Dye Tracers Reveal Potential Edge-Flow Effects in Undisturbed Lysimeters Sealed with Petrolatum

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Undisturbed soil lysimeters are widely used to study water and solute transport. During or following lysimeter collection, it is common to implement measures aimed at limiting edge flow at the interface between the soil and the lysimeter casing. The objective of this study was to use dye tracers to evaluate the effectiveness of petrolatum in suppressing edge flow in lysimeters. Eight undisturbed square lysimeters (900 cm²) with removable spacers lining the inside of the casing were collected from an agricultural field. Spacers were removed from four lysimeters and liquefied petroleum jelly was poured into the gap created after spacer removal. The lysimeters were air dried for 150 d, after which two sealed and two unsealed lysimeters were resaturated. All lysimeters were then subjected to a 1-h rainfall simulation (3.3 cm h⁻¹), with dye added to the rainfall. Rewetting both sealed and unsealed lysimeters resulted in less horizontal dye coverage compared with the dry treatments due to reduced matrix–macropore interaction. Dye staining patterns for unsealed lysimeters showed that edge flow was the predominant flow pathway through the soil regardless of soil moisture status. While sealing lysimeters with petroleum jelly largely limited flow between the soil and the casing, shrinkage cracks formed during drying that coincided with the extent of petroleum jelly infiltration into the soil. This new hydrophobic edge served as a preferential flow pathway in the sealed lysimeters under both dry and rewetted conditions. Findings suggest that maintaining adequate soil moisture before and after petroleum jelly addition is critical to avoid preferential flow along the hydrophobic edge in sealed lysimeters.

Core Ideas
- Effectiveness of petrolatum in preventing edge-flow was assessed in lysimeters.
- Edge flow was observed with dye tracers in both dry and rewetted unsealed lysimeters.
- Petrolatum sealed edges but created a new edge where it infiltrated into the soil.
- Preferential flow occurred at this new edge in dry and rewetted sealed lysimeters.
- Maintenance of soil moisture is critical when sealing lysimeters with petrolatum.

Drainage lysimeters (also referred to as soil monoliths or soil columns) have been used extensively to measure percolation of water through soils, quantify solute and contaminant transport, and investigate evapotranspiration and gas fluxes (Singh et al., 2018). Given the breadth of studies that have utilized lysimeters, numerous variations of lysimeter size, lysimeter design, casing material, and collection methods have been described in the literature (e.g., Bergström, 1990). Many of these modifications have centered around preventing or limiting edge-flow effects. Edge flow between the soil and the lysimeter casing can be problematic in lysimeter studies because water and solutes transported as spurious leachate at this interface can have a profound influence on results (Cameron et al., 1990). For instance, Till and McCabe (1976) examined edge-flow effects by applying a radiotracer either near the edge or in the center of lysimeters. They observed that four times more tracer was recovered in leachate when it was applied near the edge rather than in the center of the lysimeter, highlighting the necessity to limit edge flow to ensure accurate drainage and solute transport rates.

Collecting undisturbed lysimeters that are sufficiently large (i.e., >0.05 m² surface area) has been recommended to reduce edge-flow effects (Bergström, 1990). Also, collecting soils under dry antecedent conditions has been suggested to limit edge flow, as rewetting the soil will cause the soil to expand and fill the lysimeter casing (Bergström, 1990). Sealing or filling the gap between the soil and the lysimeter casing is another commonly used approach to reduce edge flow (Cameron et al., 1992). Various sealants including

Abbreviations: PVC, polyvinyl chloride.
When sealants are used to suppress edge flow, it is often noted that the method was effective for sealing the gap between the soil and lysimeter casing; however, data documenting sealant effectiveness is rarely reported.

In the current study, eight undisturbed lysimeters were collected to evaluate the effectiveness of petroleum jelly as a sealant to prevent edge flow following a drying and rewetting cycle, where the gap between the soil and lysimeter casing was sealed for four of the lysimeters and the remaining lysimeters were unsealed. Specific objectives were to: (i) conduct a literature review on studies using petroleum jelly as a sealant given its widespread use in lysimeter studies; (ii) examine flow pathways in undisturbed lysimeters either unsealed or sealed with petroleum jelly using dye tracers; and (iii) provide recommendations for future studies using petroleum jelly to limit the effects of edge flow.

Literature Review

Google Scholar (https://scholar.google.com) was used to conduct a review of studies where petroleum jelly was used for lysimeter edge-flow suppression. Search terms lysimeter and petroleum jelly or lysimeter and petrolatum were used; a full list of references can be found in the Supplemental Material. Applying these search criteria, Monaghan et al. (1989) was the first to make use of petroleum jelly, whereby the inner wall of a polyvinyl chloride (PVC) column was coated with a thin layer of petroleum jelly, and then soil was repacked into the column. Since this initial study, an additional 120 peer-reviewed papers have been published, with the number of published papers where petroleum jelly has been used as an edge-flow suppressant having steadily increased with time (Fig. 1). The vast majority of these studies have been focused on nutrient dynamics (nitrogen \( n = 71 \), phosphorus \( n = 16 \)), while a few studies have examined microbial (\( n = 9 \) and heavy metal (\( n = 4 \)) leaching.

Researchers often suggest that petroleum jelly was selected as a sealant due to its inherent properties such as low melting temperature, ability to be poured or injected as a low-viscosity liquid, quick setup time, and flexibility and tackiness in the solidified state (e.g., Feyereisen and Folmar, 2009). Additionally, several researchers observed that the petroleum jelly did not penetrate significantly into the soil and plant roots did not grow into the petroleum jelly (e.g., Cameron et al., 1992). Despite its widespread use, only Cameron et al. (1990) directly compared sealed and unsealed lysimeters. In their study, they measured hydraulic conductivity and solute leaching rates in sealed and unsealed lysimeters. They found that the hydraulic conductivity in unsealed lysimeters was two to three times greater than in sealed lysimeters, and solute breakthrough also occurred faster in unsealed lysimeters. Indeed, many of the published studies found as part of the literature review cite Cameron et al. (1990, 1992) for the effective prevention of edge flow. Using only lysimeters sealed with petroleum jelly, several researchers have measured water flow rates and chloride tracers to suggest that edge flow was probably not occurring (Bowman et al., 2002; Brookman et al., 2002). Feyereisen and Folmar (2009) also observed that dye tracers applied to sealed lysimeters indicated that little edge flow had occurred during their leaching experiment.

Methods

Lysimeter Collection and Preparation

Eight undisturbed lysimeters were collected from a tile-drained agricultural field located in the Matson Ditch subwatershed of the Upper Cedar Creek in northeastern Indiana (48°28′20.19″ N, 84°59′28.50″ W). The field was farmed with a 4-yr crop rotation of corn (Zea mays L.), soybean (Glycine max (L.) Merr.), oat (Avena sativa L.), and wheat (Triticum aestivum L.), with lysimeter collection occurring in the spring prior to tillage and oat planting. Soils at the site are Glynwood loam (a fine, illitic, mesic Aquic Hapludalf) derived from Wisconsinan glacial till. Glynwood soils are characterized as moderately well drained, with saturated hydraulic conductivities decreasing from approximately 30 mm h\(^{-1}\) in silt loam surface horizons (Ap, 0–20 cm) to <3 mm h\(^{-1}\) in silty clay to clay subsurface horizons (Bt, 20–60+ cm).

Square steel lysimeter casings (30 by 30 by 30 cm, 0.5 cm thick) were used to collect soil monoliths similar to the methods described by Cameron et al. (1992). Briefly, the steel lysimeter casings were lined with 1.0-cm plastic PVC spacers, and a removable cutting head was mounted on the bottom of the casing prior to insertion into the soil (Fig. 2). The casing with cutting head was then pushed down over the soil monolith using the bucket of a front-end loader. This process was repeated several times until the lysimeter casing was almost completely filled. The soil monolith was then separated from the soil.

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![Graph showing number of publications over time](image-url)
below, the cutting head and any extra soil removed, and a perforated PVC plate (1.3 cm thick) with geotextile fabric was attached to the bottom of the lysimeter casing. Upon return to the laboratory, the plastic spacers lining the inside of the casing were removed from four randomly selected lysimeters. Liquefied petroleum jelly was poured into the gap created after spacer removal to within 1.0 to 2.0 cm of the soil surface (Fig. 2). After the petroleum jelly solidified, paraffin wax was poured on the petroleum jelly to the level of the soil surface (Feyereisen and Folmar, 2009). The plastic spacers lining the four remaining lysimeters were kept in place, as these lysimeters were considered unsealed.

Rainfall Simulation

During the weeks following lysimeter collection, the soil water content was maintained near field capacity with regular additions of deionized water. Two rainfall simulations were performed during a 30-d period as part of a separate study using the lysimeters (Williams et al., unpublished data). After the second rainfall simulation, the lysimeters were stored in the laboratory (average air temperature ~22°C) with little exposure to natural light for 150 d. During this time, no additional water was added to the lysimeters. Two sealed lysimeters and two unsealed lysimeters were subsequently rewetted from the bottom up by placing the lysimeters in a pool of deionized water for 4 d. These lysimeters were then removed from the pool of water and allowed to drain to field capacity for 3 d. This resulted in four treatments with two lysimeters per treatment: (i) sealed, wet; (ii) sealed, dry; (iii) unsealed, wet; and (iv) unsealed, dry. This experimental scenario was chosen for testing because it was hypothesized that edge flow would be greatest in unsealed lysimeters subjected to long periods of drying, where a gap could form between the soil and the lysimeter casing as the soil shrinks. Given the flexibility of the petroleum jelly, it was also postulated that even under dry conditions, the petroleum jelly would seal any gaps between the soil and the lysimeter casing and, therefore, limit edge flow.

All lysimeters were subjected to a 1-h rainfall simulation (3.3 cm h⁻¹), which was equivalent to a 2-yr return interval for Waterloo, IN (NOAA, 2018). The soil surface was positioned 2.0 m below the nozzles (VeeJet 80-100, Spraying Systems Co.) of the rainfall simulator. The dye tracer Brilliant Blue FCF, which is nontoxic and has good visibility and low retardation in the soil, was added to the rainwater (4 g L⁻¹) to visualize flow pathways through the soil (Weiler and Flühler, 2004). Following the rainfall simulation, the lysimeters were allowed to drain for 3 d and then dissected by hand in 5-cm depth intervals (5, 10, 15, 20, and 25 cm). At each depth interval, horizontal dye patterns were photographed.

Horizontal Dye Pattern Analysis

Photograph processing and determinations of dye coverage at each of the horizontal cross-sections was completed using the GNU Image Manipulation Program (GIMP) Version 2.8 (https://www.gimp.org). All photographs were first cropped to the area of the soil within the lysimeter (i.e., excluding plastic spacers and petroleum jelly) (Fig. 3). Soil moisture sensors and ceramic suction cups installed in each lysimeter as part of the previous experiment were also cropped from each photograph. Following the procedures of Laine-Kaulio et al. (2015), the colors of the photograph were converted to red, green, and blue such that the dyed soil could be distinguished from undyed soil (Fig. 3). Black and white images were then created, where the dyed areas were presented in black and the undyed areas in white (Fig. 3). The percentage of each horizontal cross-section that was dyed was calculated using the Histogram tool in GIMP. To determine
the effects of edge flow, the dyed area 0.0 to 1.0, 1.0 to 2.5, and 2.5 to 5 cm from the soil–spacer or soil–petroleum jelly interface was determined and compared with the total dyed area for the cross-section.

Data Analysis

Spatial dye patterns and the fraction of the dyed area of each horizontal cross-section are shown for each of the eight lysimeters. Visual assessment of dye patterns was used to infer potential flow pathways and processes. The number of replications per treatment \((n = 2)\) precluded traditional comparative statistics and is a limitation of the current study. Previous research using undistributed lysimeters and rainfall simulations suggest, however, that additional replications may not have yielded statistically significant differences among treatments due to macropore flow and flow heterogeneity in undisturbed soils (e.g., Shipitalo et al., 1990; Shipitalo and Edwards, 1996). All data collected from each of the lysimeters is therefore presented and described here.

Results

Dye Patterns following Soil Drying

Horizontal cross-sections showing dye patterns for sealed and unsealed lysimeters that remained dry prior to the rainfall simulation are shown in Fig. 4. Total dyed area generally decreased with depth, with a range of 46 to 84% at a depth of 5 cm and 7 to 21% at a depth of 25 cm (Fig. 5A–5D); however, dye coverage was greater in some cross-sections than the depth immediately above it for the sealed lysimeters (Fig. 5C–5D). Unsealed lysimeters had a larger fraction of dyed soil (depth-averaged dye coverage 42–50%) compared with sealed lysimeters (depth-averaged dye coverage 20–31%).
Dye in the unsealed lysimeters tended to be disproportionately concentrated near the soil–spacer interface. Across all depths, on average, 23% (range 14–34%) of the total dyed area in the unsealed lysimeters was found within 0 to 1 cm of the soil–spacer interface, which equaled 13.8% (108 of 784 cm²) of the lysimeter cross-sectional area (Fig. 4 and 5). In comparison, only 13% (range 8–21%) of the total dyed area, on average, was observed within the outer 1 cm of the sealed lysimeters. This spatial pattern was particularly evident at the 5-, 10-, and 15-cm cross-sections, where the dyed area often extended to the soil–spacer interface in the unsealed lysimeters but did not often extend to the petroleum jelly in the sealed lysimeters (Fig. 4). Indeed, much of the total dyed area at all depths in the sealed lysimeters occurred between 1 and 5 cm (352 of 784 cm²) from the soil–petroleum jelly interface (average 46%, range 34–56%). This effectively resulted in ring-shaped dye patterns in the upper cross-sections of the sealed lysimeters (Fig. 4D). Dye moving through the remainder of both the sealed and unsealed lysimeters (i.e., excluding the outer 5 cm; inner 324 of 784 cm²) was largely constrained to the upper 15 cm of the soil (Fig. 4). At a depth of 25 cm, between 8 and 14% of the total dyed area was contained within the remainder of the lysimeter for both sealed and unsealed lysimeters (Fig. 5).

**Dye Patterns following Soil Drying and Rewetting**

Dye coverage for sealed and unsealed lysimeters brought to field capacity prior to the rainfall simulation decreased with depth similar to the dry lysimeters (Fig. 5). Horizontal cross-sections showing dye patterns for sealed and unsealed lysimeters that were rewetted prior to the rainfall simulation are shown in Fig. 6. Total dyed area ranged from 38 to 76% at a depth of 5 cm and decreased to between 2 and 18% at a depth of 25 cm. Depth-averaged dye coverage for the sealed and unsealed lysimeters were similar after rewetting, with values ranging between 14 and 31%. Rewetting the
lysimeters therefore resulted in lower depth-averaged dye coverage than the dry lysimeters (range 20–50%) (Fig. 5).

In the unsealed lysimeters, dye coverage was concentrated near the interface between the soil and the spacer, especially in the corners of the lysimeter at depths >10 cm (Fig. 6). On average, 40% (range 18–55%) of the total dyed area regardless of depth was found within 1 cm of the soil–spacer interface for the unsealed lysimeters (Fig. 5). Excluding the 5-cm depth, <9% (average 2%) of the total dyed area was contained within the remainder (i.e., excluding the outer 5 cm; inner 324 of 784 cm²) of the unsealed lysimeters. In comparison, sealed lysimeters had only 22% (range 12–51%), on average, of the total dyed area within 1 cm of the soil–petroleum jelly interface. On average, however, 83% (range 55–97%) of the total dye coverage fell within 5 cm of the soil–petroleum jelly interface (Fig. 5 and 6). A greater proportion of the total dyed area for both the wet, sealed and unsealed lysimeters was found near the edge of the lysimeter (<5 cm) compared with the dry, sealed and unsealed lysimeters (Fig. 5). Spatial dye patterns for the wet, sealed lysimeters also resembled a ring in some soil layers (e.g., Fig. 6C and 6D; 10 cm) similar to the dry, sealed lysimeters (e.g., Fig. 4D) whereby less soil tended to be dyed near the soil–petroleum jelly interface but the dye was located between 1 and ~3 cm from this interface.

**Discussion**

**Edge Flow in Unsealed and Sealed Lysimeters**

Dye tracers revealed the occurrence of edge flow in unsealed lysimeters after both 150 d of drying and subsequent rewetting. As expected, during the drying period, small (1–2-mm-wide) cracks developed across the soil surface, with larger cracks (4–5 mm wide) forming between the soil and the plastic spacers lining the inside of the lysimeter casing. Upon rewetting, these cracks were
no longer visible on the soil surface and the soil appeared to fill the entire lysimeter. Visual observations during lysimeter dissection indicated that most dye transport through the soil profile was associated with these cracks. While earthworm burrows were observed at depth in several of the lysimeters, they were often undyed because they were not directly connected to the soil surface. The annual tillage operations at the field where the lysimeters were collected precluded the formation of surface-connected biopores that are often observed in agricultural fields with reduced tillage or no tillage (e.g., Kladivko et al., 1997).

Dry, unsealed lysimeters tended to have greater dye coverage than wet, unsealed lysimeters, with horizontal dye patterns as a potential indicator of the interaction between macropores and the surrounding soil matrix (Weiler and Flühler, 2004). A larger fraction of dyed area observed for the dry, unsealed lysimeters therefore suggests that matrix–macropore interaction was likely greater than for the wet, unsealed lysimeters. Previous studies have documented the effect of antecedent wetness on macropore flow. For instance, Jaynes et al. (2001) and Kung et al. (2000) both found that pesticide transport from surface soils to subsurface tile drains increased during irrigation experiments as the soil became progressively wetter. Higher antecedent soil moisture has been shown to not only increase total leachate volume but also reduce lateral flow into the soil matrix (Beven and Germann, 1982; Jarvis, 2007). In contrast, Shipitalo and Edwards (1996) and Merdun et al. (2008) found that the relative contribution of macropores was greatest when the soil was dry and decreased as the soil became wetter. Differential effects of antecedent wetness on preferential flow may be related to the type of macropore, whereby flow via shrinkage cracks decreases and flow via biopores increases with increasing wetness (Lin et al., 1998; Hardie et al., 2011). Since soil cracking was the predominant preferential flow pathway in the current study, rewetting of the unsealed lysimeters limited matrix–macropore interaction, as evidenced by little dye coverage in the middle portion of the lysimeter. During the rainfall simulation, rewetted lysimeters had visible surface ponding due to reduced infiltration capacity caused by higher antecedent soil moisture, with this surface runoff likely flowing along the soil–spacer interface. Rewetting the unsealed lysimeters was therefore not adequate to seal the gap and prevent edge flow at the rainfall intensity used in the simulation (3.3 cm h⁻¹). While leachate was not collected as part of the current study, we hypothesize that the wet, unsealed lysimeters probably exhibited greater volumes of edge flow than dry, unsealed lysimeters. Indeed, Ford et al. (2017) noted the importance of coupled development of macropore pathways and an adequate supply of the macropore flow source.

Cracking of the soil surface after the extended drying period was also observed for lysimeters sealed with petroleum jelly. Unlike the unsealed lysimeters, the petroleum jelly prevented the formation of shrinkage cracks between the soil column and the lysimeter casing; however, larger cracks were noted approximately 1 to 3 cm from the soil–petroleum jelly interface. The location of this cracking coincided with a change in soil color, which was postulated to delineate the boundary of petroleum jelly infiltration into the sidewalls of the soil column (Fig. 7). When heated, petroleum jelly was able to be poured into the gap between the soil and the lysimeter casing due to its low viscosity; thus, there was potential for infiltration into soil pores as the petroleum jelly cooled and resolidified. Horizontal dye patterns for the dry, sealed lysimeters resembled a “ring” pattern in several soil layers (Fig. 4), with dye staining between 1 and 5 cm from the soil–petroleum jelly interface. While our findings suggest that petroleum jelly was effective at limiting edge flow between the soil and lysimeter casing, it may have created a new edge a few centimeters inside the soil column.

Fig. 7. Example dye pattern from a dry, sealed lysimeter (Lysimeter 7, 15 cm) showing (A) the original photograph and (B) interpretation. The photograph of the dye pattern reveals a distinct soil color change approximately 1 to 2 cm from the edge, which denotes the boundary of petroleum jelly infiltration into the soil. During drying, cracks formed at this interface, with most of the dye staining occurring in a ring pattern associated with these cracks.
The formation of cracks where the petroleum jelly infiltrated into the soil served as a preferential flow pathway for both dry and rewetted treatments. The creation of this hydrophobic edge appeared to transport water similar to flow between the soil and the lysimeter casing in the unsealed lysimeters. It is therefore critical to maintain the soil moisture in the lysimeters, once petroleum jelly is added, with a regular watering or irrigation schedule such that cracking at this interface is prevented from occurring. Findings from the current study suggest that once this cracking occurs, it may be irreversible and serve as an unnatural flow pathway in subsequent leaching experiments.

### Conclusion

Petroleum jelly has increasingly been used to limit edge-flow effects in lysimeter studies during the past 30 yr. Application of dye tracers to unsealed lysimeters after 150 d of drying highlighted the need for edge-flow prevention, as dye staining tended to be concentrated near the soil–lysimeter casing interface. Rewetting the dry, unsealed lysimeters did not decrease edge flow, with horizontal dye staining patterns indicating decreased matrix–macropore interaction in the wet, unsealed lysimeters. Decreased matrix–macropore interaction in the wet, unsealed lysimeters may have increased edge flow, although future research efforts need to test this hypothesis by measuring flow rates through the soil in addition to dye tracers. Using petroleum to seal the gap between the soil and the lysimeter casing largely prevented flow at this interface. During the drying phase of the experiment, however, cracks formed approximately 1 to 3 cm from the soil–petroleum jelly interface, which was postulated to delineate the boundary of petroleum jelly infiltration into the sidewalls of the soil column. The majority of dye transported through the sealed lysimeters for both wet and dry treatments was in close proximity of these cracks, suggesting that the petroleum jelly infiltration created a hydrophobic edge where preferential flow could occur. These findings indicate that maintaining adequate soil moisture prior to and following petroleum jelly addition to lysimeters is necessary for successful edge-flow prevention. The soil moisture level prior to petroleum jelly addition may influence the degree of infiltration into the sidewalls of the soil column, thereby influencing the drainable area of the lysimeter, whereas maintaining soil moisture after petroleum jelly addition will help prevent shrinkage cracks from forming that could lead to edge-flow effects even in sealed lysimeters.

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### Recommendations for Using Petrolatum as an Edge-Flow Suppressant

Results from the current study and others (e.g., Till and McCabe, 1976; Cameron et al., 1990) highlight the need to limit edge flow in lysimeter studies because rewetting dry soil was not adequate to seal the gap between the soil column and the lysimeter casing. Petroleum jelly was relatively easy to pour into the gap created by the removable plastic spacers, and it solidified quickly on contact with the soil (e.g., Feyereisen and Folmar, 2009). In the current study, the petroleum jelly was poured into the gap between the soil and lysimeter casing when soil moisture was 0.35 cm$^3$ cm$^{-3}$ (i.e., less than field capacity but with no visible shrinkage cracking on the soil surface) and the petroleum jelly infiltrated into the soil between 1 and 2 cm. Infiltration of petroleum jelly into the soil effectively decreases the drainable area within the lysimeter. In the current study, it was estimated that the drainage area of the lysimeter casing (30 by 30 cm, 900 cm$^2$) was decreased by 25% (26 by 26 cm, 676 cm$^2$) with the addition of petroleum jelly. If the soil moisture in the lysimeters was drier when the petroleum jelly was added, then the petroleum jelly could possibly penetrate even farther into the soil, further restricting the size of the drainable area. Thus, the size of the lysimeter casing and the soil moisture conditions at the time of petroleum jelly addition need to be carefully considered.
References


