[b]In gravimetric water content.
[c]Bulk density averages of dry soil clods for each horizon were measured using the clod method [*Blake and Hartge*, 1986]. Thus, those results exclude the contribution of larger macropores.

soil with a silty clay loam topsoil, with evidence of swelling, smectitic clays from clay mineralogy analysis. It is a dark prairie soil formed in loess over loamy outwash [*Soil Survey Staff*, 2008]. Table 1 provides a summary of the soil properties at the surface horizon and the subsurface layer immediately below it. A site location map including the cracking pattern observed at the start of each field trial is presented in Figure 1.

[5] Tile drains spaced approximately 20 m apart with approximate depth of 0.90 m had been installed throughout the entire field and were avoided during the field trials using tile drain maps developed by *Naz and Bowling* [2008]. A corn crop was planted with 76 cm (30 inch) row spacing on 22 May 2009. The experimental field trials were conducted on the southeast corner of field 115 in ACRE at latitude 40°29′38″ north and longitude 86°59′35″ west in an area which has been managed under no-till corn-soybean rotation for over 20 years. Field records (Figure 2) indicate the following mechanical activity in 2009: (1) planting on 22 May, (2) surface-applied pesticide/herbicide on 23 May, and (3) side-dress application of 28% liquid nitrogen on 10 June. The 28% liquid nitrogen fertilizer was injected 5–8 cm into the soil profile via a metal shank. Further details on the field conditions are given by *Sanders* [2010].

2.2. Experimental Methods

[6] The general method of this research involved comparing natural untreated field plots with plots having their surface-connected PFPs sealed with liquid latex. To account for the inherent spatial variability, each trial was composed of six frames (3 control and 3 latex) where the surface-connected PFPs of three of those frames were sealed with latex (latex frames). The stainless steel frames had dimensions of 32 cm × 45 cm × 25 cm high [*Abou Najm et al.*, 2010], and served also as an infiltrometer for the infiltration event. Each trial required 3–4 days of field work in order to prepare soil surfaces in the treatment and control frames, perform an infiltration event, and excavate the frames in 10 cm layers. Soil moisture contents and

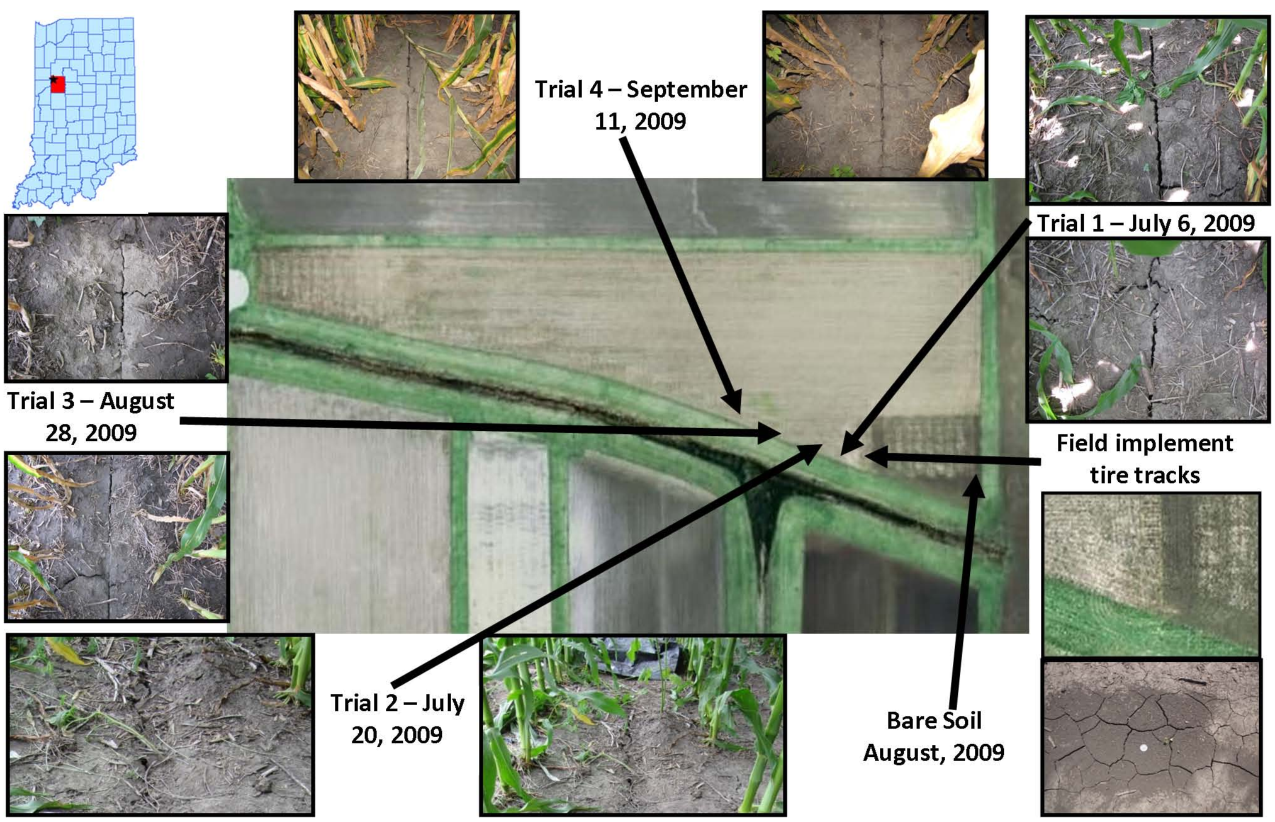

Figure 1. Site location map illustrating the representative cracking pattern observed in each trial area.

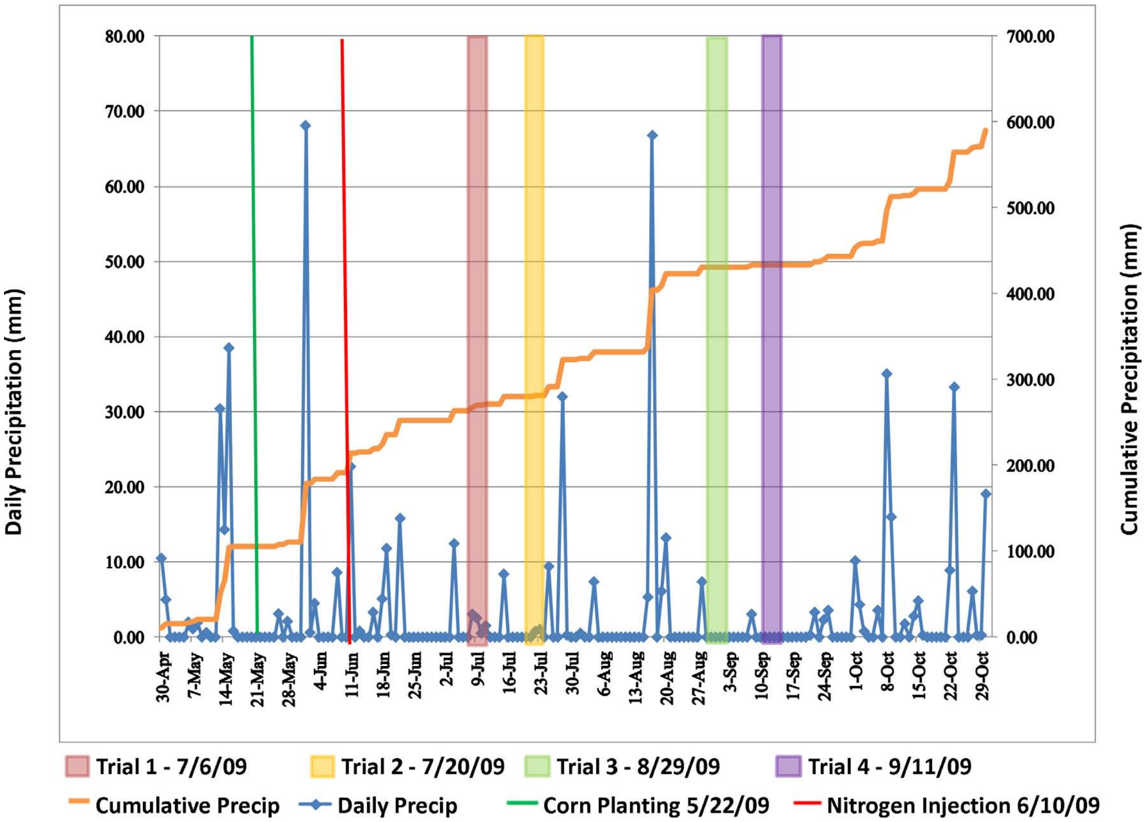

Figure 2. Rainfall hydrograph and field activity summary. Precipitation data were obtained from the Indiana State Climatologist Office and the National Climatic Data Center.

preferential flow pathway volumes were then examined to 60 cm depth for all trials at various moisture contents.

[7] A total of four trials (including 12 latex frames and 12 control frames) were completed during the 2009 growing season. Soil samples were taken from around each trial area on the first (initial moisture conditions) and last (background for postinfiltration comparison) days of each field trial at the following depth intervals: 0–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, 50–60 cm using a one inch diameter soil probe.

[8] On day 1, initial soil moisture samples were collected and frames were installed to 15 cm depth within close proximity to each other to minimize spatial variability. The frames had a beveled edge to cut through the soil surface with minimal damage to the cracking pattern during installation. The soil surfaces in each frame were prepped in the same manner by removing the top 1–3 cm to eliminate debris and to create a level surface. In three frames, latex was then carefully poured into obvious (i.e., large) surface macropores to seal them while leaving the soil matrix exposed.

[9] On day 2, a short-term ponding technique was used to compare the intake rates of the untreated and latex-sealed plots. Four liters (28 mm) of water were applied using the same technique on all frames. A point gauge was attached to the same location on each frame to monitor changes in water depth over time. Water levels were measured and recorded at time intervals appropriate for the intake rate observed for that frame until approximately 10% of the soil surface was exposed. Regardless of treatment, 2 h or less were required for all water to infiltrate into the soil profile (except for one replicate in trial 3 which took over 3 h). Water was allowed to redistribute down the soil profile for 18–20 h or 38–40 h before excavating and sampling.

[10] The contribution of latex sealed pores to infiltration was calculated by finding the percent difference in the intake rates using

$$[(\text{Control Intake} - \text{Latex Intake})/\text{Control Intake}] \times 100 \quad (1)$$

[11] By finding the percent difference in the treatments, the contribution of surface-connected preferential flow through the larger cracks and biological pathways can be estimated for the given field conditions.

[12] On the third and fourth field days, two reference rods were driven to 60 cm into the ground on two opposite corners of the frames. Frames were slowly excavated at 5 or 10 cm layer depths (0–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–60 cm). The soil from each layer was placed into a separate container and a composite sample was then placed into a plastic bag for moisture content analysis. Moreover, soil samples from outside the frame extent were collected as the background moisture content, later to be compared with the water contents from under the frames.

[13] The soil samples were oven dried for gravimetric water content while the clod method [*Blake and Hartge*, 1986] was used for bulk density assessment using soil clods collected from the field. Soil texture was estimated using the hydrometer method [*Bouyoucos*, 1962] and water retention at field capacity and wilting point were determined in the laboratory using method MSA Part 1 pp. 273–278

[*Klute*, 1965]. The latex removed from each sublayer was thoroughly cleaned with water and allowed to dry. Biological and desiccation volumes retrieved from the latex frames were separated by shape (cylindrical and planar, respectively) and measured per trial.

3. Results and Discussion

3.1. Observed Influences on Soil Cracking Patterns

[14] Field observations indicated that predominant cracking patterns in the corn field were large continuous cracks formed in the center of corn rows with a few nearly perpendicular cracks extending from the central crack to the corn rows. Similar cracking patterns have been observed by others in row crop systems [*Abou Najm et al.*, 2010; *Flowers and Lal*, 1999; *Johnston*, 1944; *Yoshida and Adachi*, 2004]. Figure 3 shows the average initial moisture contents collected during the first day for each trial from each depth (Figure 3a) compared to the surface-connected latex-filled macroporosity for each trial (Figure 3b). The error bars in Figures 3a and 3b represent the standard deviation from all soil probe locations around each trial area or the standard

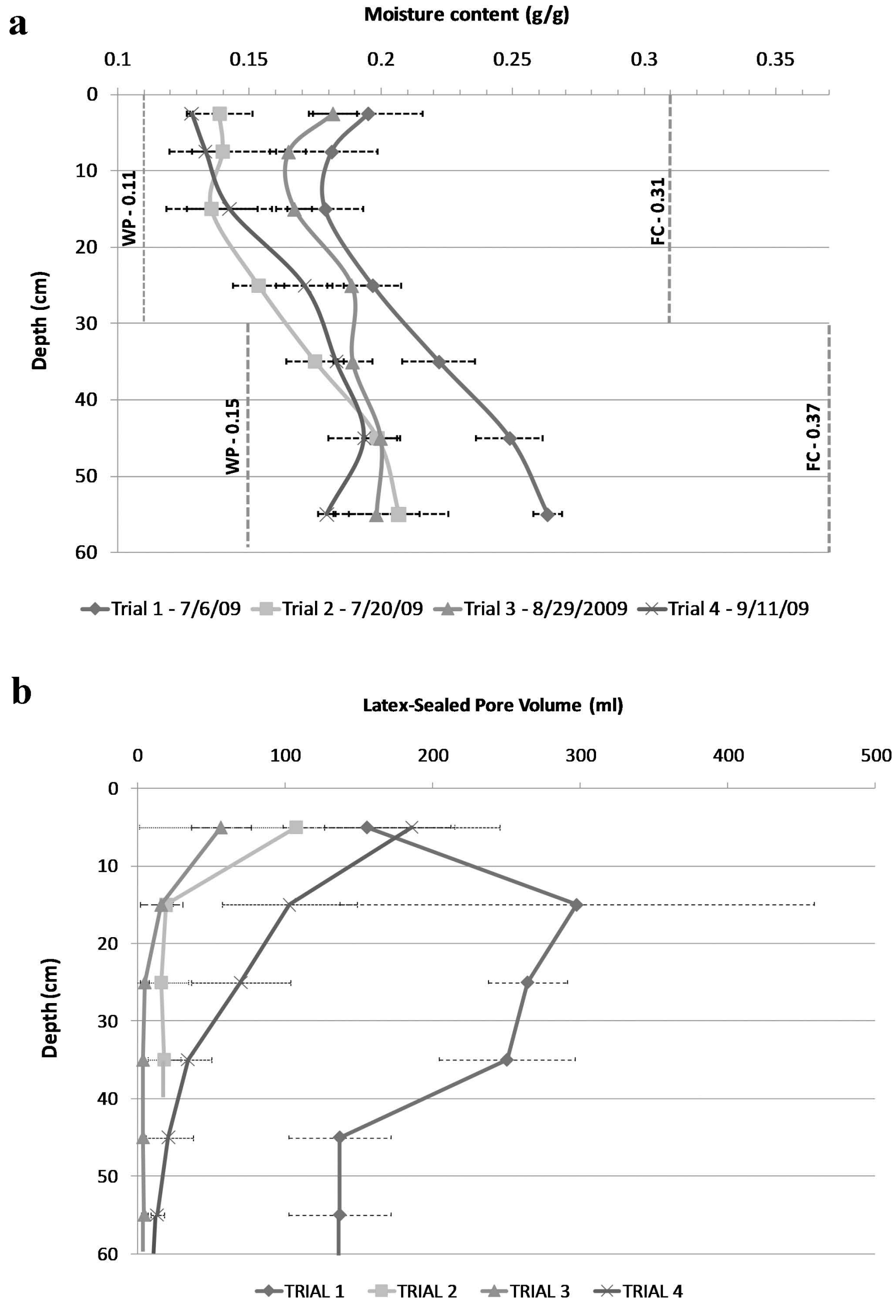

Figure 3. (a) Average initial moisture conditions in all trials collected on field day 1 in each trial compared to (b) average latex-filled macropores volumes from each trial. Those volumes can be transformed to porosities through dividing the latex-filled pore volumes by the soil layer volume (32 cm × 45 cm × layer depth). WP is wilting point (15 bars), and FC is field capacity (1/3 bar) for the upper (0–30 cm) and lower (30–60 cm) soil horizons (WP and FC are provided in gravimetric water contents).

deviation of the latex volumes in treatment frames, respectively.

[15] Initial moisture conditions showed little variability with depth down to 60 cm within trials, and a maximum variation of 0.08 g g^{-1} between trials (i.e., trial 1 compared to trial 4). Surface-connected latex-sealed pore volumes seemed only weakly correlated with soil moisture profiles. Trial 1 had the highest initial moisture conditions, and yet had the largest and deepest latex-sealed pore volumes measured. On the other hand, trial 2 had the shallowest cracking patterns (Figure 3b), most probably because of heightened root activity and rapid corn growth in the period between trials 1 and 2. Thus, it seems that the volume and depth of surface-connected cracks and biopores is the result of a complicated interaction between the soil, weather, fauna, flora, and human interventions, where simple characterization of soil coupled with monitoring the moisture profile may not be sufficient to predict their volume and depth.

3.2. Contribution of Surface-Connected Preferential Flow to Surface Intake Rates

[16] Table 2 presents the intake rates based on the time taken for 1 L (approximately 0.7 cm per frame area) and all 4 L (approximately 2.7 cm per frame area) to infiltrate into the soil profile. The 1 L intake rates capture the initial fast intake of the soil, whereas the 4 L intake rates represent the time necessary for all water to infiltrate. A total volume of 4 L was chosen for this field experiment on the basis of the rough estimation of the infiltration depth using a target of 0.10 g g^{-1} change in moisture content for a depth of approximately 30–40 cm. Table 2 compares the intake rates for each treatment to the total latex-sealed pore volume and average background moisture conditions for all depths. The biopore and desiccation crack volumes retrieved from the latex frames are shown as the percentage of the total latex-sealed pore volume in that trial.

[17] Figure 3a and Table 2 show that trials 2 and 4 had the driest initial conditions with both showing similar contributions of latex-sealed pores to infiltration. The latex treated frames in trial 2 had the greatest average intake rate and variability. This variability is partially due to observed overnight biological activity (new earthworm burrows connecting to the surface) following the application of latex, thus allowing for new and active surface-connected PFPs. On the other hand, trial 3 had relatively wetter conditions than trials 2 and 4, smaller volume of latex-sealed pores

Table 2. Intake Rates Based on the Time Required for 1 L and 4 L to Infiltrate

Trial	Frame	Treatment	1 L Rate[a] (cm min^{-1})	1 L Avg.[a] (cm min^{-1})	1 L PFP Contrib. to Flow (%)	4 L Rate[b] (cm min^{-1})	4 L Avg.[b] (cm min^{-1})	4 L PFP Contrib. to Flow (%)	Aver. Latex Vol. (mL)[c]	Biological PFPs (%)	Desiccation PFPs (%)	Avg. Moisture Content (g g^{-1})[d]
1	2	Control	33.36	31.5 ± 3.21[b]	99.2	33.36	31.5 ± 3.21	99.3	1241	14.5	85.5	21.2%
	4	Control	27.8			27.80						
	6	Control	33.36			33.36						
	1	Latex	0.14	0.245 ± 0.192		0.103	0.226 ± 0.206					
	3	Latex	0.1273			0.111						
	5	Latex	0.4667			0.463						
2	2	Control	1.166	1.15 ± 0.207	54.0	1.090	1.12 ± 0.056	60.5	155	25.1	74.9	16.4%
	3	Control	1.3461			1.183						
	5	Control	0.9333			1.082						
	6	Latex	0.8485	0.529 ± 0.291		0.863	0.442 ± 0.367					
	4	Latex	0.28			0.192						
	1	Latex	0.4575			0.271						
3	2[e]	Control	0.0175	0.07 ± 0.042	9.7	0.015	0.063 ± 0.023	34.1	89	36.1	63.9	18.4%
	4	Control	0.1			0.079						
	6	Control	0.04			0.047						
	5	Latex	0.0875	0.063 ± 0.034		0.056	0.042 ±0.020					
	3	Latex	0.0389			0.028						
	1[f]	Latex	0.1474			0.126						
4	2	Control	0.175	0.292 ± 0.101	43.6	0.111	0.237 ± 0.119	67.6	428	19.3	80.7	16.2%
	4	Control	0.35			0.253						
	6	Control	0.35			0.348						
	1	Latex	0.35	0.165 ± 0.167		0.185	0.077 ± 0.094					
	3	Latex	0.1167			0.026						
	5	Latex	0.0269			0.019						

Notes: Frame dimensions are 32 cm × 45 cm and 4 L was applied to each frame.
[a]Intake rates are based on the time required for 1 L to infiltrate the soil surface except in Trial 1 control frames, which are based on 4 L intake.
[b]Trial intake rates are based on the time required for all 4 L to infiltrate the soil surface.
[c]Avg. latex volumes (mL) were calculated using the water displacement method.
[d]Avg. moisture content (g g^{-1}) was determined for the entire depth from 0 to 60 cm from soil cores collected around each trial area.
[e]Trial 3 Frame 2 was considered an outlier because of a low intake rate compared with the other control frames in all trials and thus its data were removed from the rate calculation.
[f]Trial 3 Frame 1 was considered an outlier and not included in the latex intake rate calculation because earthworm activity observed during the infiltration event created an unsealed PFP.

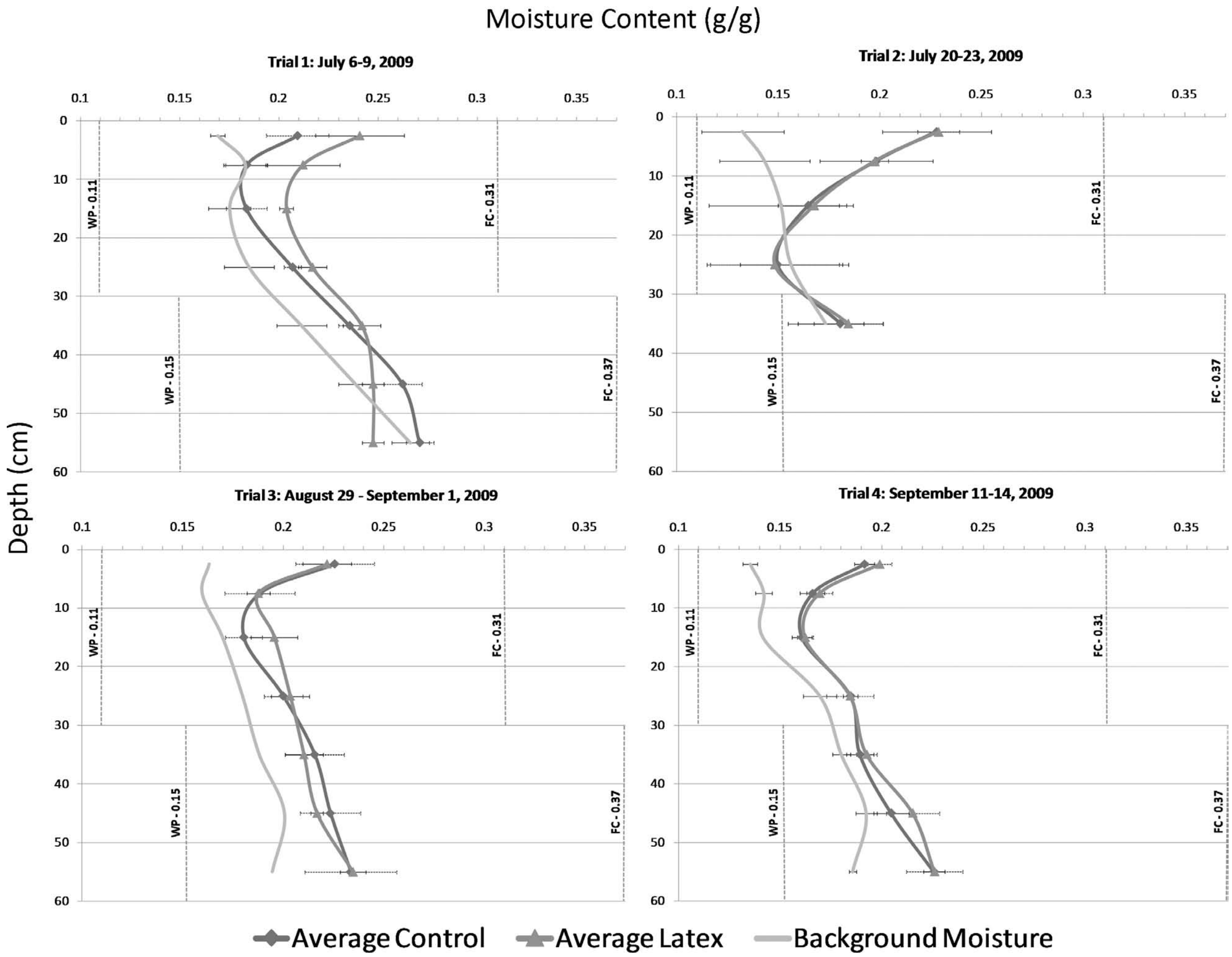

Figure 4. Postinfiltration moisture profiles compared to the background moisture profile for each frame in each trial. WP is wilting point (15 bars), and FC is field capacity (1/3 bar) for the upper (0–30 cm) and lower (30–60 cm) soil horizons.

and thus a smaller contribution to infiltration. However, trial 1 had the highest initial soil moisture conditions down to 60 cm depth (Figure 3a), yet the greatest contribution of latex-sealed pores to infiltration.

[18] Figure 3b shows that all surface-connected latex sealed pores have terminated at depths of 60 cm or less except for trial 1 where they seemed to penetrate deeper than 60 cm. This is also reflected in their volume which is by far highest of all trials. Thus, the deep and connected cracks in trial 1 control frames allowed water to bypass the matrix and fill in the crack volume, which is reflected in the 99.3% contribution to surface-connected preferential flow. This explains why the contribution of surface-connected preferential flow is greatest in trial 1 compared to the other trials where the water would have accumulated in the crack volume and infiltrated laterally and vertically into the soil profile. Given the rapid intake rate in trial 1, the 1 L intake rate was not recorded and the 4 L rate was used. Results of trial 1 indicated that field moisture conditions at the surface are not enough to predict the contribution of the surface-connected macropores to overall flow in the soil.

[19] The intake rate statistical assessment supported the expectation that the intake rate in the control frames would be greater compared to the latex frames. A one-tailed independent *t* test of unequal variance was performed comparing the mean intake rate for the control frames to that of the latex frames in all trials. This statistical tool is used to test for a null hypothesis of equal means to determine whether the difference in the intake rates between treatments is statistically significant. The p values calculated for the 1 and 4 L data were less than 0.04 in both cases which indicates that the mean intake rates of the treatments were statistically different.

[20] Finally, a close look into the average 4 L infiltration rates in the latex-treated plots shows significantly higher infiltration rates than typical infiltration rates of clay loam soils. This is a clear indication that this method sealed only visible shrinkage cracks and biopores. Structural macropores remained active in latex and in control plots, as well as their contribution to preferential flow.

3.3. Postinfiltration Moisture Profile

[21] Figure 4 shows, for each trial, the average postinfiltration moisture profiles for both treatments (control and latex) compared to the average background moisture profile. Background moisture profiles were collected on the same day of the excavation (field day 3 or 4 in each trial) but

outside the extent of water application to represent the moisture condition if no water was applied in day 2. In all frames, the surface layer (0–5 cm) experienced the greatest increase in moisture content compared to the background moisture profile.

[22] Sealing the surface-connected larger and more obvious macropores with latex did not completely prevent preferential flow from occurring. This can be clearly observed by looking into the postinfiltration moisture profiles of the latex frames, where field capacity was not reached at any depth. Thus, the difference between control and latex frames is only due to large surface connected pores that could be sealed by latex.

[23] Interestingly, the contribution of latex-sealed pores to overall flow, obtained from the difference in the intake rates between treatments, did not correspond well with the postinfiltration moisture profiles. For example, sealing the surface-connected desiccation cracks and biopores with latex had no significant effect on the resulting moisture profiles in trials 2 and 4. The moisture profiles for the latex treated frames only varied from the control frames by approximately 2.5% or less although the contribution of surface connected PFP was about 60% in trial 2 (Table 2). This may be explained by the fact that trials 2 and 4 had the driest initial moisture conditions (Figure 3a) thus the highest sorptive capacity by the soil matrix. Even though intake rates were significantly different between control and latex frames (Table 2), the relatively shallow surface-connected PFPs (Figure 3b) may have allowed for lateral moisture redistribution and did not allow for deep water infiltration, thus giving way for the soil matrix, particularly its macropores to dominate the flow redistribution.

[24] On the other hand, the results of the latex frames of trials 1 and 3 showed an increase in moisture content in the surface horizons (top 20–30 cm), while the control frame had greater moisture content in the subhorizon (below 30 cm) after 1–2 days of redistribution. In other words, with surface-connected preferential flow contributing to the flow regime (control frames), infiltrated water redistributed deeper into the soil profile compared to latex frames.

4. Conclusions and Recommendations

[25] A new field method is presented to quantify the contribution of surface-connected macropores to overall water flow, following 1–2 days of water redistribution. The primary results from this research indicated that the contribution of flow from surface-connected larger macropores (biopores and cracks) to surface intake rates varied, for the same soil and land use, from approximately 34%–99% depending on the initial moisture content and macroporosity present. Statistical analysis of the data showed that the difference in intake rates between treatments was significant (p value <0.04). A general increase in the contribution of latex-sealed pores to flow was observed as moisture content decreased and/or their volume increased. However, this trend was not observed in all trials (particularly trial 1 which had the wettest conditions down to 60 cm yet the deepest cracks and highest contribution of latex-sealed pores to infiltration) leading to the conclusion that preferential flow is a very complex phenomenon governed by unknown factors other than initial water content.

[26] Some challenges with this method include the lateral flow of the latex beyond the frame extent, which made total recovery and mass balance difficult and therefore was not attempted. Also, changing field conditions such as overnight biological activity which occurred after the latex was poured, but before or while infiltration was performed affected the intake rates. It seems that liquid latex only seals the largest surface connected macropores and does not completely eliminate nonequilibrium flow.

[27] Finally, a variety of limitations were discussed in section 3, Results and Discussion. Though this could be viewed as a limitation of the method, it is beneficial to have experimental methods which allow the manipulation of boundary conditions for modeling the soil water interaction.

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