New method for the characterization of three-dimensional preferential flow paths in the field

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[1] Preferential flow path development in the field is the result of the complex interaction of multiple processes relating to the soil’s structure, moisture condition, stress level, and biological activity. Visualizing and characterizing the cracking behavior and preferential paths evolution with soil depth has always been a key challenge and a major barrier against scaling up existing hydrologic concepts and models to account for preferential flows. This paper presents a new methodology to quantify soil preferential paths in the field using liquid latex. The evolution of the preferential flow paths at different soil depths and moisture conditions is assessed. Results from different soil series (Savage clay loam soil versus Chalmers clay loam) and different vegetation covers and soil managements (corn/tilled field versus soybean no-till field in the Chalmers soil series) are presented.


1. Introduction

[2] Understanding and modeling water flow behavior in the field and catchment scales is integral to various environmental and agricultural applications. Unfortunately, this understanding is challenged with preferential flow attributed to soil’s shrinkage-swelling behavior and biological activities rendering the use of Darcian fluxes, developed at the laboratory scale for soil matrix flow, unable to describe the flow in the field.

[3] Review of the literature from multiple disciplines on preferential paths in soils shows its level of complexity and interdisciplinarity. In fact, it is no secret that a universal definition of what a crack or a preferential path is does not exist despite the various attempts to describe them based on their morphology [Brewer, 1976], geometry [Perret et al., 1999], hydraulic effectiveness and functionality [Bouna et al., 1977; Beven and Germann, 1982, Chen et al., 1993], equivalent pore diameter [Luxmoore, 1981], or size [Feld et al., 1996]. The term “macropore” has been widely used in the soil literature to represent the whole spectrum of pores ranging from inter-aggregate pores, shrinkage cracks, and fissures to earthworm and root channels. In this paper, we follow the structural hierarchy approach [Tisdall and Oades, 1982; Elliott, 1986; Oades, 1993; Amezketa, 1999; Braudeau et al., 2004; Bronick and Lal, 2005] in defining preferential flow paths as the interconnected network of pores (caused by the shrinkage/swelling of soils as well as by biologic activities) where flow is not interrupted by the soil matrix. The soil matrix is defined as the evolution of soil primary particle and clay microstructure into micro-aggregates that bond to form macro-aggregates that combine to form elods [Oades, 1993]. The pore structure within the soil matrix is divided into micropores (within the primary particles and clay microstructure) and macropores (at the inter-aggregate level) similar to the mobile-immobile dual-permeability model (described by Simunek and van Genuchten [2008]), the pedostructure model [Braudeau and Mohtar, 2009], and many others. Thus, we distinguish (Figure 1) between macropores (defined here as the inter-aggregate pores within the soil matrix) and preferential flow paths (defined here as the pore structure that is not considered part of the soil matrix), although we acknowledge the presence of some preferential flow at the macropore or even at the submillimeter scales [Chen et al., 2008] that are beyond the scope of this paper. Moreover, preferential flow paths are restricted in this paper to those caused by surface-interconnected network of pores being most probably the first to be filled. Finally, we acknowledge that such classification, though ideal for swelling soils, may be inappropriate for sandy and water-repellent soils where preferential flow paths are mainly caused by the instability of the wetting front.

[4] The general form of the bulk volume of soil at the field scale (Figure 1) assuming dual flow and pore systems at the soil matrix scale is

\[
V_{\text{layer}} = V_{\text{solids}} + V_{\text{micro, matrix}} + V_{\text{macro, matrix}} + V_{\text{preferential paths}} + V_{\text{stone}}
\]

(1)

where \(V_{\text{layer}}\) is the total volume of the bulk soil in any layer (Figure 1); \(V_{\text{solids}}\) is the volume of soil particles; \(V_{\text{stone}}\) is the volume of bulk stones and solid organic content; \(V_{\text{macro, matrix}}\) is the volume of the micropores within the soil aggregates that form the soil matrix (intra-aggregate porosity); \(V_{\text{macro, matrix}}\) is the volume of macropores between soil aggregates inside the soil matrix (inter-aggregate porosity);
Figure 1. Pore structure in soil at the field scale. Notice the clear distinction between macropores and preferential flow paths represented by cracks and biological activities. See color version of this figure in the HTML.

and \( V_{\text{preferential paths}} \) is the total volume of the preferential paths that include desiccation cracks, fissures, and biological (fauna and flora) pores. Note that \( V_{\text{solids}} + V_{\text{micro matrix}} + V_{\text{macro matrix}} = V_{\text{pedostructure}} \) [Braudeau and Mohtar, 2009]. Thus,

\[
V_{\text{preferential paths}} = V_{\text{cracks, fissures}} + V_{\text{biological}},
\]

where \( V_{\text{cracks, fissures}} \) is the volume of desiccation cracks and fissures that may be estimated from the shrinkage/swelling curves and \( V_{\text{biological}} \) is the volume of pores that results from the wide spectrum of biological activities including insect and earthworm burrows and biodegraded roots. The rest of section 1 summarizes existing methods and tools to characterize preferential paths.

At the laboratory scale, preferential flow paths were studied in the context of pore structure, shape, and pattern with the aid of digital image analysis and processing [Ringrose-Voase and Bullock, 1984] or electro-optical techniques [Jongerius et al., 1972] using dye or fluorescent stains. One-dimensional analysis in the form of test lines was performed on 2-D images to extract structural indices like intercept length distributions [Ringrose-Voase and Nys, 1990; Ringrose-Voase, 1987, 1990], distance distribution between cracks [Scott et al., 1986], or percent crack area occupied by the corresponding crack width [Velde et al., 1996]. Connectivity density and pore network frequency were assessed by introducing the topology of patterns of cracks in soils using a sequence of 2-D digital images representing various sections/slices of the three-dimensional (3-D) soil sample [Scott et al., 1988a, 1988b]. Moreover,
digital imagery pattern recognition techniques were employed to distinguish among different pore classes (packing voids, channels, planes, and vughs), recognizing the differences in their functional properties [Bouma et al., 1977; Ringrose-Voase and Bullock, 1984; Murphy et al., 1977a, 1977b; Moran and McBratney [1992a, 1992b] used dual impregnation (in the field and in the laboratory) with different fluorescent dyes to assess connectivity of pores. Deeks et al. [1999] impregnated soil samples with cryogenic resin and a UV-sensitive dye to distinguish voids under UV light.

[5] Nondestructive 3-D quantification of the preferential paths network was conducted using electric resistivity imaging for detecting cracks at the centimeter scale [Samouelian et al., 2003]. Moreover, the geometry and topology of 3-D preferential paths networks were assessed using computer-aided tomography scanning and 3-D reconstruction techniques [Warner et al., 1989; Heijts et al., 1996; Perret et al., 1999; Jassogne et al., 2007]. Alternatively, Vogel et al. [2005] presented a methodology for quantitative description of soil surface cracking pattern using Minkowski functions.

[7] In the field, visualization of preferential flow paths was established by means of spray techniques of dye tracers [e.g., Lu and Wu, 2003] coupled with various image analysis methods [Aebi et al., 1997; Forrer et al., 2000; Bogner et al., 2008]. Kasteel et al. [2005] obtained high-resolution spatial maps of brilliant blue (BB) dye concentrations following the image analysis method of Forrer et al. [2000] using single calibration relationship between BB concentration and color spectra. Alternatively, and for relatively larger cracks, Dasog and Shashidhara [1993] quantified crack volumes by filling cracks with sand, whereas Deeks et al. [1999] traced large pores (>1 mm) by drawing them onto overhead projection paper using chinograph pencils. Zein El Abedine and Robinson [1971] developed a procedure to quantify depth, width, and volume of relatively large vertisol cracks by using thin flexible metal probes (for depth) and by calculating the number and width of surface cracks over two intersecting 20 m long straight lines. A variation of this approach (taking width of cracks over a series of 1 m diameter semicircles) was also developed by Ringrose-Voase and Sanidad [1996], allowing different shaped models for the crack cross section (triangular or V shaped, rectangular, and square-root shaped). Bhushan and Sharma [2002] and Bandyopadhyay et al. [2003] evaluated soil cracking in 1 m × 1 m plots by tracing the length of the cracking network over the entire plot and calculating the crack depth at different intervals with 1.5 mm and 2 mm diameter rods, respectively. They calculated crack width at different intervals (with Bhushan and Sharma [2002] dividing cracks into five width classes ranging from <5 mm to >20 mm) and calculated crack volume assuming triangular shape of cracks. Flowers and Lal [1999] obtained surface cracking area by digitizing photographs of 0.4 m × 0.4 m plots with crack depth obtained using a 1 mm rod. Mitchell and van Genuchten [1993] observed cracking patterns from the natural process of freezing in the field. As to earthworm burrows, Lighthart et al. [1993] studied their spatial structure using serial sectioning of the soil. Connectivity of earthworm burrows and cracks was assessed by smoke injection method [Shipitalo and Gibbs, 2000] and by pouring dye into cracks adjacent to earthworm burrows [Shipitalo et al., 2004].

[8] The effect of vegetation cover was also studied by different researchers, leading Dasog et al. [1988] to show that vegetation and management are major contributors to the soil cracking potential in addition to moisture and swelling potential. Furthermore, Dasog and Shashidhara [1993] showed through crack measurements at different crop covers that crack volume is the most suitable crack characterization index (among crack length, depth, width, and volume). They showed (for the same soil type) that crack width and depth was smallest in fallow plots that had the highest crack length. Crack depth was highest for safflower plots because of their deep and efficient root system. Overall, safflower plots had the highest crack volume, followed by wheat, chickpea, and fallow plots.

[9] Some examples of empirical approximations include the development of pedotransfer functions relating soil cracking properties (area, length, width, size of pedds) to soil parameters including water content, coefficient linear extensibility (COLE) index, bulk density, and time after drainage [Kosmas et al., 1991; Jassogne et al., 1994; Bandyopadhyay et al., 2003; Ringrose-Voase and Sanidad, 1996]. Another example is the work of Germann and Beven [1981c] who developed an empirical approximation linking saturated macropore to the square of macroporosity. They proposed [Germann and Beven, 1981a, 1981b] the estimation of preferential paths volume from the potential curve, where they modeled macropore assuming laminar film flow. Others [Zein El Abedine and Robinson, 1971; Yaalon and Kalmar, 1984; Waller and Wallender, 1993] related the volume of cracks to the duration following rainfall events or the irrigation process.

[10] In addition to visualization, cracking networks were predicted geometrically using the fractal approach. For example, two-dimensional porous structures with different pseudolevels of aggregation and cracking patterns were constructed using fractal fragmentation algorithms [Perrier et al., 1995]. Another approach was used by Beven and Clarke [1986] who stochastically modeled the spatial distribution or occurrence of preferential flow channels.

[11] Moreover, some researchers approached crack network prediction following the stress approach. For example, Konrad and Ayad [1997] developed CRACK, a linear elastic fracture mechanics (LEFM) model that predicts the average crack depth and spacing between primary cracks assuming homogenous soils. Moreover, Chertkov and Ravina [1998] modeled cracking network geometry of swelling soils due to shrinkage based on similarity between cracks in rocks and swelling soils. Vogel et al. [2005b, p. 223] presented a linear elastic model that mimics the shrinkage-cracking process in a model of lattice of Hookean springs of finite strength and demonstrated that 2-D cracking pattern can be quantified by the "evolution of Minkowski densities during cracking formation."

[12] While the above-described reviews show an extensive amount of methodologies and tools to assess and deal with preferential flow paths, they all come with limitations that restrict their use as standard methods for the characterization of preferential paths in the field. Some are not scalable to the field scale, whereas others rely on soil physical methods for quantifying volumes of shrinkage cracks (see Abou Najm [2009] for a review of those methods) and are thus unable to quantify biological macro-
pores or cracking pattern. Furthermore, field methods sampling crack width and depth along predefined paths or within predefined plots simplify crack geometry [e.g., Zein El Abedine and Robinson, 1971] and thus are not suitable for complex pore networks. Thus, there is a need for characterization methods that can quantify and assess the evolution of preferential paths in the field.

[13] This paper presents methodologies (1) for monitoring the evolution of surface cracks using digital imagery and (2) for 3-D visualization of the preferential flow paths network in soils using liquid latex. Results from the Savage clay loam soil in Montana and the clay loam Chalmers soil in Indiana are presented with discussion covering some of the factors contributing to the evolution of preferential paths in the field.

2. Materials and Methods

2.1. Materials

[14] The experimental procedure was conducted in three fields: (1) a bare clay loam Savage soil adjacent to a conventionally tilled field that has been in a 2 year sugar beet/small plants (weeds) rotation; no nitrogen was injected prior to plantation; (2) for 3-D visualization of the preferential flow paths network in soils using liquid latex. Results from the Savage clay loam soil in Montana and the clay loam Chalmers soil in Indiana are presented with discussion covering some of the factors contributing to the evolution of preferential paths in the field.

2.2. Methods

2.2.1. Methodology to Monitor the Evolution of Surface Cracks

[16] Series of digital images for a fixed frame of predefined dimensions were captured in the field (Figure 2) along with (1) multilayer water content, (2) temperature measurements, and (3) weather data (temperature, rainfall intensity). The dimensions of the frame (32 cm x 45 cm) were defined so that at least 10 mature peds could be captured within the frame when the soil was dry. A 6 megapixel digital camera (Canon Powershot 3S IS) was chosen because of its good resolution and because of the presence of an intervelometer option allowing the camera to automatically take up to 100 shots at fixed intervals of time (up to 1 h per interval). The camera was mounted on top of the frame and was protected inside an insulated box from weather. Images were collected on an hourly basis over the same location during two seasons in 2007 (between 17 September and 23 October) and 2008 at the Savage soil field site in Sidney. (Because of technical difficulties, the following periods were covered during the second season: 7–14 August, 2–30 September, and 7–27 October.) Watermark water potential and temperature sensors (Irrometer, Riverside, California, www.irrometer.com) were installed at multiple soil depths for future assessment and the anticipated correlation of surface crack area to water content at various soil depths.

2.2.2. Methodology for the 3-D Visualization and Characterization of Preferential Flow Paths

[17] As explained in section 1, the pore structure inside the soil matrix may be estimated by the soil's shrinkage and swelling properties. Our interest in this study is to characterize the preferential paths structure beyond the inter-aggregate pores.

[18] The methodology adopted to visualize and characterize preferential paths is to pour liquid latex into preferential paths from the surface, wait for the latex to solidify, excavate the latex, and characterize the crack volume as a function of soil depth using the water displacement method.

[19] In the soil literature, similar "casting" material was used for the characterization of earthworm burrows and biological pores. For example, Vandenberggaard et al. [2000] combined polyester resin containing a fluorescent dye and digital image analysis to access the pore structure of small soil blocks. Shipitalo and Gibbs [2000] and Shipitalo et al. [2004] characterized earthworm burrows by pouring fiberglass resin into the burrows, whereas Garner [1953] used liquid latex. A similar method was adopted by E. Kladiyko (personal communication, 2008). Our methodology builds

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### Table 1. Properties of the Two Soils Used in the Analysis

<table>
<thead>
<tr>
<th>Property</th>
<th>Savage Soil Series</th>
<th>Chalmers Soil Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent sand</td>
<td>24</td>
<td>15</td>
</tr>
<tr>
<td>Percent silt</td>
<td>42</td>
<td>45</td>
</tr>
<tr>
<td>Percent clay</td>
<td>34</td>
<td>40</td>
</tr>
<tr>
<td>Soil textural class</td>
<td>clay loam</td>
<td>clay loam</td>
</tr>
<tr>
<td>Percent organic matter</td>
<td>1.6</td>
<td>4.3</td>
</tr>
<tr>
<td>pH</td>
<td>8.2–8.6</td>
<td>5.7–6.5</td>
</tr>
<tr>
<td>CEC (meq/100 g)</td>
<td>22.7–24.7</td>
<td>24.1–28.8</td>
</tr>
<tr>
<td>Magnesium (ppm)</td>
<td>482–936</td>
<td>810–825</td>
</tr>
<tr>
<td>Potassium (ppm)</td>
<td>104–183</td>
<td>215–226</td>
</tr>
<tr>
<td>Treatment</td>
<td>bare soil inside the frame; small plants (weeds) inside the sampling area were pinched by hand and removed; plants outside the sampling area were pulled or spayed with glyphosate; the area was not plowed and was neither tilled nor fertilized</td>
<td>field 1 (corn): this is a conventional tillage field on corn/soybean rotation; nitrogen was injected at 15–22 cm depth prior to plantation at 75 cm spacing field 2 (soybean): this is a no-till field on corn/soybean rotation; no nitrogen was injected prior to plantation; soybean was planted with starter fertilizer at 75 cm spacing</td>
</tr>
</tbody>
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on the successes of those field experiments to propose a complete method capable of characterizing not only earthworm burrows but also all the components of preferential flow paths (as defined in this paper) in soil. It is capable of obtaining relevant hydrologic data using the water displacement method. The methodology is summarized below:

1. Carefully select a representative area of the cracking network in the field for the frame dimensions of 32 cm x 45 cm. Collect field notes and digital photos of the surface cracking network in and around the frame (Figure 3a).

2. Sample in duplicates (two frames at a time) to check the variability of the preferential paths at similar field conditions.

3. Seal the boundaries of the frame with relatively wet soil to ensure that latex will not escape the frame area because of surface roughness (Figure 3b).

4. Pour liquid latex slowly inside the preferential paths and continue to add the liquid latex until all the pores are sealed and the whole frame area is saturated with liquid latex (Figure 3c). This may take over an hour, as the latex continues to fill deeper and smaller cracks, thus requiring additional latex to be added from the surface. The liquid latex material used was a high-tear-strength latex rubber with minimum recovery (hysteresis) of 95% and 60% total solids.

5. Collect soil cores to measure the water content (oven drying method) and the bulk density (core method) at multiple depth intervals (Figure 3d).

6. The liquid latex usually solidifies within 8–12 h. To remove the latex from the ground, two different approaches are adopted. The first approach is simple and requires careful excavation around the frame using a shovel (Figure 3e). This approach is ideal for shallow preferential paths with the majority of cracks terminating at around 5 cm depth. The second approach is more cumbersome, as it requires careful excavation using smaller tools (e.g., screwdrivers) to remove soil aggregates from around the dry latex without destroying the latex structure (Figures 3f and 3g). This approach is ideal for deep cracks and complex preferential paths networks.

7. After careful excavation, clean the latex to remove all remaining soil particles and attach the latex frame into a rigid surface. Water displacement method will be used by gradually inserting the latex in a water tub (Figure 3h) to estimate the volume of preferential paths for each depth interval starting with zero at the lowest preferential paths depth. Add detergent to the water before dipping the latex frames if surface tension is a concern.

For this paper, eight frames (in four “duplicates”) were sampled in the Savage field. Furthermore, four frames were sampled in the Chalmers soybean field (in two “duplicates”) and four frames in the Chalmers cornfield (because of field problem, one duplicate and two single frames were sampled). In some cases, lateral cracks were observed extending beyond the area of the frame. Although lateral cracks are important to understand the connectivity of the preferential paths network (in the lateral direction), reporting the total volume, including those lateral cracks,
Figure 3. Procedure for 3-D preferential flow visualization using liquid latex. See color version of this figure in the HTML.
may be an overestimate of the total preferential paths volume per unit area of the soil. Thus, and for this study, the volume of lateral cracks was calculated also using the water displacement method (after the total volume was also calculated) and then subtracted from the total volume (assuming uniform lateral crack distribution as function of depth). An alternative method that was not tested in this study is to cut the lateral cracks from the latex frame before applying the water displacement method. Taking field notes and photographs during the latex excavation was very helpful in readjusting the latex network to be as close as possible to the original preferential paths network. Finally, soil surface roughness (causing large volumes of latex to accumulate at the top few centimeters of the frame) may play a major role in increasing the volume of latex in the last 1–2 cm. To tackle this problem, an “if statement” was developed in Excel to check for each depth interval whether the volume of cracks exceeds an upper predefined threshold. This threshold was estimated at 10% of the total volume, referring to a maximum surface cracking area of around 10%.

3. Results and Discussion
3.1. Surface Cracking Pattern

[28] Both recurring (returning with same location) and changing surface cracking patterns have been reported in the soil literature [Kosmas et al., 1991; Wells et al., 2003]. Wells et al. [2003] noted that surface cracks were not repetitive in the lysimeter experiment with the Sharkey clay. Waller and Wallender [1993], on the other hand, conducted field shrinkage and cracking analysis to study the effect of salinity on the cracking behavior of soil and found out that shrinkage and swelling increased with salinity and that the soil peds reformed in the same shape and location after irrigation. White [1970] studied giant desiccation cracks and concluded that their formation is an evolution of multiple years where they undergo several shrinkage-swelling cycles. Moreover, Kosmas et al. [1991] suggested that cracks that completely seal do not reform at the same location in the next drying cycle, whereas cracks leaving “shallow U-shaped traces” on the surface develop in the same place.

[29] Analysis of the hourly digital images of the Savage soil revealed that the soil maintains the cracking pattern as long as the cracks are not totally sealed. Small rainfall events (with insufficient amounts of water to cause complete soil swelling or crack closure) did not alter the cracking pattern in the next drying cycle. However, strong rainfall events (and later snow) where all cracks within the frame were completely sealed caused alteration in the cracking pattern. Here, it is important to note that change in cracking pattern is scale dependent. Digital imagery analysis is used to check whether cracks returned to the exact same location after they were sealed. At that fine scale (pixel dimension ranged between 0.19 and 0.33 mm, i.e., pixel area of 0.03–0.11 mm²), cracking pattern for the Savage soil was not repetitive (Figure 4), since cracks did not return to the exact same location (or pixels). However, at coarser scales where the average area of the ped is what matters, preliminary inspection of the average size of surface peds did not change much irrespective of the rainfall intensity. Such observation, however, requires more quantitative and detailed analysis (where multiple peds must be digitized at different time intervals and their corresponding areas must be compared) that is beyond the scope of this paper.

[30] Figure 4 shows a digitized crack network (in red) from one image superimposed on top of the crack network of the same area but after a large rainfall event. It is clear that the crack network is not the same, although the size of peds has been maintained to some extent. Figure 5 shows
Figure 5. Snapshots of the crack network of the same area at different time intervals showing the change in cracking pattern (following rainfall or snow events). See color version of this figure in the HTML.

series of snapshots of the crack network of the same area at different times showing the change in cracking pattern following major rainfall events (e.g., 7 October) or snow events (e.g., 13 October). On the other hand, the cracking network did not seem to change much between 3 and 11 September, although some relatively small showers took place (see the intensity and cumulative rainfall intensity graph in Figure 5).

3.2. Three-Dimensional Preferential Paths: Visualization Using Liquid Latex

[31] In comparison with the existing method, the latex method provides more detail about the shape and complexity of the preferential flow paths network (Figure 6) than the dye tracer, sand filling, or smoke injection techniques or other field techniques. It works for more complicated preferential flow paths than those analyzed with the simple methods proposed by Zein El Abedine and Robinson [1971], Ringrose-Voase and Sanidad [1996], or Bandyopadhyay et al. [2003]. In other words, preferential flow paths need not be triangular or simple in geometry to deduce their volume from simple width, length, and depth calculations. Moreover, they do not have to be vertical and larger than the metal rod diameter of 1–3 mm (as used in the previously mentioned studies) to be captured. In fact, the use of thin metal rods to estimate the depth of the cracks in the Chalmers or Savage soil gave much lower estimates of crack depth than those detected by the latex method because of the irregular cracking shapes.

[32] In comparison with dye tracer methods, Kasteel et al. [2005] showed results of 3-D BB concentrations by serial sectioning of four 1 m² plots using image analysis methods. They explained some of the technical challenges as they observed small isolated surfaces and disconnections in the preferential flow pathways that they attributed to incorrect pixel assignments and the use of “relatively coarse vertical sampling distance” of 5 and 10 cm [Kasteel et al., 2005]. This problem is resolved in the latex method because of its capability to show continuous 3-D network.

3.2.1. Pore Classification

[33] The most widely accepted morphologic pore classification was set by Brewer [1976] who identified preferential paths into six main types: (1) packing pores, (2) vughs, (3) channels, (4) planes, (5) chambers, and (6) vesicles (see VandenBygaart et al. [2000] for brief description). Such classifications may provide very helpful hints to hydrologic models that still observe preferential paths as single lumped entities usually abstracted by accounting for their effect through another flow parameter or sink in the continuity equation. Thus, linking morphologic pore classification with hydraulic functionality (such as the classification of Bouma et al. [1977], Beven and Germann [1982], and Chen et al., 1993)) is important to the advancement of preferential flow modeling. This however requires additional advance-
Figure 6. Hydrological functionality and types of preferential flows. See color version of this figure in the HTML.
ments in morphometric methodologies to enable visualizing preferential paths and dividing their total volumes depending on their types, functionality, connectivity, and evolution. The method provided in this paper is a step toward achieving this link.

Figure 6 shows various types of preferential paths existing in the Chalmers soil. For example, Figures 6a and 6g show a lateral crack extending beyond the ground from the upper right corner of the latex frame. This is an indication of crack network connectivity in the subsurface even if this is not clear from the surface cracks. It was observed that lateral cracks tend to extend more beyond the frame dimension as the soil gets drier or as the period from the last rainfall or irrigation event increases. Figure 6b shows the diversity of preferential paths types under the no-till Chalmers soil, where the linear cylindrical pores represent earthworm channels. This is an interesting observation for some of the shallow earthworm channels, as it is clear in Figure 6b that two of those channels are connected to the surface from two points forming an arc-like preferential path. Figure 6c presents another interesting type of preferential paths. It is characterized by very complex structure and interconnectivity similar to the sponge network. This type of preferential paths has most probably evolved because of the combination of tillage, biodegradation of roots in the subsoil layers, and damage to soil’s interaggregate structure due to tillage. This type of preferential paths was only observed in the Chalmers soil at the four frames of the tilled cornfield. In terms of hydrologic functionality, this type of preferential paths is very effective at spreading the water (and whatever chemicals it carries) into a large volume of soil because of its wide and complex network, which means a large surface area of preferential paths per unit volume. Another type of earthworm channels is shown in Figures 6d and 6f where preferential paths channels are deeper and more vertical. Their depth varied between as shallow as 5–10 cm and as deep as 100 cm as the one shown in Figure 6f. From the two Chalmers fields, it was observed that earthworm channels tend to increase in depth, density, and complexity with no-till soils compared with tilled soils. This observation is common in the soil literature as morphometric image analysis, and population count studies have revealed that tillage has major impact on decreasing earthworm channels and populations compared with no-till fields [VandenBygaart et al., 2000; Kladivko, 2001]. Finally, Figure 6e shows interesting preferential paths chambers (ranging in size from few millimeters to around 5 cm) that form at the ends of some of the channels. Brewer [1976] attributed their presence to fauna activity, since they exist at the end of earthworm burrows or ant or termite galleries. Other potential explanations include (1) the biodegradation of roots that contain nodules [Black, 1984] that form because of nitrogen fixation and bacterial activities (rhizobia) or (2) air entrapment during drying process following heavy rainfall [Pagliai et al., 1981; Pagliai, 1988].
3.2.2. Preferential Paths Connectivity

[35] It is very important to understand how preferential paths are connected. The latex experiments provided valuable insights on this concept. Figure 7a shows that some preferential paths under the selected frame (Chalmers soil, cornfield) may not be filled with latex because they were not connected to the preferential paths network below the frame. In this specific example, the earthworm channel shown in Figure 7a may have originated somewhere outside the frame (where the latex was poured from the surface) or may simply have been blocked at the surface (possibly because of planting or fertilizing activities).

[36] Figure 7b shows another dimension of connectivity with one of the frames taken at the Chalmers tilled cornfield. It is clear from Figure 7b that there is a major crack extending beyond the frame dimension. However, its extent and size were quantified from pouring the latex inside the frame dimension and observing the preferential paths network extending more than double the dimension as a lateral crack.

3.3. Effect of Vegetation Cover

[37] Johnston and Hill [1945, p. 28] observed different cracking patterns under different types of vegetation when planted in rows. They observed a "large continuous crack in the row middle with other cracks meeting it at approximate right angles" for corn and cotton vegetation. Similar behavior was observed by Sharma and Verma [1977] under wheat crop, by Yoshida and Adachi [2001] under paddy rice planted in rows, and in the Chalmers cornfield where four latex frames were taken.

[38] This pattern may theoretically be justified knowing that suction is highest under the corn plants because of transpiration, resulting in highest shrinkage around the roots. This leads to the highest tensile stress at the interface with the high suction area that (given the field conditions) happens to be at the row middle where the soil is weakest (having the highest water content). The combination of high tensile stress and weaker soil will eventually cause cracking to take place when the tensile stresses exceed the tensile strength. Yoshida and Adachi [2004] presented a numerical model using Biot's 2-D consolidation theory to predict crack generation under row-planted vegetation. Their model showed that the linear inter-row cracks are highly dependent on row spacing, transpiration rate (water fluxes), thickness of relevant soil layers, soil strength, and moisture conditions. In fact, they shared results from experimental paddy fields where two inter-row cracks developed when row spacing was increased from 60 cm to 90 cm.
Figure 9. Preferential flow volumes, bulk density (g cm⁻³), and gravimetric water content (%) for the eight latex frames obtained from the Savage soil. See color version of this figure in the HTML.

[39] Other factors that may influence the cracking pattern include field management, type of machinery used, and soil compaction level. Figure 8 shows (in the Chalmers cornfield) a straight preferential path that was observed 16–18 cm below the surface extending around 150 cm in both sides. The straight-line shape may imply that its formation is attributed to some mechanically induced activity. It was later discovered that the blade used for nitrogen injection prior to corn plantation caused this cavitation at the observed depth, although the upper part of the induced cut was sealed with time. Interestingly, nitrogen injection lining did not coincide with the middle of the cornrows contrary to the main preferential flow network. In fact, a distance of around 20 cm (Figure 8) between the observed deep straight-line pore and the main crack network (which passes in the middle of the cornrow) may be an indication that nitrogen injection process had little effect on the evolution of the main preferential flow network.

[40] On the other hand, patterns of preferential flow paths are not always simple. Johnston and Hill [1945] observed more uniform, mud-like cracking patterns in grain sorghum vegetation. They attributed this pattern mainly to the more
uniformly spread root system of sorghum compared with the concentrated root system for cotton and corn. We observed a similar behavior for soybean in the Chalmers no-till field where preferential paths patterns were similar to mud cracking pattern. However, we argue that it may not only be the root structure of soybean but may rather be the collective effects of all factors described in the previous section that caused this pattern.

3.4. Results From Water Displacement: Preferential Paths Representation

[41] Any potential use of morphologic results in hydrologic models requires unit compatibility. For example, reporting number of cracks or the average width and depth per unit length may be incompatible with hydrologic models. Thus, we propose to incorporate the concepts of representative elementary volume (REV) or structure representative elementary volume (SREV) [Braudeau and Mohtar, 2009] in preferential paths characterization as a first step toward the coupling of preferential paths characterization methods and hydrologic modeling.

[42] For REV [see Bear, 1972; Hassanizadeh and Gray, 1979; Baveye and Sposito, 1984], the soil is composed of layers of fixed volumes that allow the soil, water, and air to move across each layer’s boundary. An ideal representation of preferential paths under such representation is volumetric in terms of volume of preferential paths per unit volume of soil layer (h_{layer,n}) across the soil profile. Thus,

\[ \text{REV} \quad V_{\text{preferential paths},n} = \frac{V_{\text{preferential paths},n}}{A_{\text{latex frame}} \times h_{\text{layer},n}}, \]

where \( V_{\text{preferential paths},n} \) is the volume of preferential paths under the area of the latex frame (45 cm \times 32 cm) \( A_{\text{latex frame}} \) in layer \( n \) and \( V_{\text{preferential paths},n} \) is the volume of preferential paths per unit volume of soil at layer \( n \).

[43] For SREV [Braudeau and Mohtar, 2009], the soil is composed of layers of fixed soil mass that allow only the water and air to move across each layer’s boundary. An ideal representation of preferential paths under such representation is gravimetric in terms of volume of preferential paths per unit mass of each soil layer across the soil profile, \( M_{\text{solids},n} \). Thus,

\[ \text{SREV} \quad V_{\text{preferential paths},n} = \frac{V_{\text{preferential paths},n}}{M_{\text{solids},n}}. \]

[44] As the results in the next sections would show, we would like to stress that no matter how the data are presented (REV, SREV, or any other way), results obtained from one latex method experiment present the preferential flow volumes at a specific field and moisture condition. Thus, multiple frames at different field conditions are required to understand the patterns of evolution of those preferential flow paths. Therefore, a complete framework for the coupling between this method and hydrologic models is beyond the scope of this paper and can only be established with further testing of the latex method under different soils as well as moisture and field conditions.

3.4.1. Results From the Savage Soil, Montana

[45] Figure 9 presents the results of the cumulative volume of preferential paths (\( V_{\text{preferential paths},n} \)) as function of depth, starting with zero value at the point of deepest preferential path for each frame. For each frame, a graph showing the variation of water content and bulk density with depth is also provided. Results show that each pair of latex frames (collected at the same day and from close locations) provided comparable volumes ranging from as good as (1096, 1120) cm³ for the (F3, F4) pair to (798, 508) cm³ for the (F7, F8) pair with an overall \( R^2 = 0.65 \). It was observed (Figure 9 for Savage and Figure 11 for Chalmers) that pairs with the largest variability (in terms of total volumes) have bulk density and water content profiles that are different because of the variability at the field scale. One way to address this heterogeneity and maybe improve the repetitiveness of frame replicates is to increase the number of frames per trial and consider reviewing the frame locations.

Table 2. Average Hourly Temperature, Relative Humidity, Wind Speed, and Cumulative Rainfall for the Past 2, 5, and 10 Days Before Pouring Latex in the Savage Soil Field^a

<table>
<thead>
<tr>
<th></th>
<th>Temperature, °C</th>
<th>Relative Humidity</th>
<th>Wind Speed, mph</th>
<th>Maximum Wind Speed, mph</th>
<th>Solar Radiation</th>
<th>Cumulative Rainfall, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savage Soil Frames 1 and 2, 30 July 2008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average 2-day</td>
<td>21.93</td>
<td>57.3</td>
<td>5.57</td>
<td>10.77</td>
<td>27.67</td>
<td>0.11</td>
</tr>
<tr>
<td>Average 5-day</td>
<td>22.66</td>
<td>60.2</td>
<td>5.13</td>
<td>10.41</td>
<td>25.76</td>
<td>1.11</td>
</tr>
<tr>
<td>Average 10-day</td>
<td>23.04</td>
<td>61.0</td>
<td>5.51</td>
<td>11.10</td>
<td>24.44</td>
<td>1.32</td>
</tr>
<tr>
<td>Average 2-day</td>
<td>21.04</td>
<td>50.9</td>
<td>9.08</td>
<td>17.02</td>
<td>15.53</td>
<td>0.00</td>
</tr>
<tr>
<td>Average 5-day</td>
<td>18.81</td>
<td>58.6</td>
<td>6.81</td>
<td>12.77</td>
<td>18.00</td>
<td>0.03</td>
</tr>
<tr>
<td>Average 10-day</td>
<td>21.50</td>
<td>55.0</td>
<td>6.41</td>
<td>12.37</td>
<td>19.42</td>
<td>0.71</td>
</tr>
<tr>
<td>Average 2-day</td>
<td>11.93</td>
<td>83.2</td>
<td>10.94</td>
<td>17.05</td>
<td>8.19</td>
<td>0.95</td>
</tr>
<tr>
<td>Average 5-day</td>
<td>17.54</td>
<td>58.2</td>
<td>8.09</td>
<td>13.65</td>
<td>14.60</td>
<td>0.95</td>
</tr>
<tr>
<td>Average 10-day</td>
<td>18.58</td>
<td>56.2</td>
<td>7.30</td>
<td>13.08</td>
<td>15.98</td>
<td>0.95</td>
</tr>
<tr>
<td>Average 2-day</td>
<td>13.62</td>
<td>59.9</td>
<td>2.79</td>
<td>5.61</td>
<td>15.98</td>
<td>0.00</td>
</tr>
<tr>
<td>Average 5-day</td>
<td>12.87</td>
<td>55.5</td>
<td>4.65</td>
<td>8.74</td>
<td>14.85</td>
<td>0.00</td>
</tr>
<tr>
<td>Average 10-day</td>
<td>12.75</td>
<td>62.0</td>
<td>5.15</td>
<td>9.56</td>
<td>13.47</td>
<td>0.47</td>
</tr>
</tbody>
</table>

^a Average 2-day is the average of the last 2-day readings (last 48 hourly readings) starting at 1:00 P.M. of the day of latex pouring; average 5-day is the average of the last 5-day readings (last 120 hourly readings) starting at 1:00 P.M. of the day of latex pouring; average 10-day is the average of the last 10-day readings (last 240 hourly readings) starting at 1:00 P.M. of the day of latex pouring. 

As presented (REV, SREV, or any other way), results obtained from one latex method experiment present the preferential flow volumes at a specific field and moisture condition. Thus, multiple frames at different field conditions are required to understand the patterns of evolution of those preferential flow paths. Therefore, a complete framework for the coupling between this method and hydrologic models is beyond the scope of this paper and can only be established with further testing of the latex method under different soils as well as moisture and field conditions.
Figure 10. Sensitivity of the total volume of cracks in the eight latex frames of the savage soil to cumulative rainfall, maximum wind speed, solar radiation, and average hourly temperature, all taken as 2, 5, and 10 day averages, as well as the sensitivity of total volume of cracks to bulk density and gravimetric water content at the 5–10 cm soil layer. Only linear correlation between \( V_{\text{preferential paths}} \) and other data was explored in this study. See color version of this figure in the HTML.

Provided good starting point, the arbitrary frame dimension of 45 cm \( \times \) 32 cm should not be considered a standard for all soil types. Our approach was to use the number of peds per frame as a guideline and make sure that at least 10 mature soil peds were included within the representative frame area. Testing the effect of increasing the frame dimension on improving repetitiveness of the total volume of latex is highly recommended.

Results from Figure 9 show that the preferential paths in the savage soil are mostly due to surface shrinkage attributed to evaporation. Most of the preferential paths terminate at depths around 5 cm. This finding has triggered the attention toward checking the sensitivity of the total volume of cracks obtained for each frame to weather conditions: 2 days, 5 days, and 10 days prior to latex pouring (Table 2). Sensitivity (Figure 10) of the total volume of cracks in the eight latex frames of the savage soil was tested against cumulative rainfall and the average hourly wind speed, maximum wind speed, relative humidity, solar radiation, and temperature (over the three durations of 2, 5, and 10 days). Moreover, the sensitivity of total volume of cracks to bulk density and gravimetric water content at the 5–10 cm soil layer was assessed. It is clear from Figure 10 that none of the mentioned parameters is strictly governing the shrinkage behavior of the Savage soil. Such results were expected given the fact that none of the parameters or factors assessed is exclusively and fundamentally governing this complex behavior. Linear correlations between the 2 day average hourly temperatures \( (R^2 = 0.81) \) and 2 day average hourly solar radiation \( (R^2 = 0.60) \) were however obtained. Trends also showed that as the period increased, the correlation with the total volume of preferential paths (mostly shrinkage cracks in this case) tended to decrease (Figure 10). This may be attributed to the following reasons: (1) the formation of surface shrinkage seems more sensitive to the temperature or solar radiation in the
and (874, 827) cm$^3$ for the (Corn2, Corn3) pair). However, latex volumes in the cornfield were higher, most probably because of the different preferential flow patterns and root systems.

For the com frames, preferential paths volumes can be explained by the fact that a 5 cm rainfall event took place right after the first com frame, followed by a period of no rain or irrigation. This caused the second and third frames (collected in the same day) to show total volume of preferential paths less than the first frame. As the soil continued

Figure 11. Preferential flow volumes, bulk density (g cm$^{-3}$), and gravimetric water content (%) for the four latex frames obtained from the Chalmers tilled cornfield and the four latex frames obtained from the Chalmers no-till soy field. See color version of this figure in the HTML.

3.4.2. Results From the Chalmers Soil, Indiana

Figure 11 present the preferential paths volumes for the latex frames obtained from the corn and soybean Chalmers soil fields. The first and second soybean latex frames as well as the second and third corn latex frames were collected in the same period (soybean pair: 22 September 2008; corn pair: 25 September 2008). Each pair gave comparable results ((623, 617) cm$^3$ for the (Soy1, Soy2) pair and (874, 827) cm$^3$ for the (Corn2, Corn3) pair). However, latex volumes in the cornfield were higher, most probably because of the different preferential flow patterns and root systems.

For the corn frames, preferential paths volumes can be explained by the fact that a 5 cm rainfall event took place right after the first corn frame, followed by a period of no rain or irrigation. This caused the second and third frames (collected in the same day) to show total volume of preferential paths less than the first frame. As the soil continued
to dry, the fourth frame showed larger preferential paths volumes than the previous pair. In terms of repetitiveness, only the (Corn2, Corn3) pair gave very close latex volumes (874, 827 cm$^3$).

[50] As to the soybean frames, each pair of the four frames was collected at the same day with 1 week between the two pairs. Higher volumes of preferential paths in the second pair confirms the trend (see Sharma and Verma [1977], Ringrose-Voase and Sanidt [1996], and Bandyopadhyay et al. [2003], among others) that the total preferential paths volume increases as the period from the last rainfall or irrigation event increases because of the obvious effects of infiltration and evapotranspiration. The difference in preferential paths depth between the third and fourth frames in the soybean field is due to the presence of one deep earthworm burrow (100 cm) in the third frame (as shown in Figure 6f). Repetitiveness seems promising with values as good as (623, 617) cm$^3$ for the (Soy1, Soy2) pair and to a lesser extent (1177, 729) cm$^3$ for the (Soy3, Soy4) pair. However, results of two pairs are not enough to assess the repetitiveness from a statistical perspective.

3.4.3. Estimation of Volume of Shrinkage Cracks and Biological Preferential Paths

[50] A future step is to be able to divide the total volume of preferential paths ($V_{\text{preferential paths}}$) into $V_{\text{cracks, fissures}}$ and $V_{\text{biological}}$ (as described in equation (2)) or more generally into the various preferential paths classes (given a certain criteria). In this paper, we will introduce a proposed methodology allowing for more detailed preferential paths characterization per layer.

[51] The methodology is simply to cut or trim the latex starting from the lowest depth at the desired depth intervals. Once the latex trims are separated from the main latex frame, functional classification of the latex trims can be applied where volumes of shrinkage-induced cracks (for example) can be obtained separately from biological preferential paths for each depth layer. While the distinction between some classes may not be obvious for some of the preferential paths patterns, it is quite clear when it comes to distinguish between plane-like shrinkage cracks and round and long earthworm burrows. An additional advantage of this method is that it is more accurate than the water displacement method where surface water tension (even with the use of detergents) is a source of error for the volume estimation, especially for small volume increments. In this case, latex trims are weighed and their volume is more accurately determined. The only disadvantage of this method is that it is destructive and may be performed after all observations and analyses on the latex frame are concluded.

4. Concluding Recommendations and Remarks

[52] A new methodology to estimate and characterize soil's preferential flow paths was presented and tested on two soils with different vegetations and management methods. Results have led to the following conclusions:

[53] 1. Digital imagery analysis of the Savage soil shows that soils with shallow surface cracks may exhibit preferential paths patterns that are not repetitive.

[54] 2. Field observations and latex frames showed that biological paths are more active in no-till fields compared with fields with conventional tillage.

[55] 3. Vegetation type, row spacing, and soil management showed major effect on preferential paths patterns with mud-like preferential paths in the no-till soybean field compared with linear large preferential paths parallel to the middle row of tilled cornfields in the Chalmers soil.

[56] 4. Total preferential paths volume (per soil depth layer) may be estimated by water displacement method using the latex method.

[57] 5. Given the distinction between macropores and preferential flow paths, the liquid latex method allows for the differentiation between the inter- and intra-aggregate porosities of the soil matrix from one side and preferential flow paths from the other. This will allow the soil structure to be observed from a triple-porosity perspective with the first two referring to the soil matrix and the third being the result of shrinkage and biological activities.

[58] Additional research is recommended to understand the evolution of the preferential paths volumes probably by multiple-frame analysis at different moisture conditions, shrinkage/swelling paths (to test for potential hysteresis), soil managements, slopes, and vegetation types. Moreover, a comprehensive and theoretical framework explaining the cracking behavior and biological activities is needed. This requires the coupling of shrinkage/swelling dynamics and soil's mechanical behavior with understanding of the effects of soil's structural evolution, field morphology, cropping types and patterns, field management, and fauna/flora activities. With respect to shrinkage/swelling, their dynamics are not fully understood. In fact, without proper understanding of those dynamics, factors like initial field moisture content, rainfall intensity, and hydrophobicity will continue to be monitored empirically, and their effect on soil water interaction may not be completely understood.

[59] In addition, a study on the effect of frame dimensions with respect to replicate repetitiveness and representation of field behavior is highly recommended. Moreover, we believe that further classification of preferential paths may be achieved by latex-destructive method described in section 3.4.3. Finally, we hope that this method will help answer many of the pending "how" and "why" questions within the domain of preferential flow paths and will aid the research targeting their characterization and modeling.

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References


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