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Bromide and chloride tracer application to determine sufficiency of plot size and well depth placement to capture preferential flow and solute leaching

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ABSTRACT

Preferential flow paths in soils, including sandy soils, present a problem in determining contaminant leaching to groundwater, but conservative tracers can be used to examine whether large-scale plots, in a complete randomized block design, are sufficient for solute measurements. In this study, two tracers, bromide (Br^-) and chloride (Cl^-) were applied to the standard agronomic large-scale plots at the University of Wisconsin-Madison Hancock Agricultural Research Station on Plainfield loamy sand. Over two years, 2010 and 2012, two fields were divided into twelve plots each approximately 15 m × 15 m, arranged six plots long by two plots wide. In 2010, Br^- and Cl^- were applied to two plots in a staggered pattern. Groundwater monitoring wells were installed diagonally across all plots and water samples were assessed for Br^- and Cl^-. The Cl^- data were inconclusive as background Cl^- concentration was elevated and present in several wells in plots that did not have Cl^- applied, and breakthrough curves (BTCs) could not be verified. Therefore, only Br^- was applied to the plots in 2012. Br^- results show that leaching to groundwater beneath a given plot was confined to the plot of application. There was movement of tracers from one plot to the groundwater beneath another plot, however this was from horizontal groundwater flow and the time for this flow between plots to occur was four to five months.

1. Introduction

Nitrate nitrogen (NO_3-N) contamination of surface and groundwater from agricultural processes is a problem in many parts of the United States, and worldwide, but it is of major groundwater concern in the Central Sands Area of Wisconsin. Fertilizer rates and irrigation have contributed to concentrations of NO_3-N in the groundwater that are 2–4 times the maximum contaminant level (MCL) of 10 mg L^{-1} as recommended by the U.S. EPA (2009). In previous studies on nitrogen leaching associated with fertilizer, the focus has been on determining NO_3-N flux through the root zone (Arriaga et al., 2009; Cooley et al., 2009; Díez et al., 1994; Errebhi et al., 1998; Wilson et al., 2010). While data from these studies indicate there are management practices that have resulted in reduced leaching in or near the root zone, determining the impact of NO_3-N reaching groundwater has only been inferred from these root zone data (Shrestha et al., 2010; Wilson et al., 2010). Thus, it is clear that a study of the impact of nitrogen management on groundwater is needed, and this should be done by sampling the groundwater directly.

There are several studies that show that water and solutes are capable of moving laterally through sandy soil and underlying sediment. Previous research at the Hancock Research Station indicates that water and solute applied uniformly to soil surfaces did not flow through the entire vadose zone, but rather preferential flow paths dominated the flow pattern (Kung, 1990a). Preferential flow paths, such as finger flow and funnel flow, may affect location where solute enters the water table as well as measured concentration levels (Brown et al., 2000). However, in a solute study, Kung (1990a) found that in a 3 m by 3.6 m plot, preferential flow channeled water laterally to a corner of the plot, thus non-uniform movement of water and solute was noted. Van Dam et al. (1990) found that water flowed through preferential flow paths or fingers in a sandy marine soil in the Netherlands. Further, localized ponding or wetting front diversion occurred as a result of lenses of differing sand grain sizes. Funneled flow can have profound implications for investigation of groundwater contamination with current soil solute sampling techniques (Kung, 1990b). The placement of wells is very important in determining effect of solute flux on groundwater (Kung, 1990a). Additionally, within any given plot, vertical within site variability of solute movement is considerable (Butters et al., 1989). Placement of the well screen interval may also be important as mixing of groundwaters with depth is limited as concentrations of solute decrease with depth (Spalding and Parron, 1994).

Given the findings of Kung (1990a), further research on N fertilizer effects on groundwater was conducted on plots sized 15 m × 15 m in

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Abbreviations: NO_3-N, Nitrate nitrogen; MCL, maximum contaminant level; Br^-, bromide; Cl^-, chloride; KCl, potassium chloride; BTC, breakthrough curve; IC, ion chromatograph.

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anticipation of avoiding the preferential flow problem (Bero et al., 2014). Bero et al. (2014) found large variations within plots and among plots, and although there were large differences determined in N available for leaching between the two years of the study (137 to 199 kg N ha^{-1} in 2010 and 107 to 162 kg N ha^{-1} in 2011), significant differences in groundwater nitrate concentration were not detected. Additional research is warranted to determine if the source of variation is caused by solute movement from plot-to-plot. Since the plots are not hydrologically isolated, lateral flow can also affect measured NO_3-N concentrations in groundwater, by mixing with waters from outside the plot area that are either rich or depleted in NO_3-N, or direct transport off plot. Knowing the timing and direction of groundwater flow may be important for understanding shallow groundwater data from large-scale field study. The flow direction of groundwater can also be determined by observing tracer movement over time by following the tracer plume. If the plot size is sufficient to negate the effect of lateral movement, with mixing of deeper groundwaters, the presence of finger and funnel flow would indicate that there is large, inherent variability in nitrate concentration at the groundwater surface.

If we are to continue to assess the fate of nitrogen fertilizers applied to large-scale plots, we need to determine whether a groundwater well sampled within a given plot represents NO_3-N concentrations specific to that plot. Conservative tracers can be applied, measured, and assessed to determine if the preferential flow paths or lateral flow are present which could affect NO_3-N measurements. Conservative tracers like Br^- and Cl^- provide a useful means of determining preferential flow paths (Jabro et al., 1994). In general, Br^- shows a strong positive correlation with leaching and sand content (Kessavalou et al., 1996). It has been shown that Br^- and NO_3-N also move at comparable rates through the unsaturated zone in the Plainfield sand (Saffigna and Keeney, 1977). Br^- is especially useful because it is generally rare in soils, has low background concentrations, is not subject to precipitation or sorption and is non-toxic and very soluble (Meiri, 1989).

The first objective of this study was to determine if the so-called large scale plots (15 × 15 m), which have been used recently at the Hancock Research Station for solute flow studies (e.g., Bero et al., 2014), is of sufficient size that vertical preferential flow paths would not move solute to a neighboring plot through the application of conservative tracers. The secondary objectives were to determine if groundwater monitoring wells with screens installed below the water table can detect solutes leaching to the water table surface and the time required for lateral groundwater flow to move solutes to adjacent plots.

2. Materials and methods

2.1. Field research site

A Br^- tracer field experiment was conducted at the Hancock Agricultural Research Station in a Plainfield loamy sand soil. The Plainfield series consists of very deep, excessively drained soils formed in sandy drift on outwash plains, valley trains, glacial lake basins, stream terraces, and moraines and other upland areas where permeability is rapid or very rapid (Soil Survey Staff, 2006). Slope in our study area was 0–6%, with the majority plot area being flat. Soil depth was approximately 1 m underlain by sandy glacial lake sediments of depths averaging 30 m. Two fields were divided into twelve 14.6 m × 15.24 m plots, arranged two plots wide by six plots long. Three wells were placed diagonally across each plot, at a distance of 4.9 m (well A), 7.6 m (well B), and 9.8 m (well C) respectively from the south edge of each plot (Fig. 1). Well installation was completed on 17 May 2010 in the first field and on 2 May 2011 in the second field. The average depth to groundwater was 6.7 m at the time of well installation in 2010. Wells were installed approximately 3.1 m below the water table, leaving the top of the screen 1.6 m below the water table. This was done to account for an anticipated summer drawdown of the water table of 1.5 m. However, the normal summer drawdown did not occur. Thus, on 14 October 2010, the center well, labeled as well B, was raised to a 7.3 m depth, which placed the top of well screen at the water table to allow for sampling at the surface of the water table and assessment of the vertical placement of well screens. On 23 May 2011, all wells in the first field were raised so that the well screens intersected the water table. Wells installed in the second field in 2011, which were used in the 2012 Br^- application, were installed at a depth of 9.1 m with 2.3 m screens. The depth to the water table at the time of installation of wells in the second field was 7.3 m. Thus, the well screens were 0.5 m above the water table. Well screens in 2012 intersected the water table at all times during the study period.

Two observation wells were installed at the north–south midpoint of both fields in both years, outside of the field boundary, to continuously record depth to water table with a submersible pressure/temperature transducer (model PS-9805, Instrumentation Northwest Kirkland, WA) placed inside the well at a depth of 1.22 m under the water table. A third observation well that only monitored depth to water table was installed approximately 1000 m south of the observation well from the field in 2010 and 500 m west of the observation well from the field used in

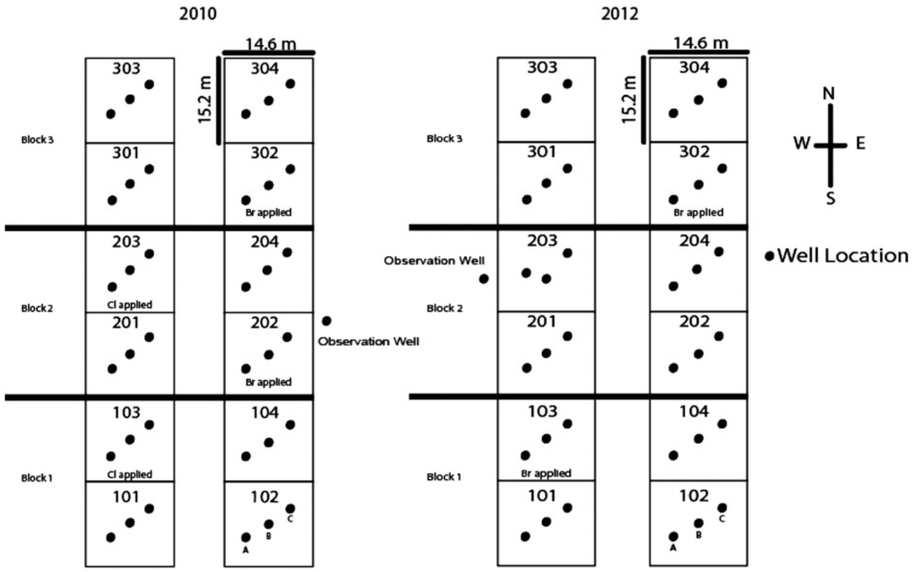

Fig. 1. Plot diagram for the 2010 and 2012 fields and identification of plots that had Br^- and Cl^- applied. Example of locations of wells A, B, and C labeled in plot 102.