DIVISION S-1—NOTES

COMPARISON OF THREE METHODS FOR FIELD MEASUREMENT OF SOLUTE LEACHING IN A SANDY SOIL

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Abstract

To identify the most suitable technique for measuring solute leaching in a sandy soil, we compared three methods in an irrigation experiment (irrigation rates: 5 and 2.4 mm h\(^{-1}\)) using Cl\(^{-}\) as a tracer. We tested tensiometer-controlled suction plates, wick samplers, and ion-exchange resin boxes installed between fiberglass pads. Ten samplers of each type were installed at a 52-cm depth (suction plates) or a 60-cm depth (wick and resin box samplers) into soil monoliths. The recovery of water and Cl\(^{-}\) by the suction plates varied little with irrigation rate (107–118%). The wick samplers performed well during 5 mm h\(^{-1}\) irrigation (Cl\(^{-}\) recovery: 111%; water recovery: 103%). However, at the irrigation rate of 2.4 mm h\(^{-1}\), the water recovery was significantly lower (70%), probably because the soil suction exceeded the maximum capillary force of the wicks. The wicks did not induce a retardation or additional dispersion of Cl\(^{-}\) compared with suction plates. The recovery of Cl\(^{-}\) by the resin boxes was only 6%. Tensiometer-controlled suction plates allowed an overall satisfactory estimation of water and solute fluxes in the sandy soil.

DIRECT FIELD MEASUREMENTS of solute leaching are necessary to calibrate and validate indirect approaches for the quantification of solute transport, for example, by means of computer models. These measurements have been realized with tensiometer-controlled suction samplers (e.g., Brye et al., 1999; van Grinsven et al., 1988). However, high costs and maintenance requirements of these systems limit the number of samplers that can be employed.

Less costly wick samplers can be applied in larger numbers, which is especially useful under preferential flow conditions (e.g., Boll et al., 1991; Brandi-Dohrn et al., 1996; Zhu et al., 2002). Knutson and Selker (1994) and Rimmer et al. (1995) presented concepts to optimize the design of wick samplers with respect to soil characteristics. The theoretical analysis of water flow in the soil-sampler system showed that wicks should be long (30 to >100 cm; Rimmer et al., 1995). However, installing long wicks is difficult and increases the disturbance of the soil profile. Wicks that extend horizontally to a trench or pit where they hang vertically would be easier to install and minimize disturbances.

Another way to quantify the flux of solutes with drainage water with a high number of samplers is the use of synthetic ion-exchange resins (e.g., Schnabel, 1983). Solutes are sorbed as the drainage passes through resin boxes or bags that are installed into the soil. The solutes are quantified by extracting them from the resin in the laboratory. Resin samplers are commonly installed from pits that are refilled (Bischoff et al., 1999; Lehmann et al., 2001). At the end of the sampling period the samplers are excavated and pits are relocated for the subsequent installation. This hampers continuous measurements at one spot and causes considerable disturbances of soil, which might be unacceptable especially if experimental plots are small. A device that allows changing the boxes at a permanent installation place would avoid these disadvantages.

Solute are easily leached from sandy soils, because of their low water retention capacity and high permeability. Therefore, methods to study solute transport in sandy soils are of special interest. Furthermore, most tests of wick samplers were performed in loamy soils (Boll et al., 1991; Brandi-Dohrn et al., 1996; Louie et al., 2000; Zhu et al., 2002) while wick samplers are probably especially suited for measurements in sandy soils (Rimmer et al., 1995).

The objective of our experiment was to compare tensiometer-controlled suction samplers, wick samplers and ion-exchange resin boxes in an irrigation experiment using Cl\(^{-}\) as a tracer to identify the most suitable method for field measurements of solute leaching in a sandy soil at the study site. Additionally, we modified the design of common wick samplers and resin boxes.

Materials and Methods

Site

The experiments were conducted close to the City of Münster (Germany). The soil at the research site is a Typic Plaggept (Table 1). The A1 horizon was turned by plowshares, while the Ap2 horizon was loosened by tines until 1993. Since then, the site lied fallow with ryegrass (Lolium perenne) as dominant vegetation.

Sampler Design and Installation

The suction plates were made from porous plates of sintered borosilicate glass (ROBU, Hattert, Germany, No 15904, nominal maximum pore width: 16 μm, bubble point: 10–14 kPa, conductivity: 13 mm h\(^{-1}\), Fig. 1A). The porous plates were mounted on a foldaway plate that was integrated into a steel box girder. The suction plates were surrounded by a 10-mm high steel ring to reduce the lateral flow of water to the plates. We pressed the suction plates against the soil with a lever and with wooden wedges to ensure good contact. The suction applied to the plates was adjusted electronically to the arithmetic mean of the matric potential that was measured individually by three pressure transducer tensiometers (Suction Control System: type SCS-8, Tensiometers: type T4, both from Umwelt Monitoring Systeme, Munich, Germany). Tensiome-

Abbreviations: BTC, breakthrough curve; CDE, convection-disper-

sion equation; CLT, convective lognormal transfer function.
The wicks did not hang vertically directly beneath the collection pan, but extended horizontally to a trench before hanging down (Fig. 1B). To match the wick sampler design to the soil characteristics, the collection area, the wick diameter, the vertical wick length may be varied (Knutson and Selker, 1994; Rimmer et al., 1995). According to the pedo-transfer function implemented in the ROSETTA software (Schaap, 1999), the soil at our research site probably drains at a rate of 100 cm from neighboring samplers. To quantify the effect that of stagnant water, we installed one tensiometer right above the steel box girders (Fig. 1B). Experimental data show that common fiberglass wicks exert a maximum suction of approximately 5 kPa (Holder et al., 1991; Boll et al., 1992). Additionally, a reduction of suction of about 2 kPa between the top of the wick and the horizontal filaments on the collection pan was reported by Wang (1993, cited in Brandi-Dohrn et al., 1996). Hence, the maximum suction that could be generated by the wicks might limit the quantitative sampling of drainage in the study soil. To maximize the suction that is exerted by the wicks, we chose a large wick diameter of 3.81 cm and a long vertical wick length of 100 cm (Thermoglass "knitted rope," medium density, 10-863KR, Amatex, Norristown, PA). A sensitivity analysis using the wick parameters for the Amatex 1-inch wick and Eq. [12] of Knutson and Selker (1994) showed that a vertical wick length >100 cm would hardly increase the suction that is generated. Wicks were heated to 400°C for 4 h before use (Knutson and Selker, 1994). They were braided at their top into single strands that were spread on the collection pan and fixed at their ends with silicone (Brandi-Dohrn et al., 1996).

The resin box samplers consisted of a rectangular box filled with a mixture of sand from the installation cave and ion exchange resin with a sand/resin volumetric ratio of 1/1 (resin: Amberlite MB 20, Rohm and Haas, Philadelphia, PA). The resin had a grain size of 300 to 1200 μm (Lehmann et al., 2001). The cross-sectional area of the boxes was 200 cm². We placed the box between two pads of fine fiberglass (Fig. 1C), which allowed the changing of them on 8. Oct. 1998. The fiberglass pads were made from 2-cm long parts of Thermoglass "knitted rope" of medium density with a diameter of 3.81 cm (10-863KR, Amatex, Norristown, PA). The short wicks were grouped parallel to each other to form a large pad by spiking them on stainless steel bike spokes that were fixed to a rectangular steel frame. To avoid the loss of resin during the exchange of boxes, the top centimeter of the box contained no ion exchange resin, only sand. Chloride was extracted from the sand/resin mixture by shaking 10 g of mixture with 100 mL of 0.5 M Na₂SO₄ solution. Chloride concentrations of the extract were measured with a Cl⁻ and sensitive electrode (Cl 500, Wissenschaftlich Technische Werkstätten, Weilheim, Germany).

We installed the samplers into monoliths of undisturbed soil that were created by excavating three trenches, each 12 m long, 1.6 m wide, and 1.2 m deep, parallel to each other with a distance of 2.2 m between them (Fig. 2). The sidewalls of these soil monoliths were covered with polyethylene foil and stabilized with a wooden board. Leaching of water along the sidewalls of the monoliths was prevented by filling gaps between soil and boarding with polyurethane foam. All samplers were installed from the middle trench into small caves that were created by pressing a square steel borer (125 by 125 by 1100 mm) horizontally into the soil with threat rods and nuts. Resin box samplers and wick samplers were installed 60 cm below the soil surface. We installed the suction plate samplers at the 52-cm depth. The original samplers were not vacuum.

![Fig. 1. Cross-sections of the sampler types. All dimensions are in millimeters.](image)
tight and had to be repaired and reinstalled into undisturbed soil at a depth of <60 cm.

There were two variants of all sampler types. Five long samplers (length: 112 cm) were used to place the collection area of the sampler at a horizontal distance of 80 to 100 cm from the trench. Five short samplers (length: 70 cm) collected solutes at a distance of 40 to 60 cm from the trench.

Irrigation

We irrigated the soil monoliths with tap water with a spraying beam that moved on rails (Fig. 2; spray tips: XR11002-VH, XR11001-VH, TeeJet Spraying Systems Co., Wheaton, IL). In a first experiment, an irrigation rate of 5 mm h⁻¹ (simulating summer rainfalls) was applied for 2 h every day from 20 Sept. 1998 to 18 Oct. 1998 after the soil had been moistened to field capacity. Between irrigation events, the soil monoliths were covered with polyethylene foil to prevent evapotranspiration and infiltration of natural rainfall. In a second experiment, the soil was irrigated 1 h daily with a smaller rate of 2.4 mm h⁻¹ to mimic winter rainfalls. The actual amount of applied water and its spatial distribution was checked during each irrigation period with 5 to 21 flat bowls of a 6.5-cm diameter. The coefficient of variation of the spatial distribution of irrigation water was 3 to 23% (mean: 11%). Irrigation and drainage water volumes were measured with graduated cylinders.

Tracer Experiment

On 21 Sept. 1998, we applied a 10-mm pulse of irrigation water containing 252 g Cl⁻ m⁻² added as NaCl salt to record breakthrough curves (BTCs) with suction plate samplers and wick samplers. Chloride mass balances were calculated for all sampler types for the high irrigation rate. Concentrations of Cl⁻ in irrigation water and drainage water were determined with an ion-sensitive electrode (Cl500, Wissenschaftlich-Technische Werkstätten, Weilheim, Germany). We plotted the normalized mass flux against time to get BTCs [1]:

\[ m_i(t) = \frac{c_i V_i}{\Delta t \sum_i c_i V_i} \]  \hspace{1cm} [1]

where \( m_i \) is the normalized mass flux (d⁻¹), \( c_i \) is the Cl⁻ concentration (mg L⁻¹), \( V_i \) is the drainage volume (L), and \( \Delta t \) is the time of the sampling interval \( t \) (1 d). Average velocities (\( \bar{v} \)) and dispersion coefficients (\( D \)) were determined by fitting the equilibrium convection–dispersion equation (CDE) to the BTCs using the least squares parameter optimization method implemented in the CXTFIT 2.0 software (Toride et al., 1995). We transformed the estimated mean velocity of the CDE model to a dimensionless mean travel time (PV) using the field capacity [2]:

\[ PV = \frac{z q_m}{\bar{v} F} \]  \hspace{1cm} [2]

where \( z \) is the depth of installation (cm), \( q_m \) is the irrigation rate (cm d⁻¹), \( \bar{v} \) is the average velocity (cm d⁻¹), and \( F \) is the field capacity (cm).

An important assumption of the CDE model is the complete mixing of solutes. This assumption is not always valid for solute transport in undisturbed soils (e.g., Vanderborght et al., 1997). In the case of an incomplete mixing of solutes between domains of different transport characteristics, the convective lognormal transfer function (CLT) model gives a better description of the transport process (e.g., Vanderborght et al., 1997). Therefore, we determined transport parameters (\( \mu \) and \( \sigma \)) for the CLT model next to CDE parameters by fitting the time series of normalized mass fluxes to Eq. [5] of Vanderborght et al. (1997) using the least squares nonlinear regression procedure of the Stastica 6.0 software (Statsoft, Tulsa, OK). The average solute particle velocity (\( \bar{v}^* \), unit: cm d⁻¹) was calculated from the CLT parameters using Eq. [8] of Vanderborght et al. (1997).

It is noteworthy that our experiment does not allow identifying which of the two models (CDE or CLT) describes the transport of Cl⁻ best, because we measured BTCs at one depth only. The identification of the underlying transport process would have required the determination of transport parameters at multiple depths (e.g., Vanderborght et al., 1997).

Statistics

The data were not normally distributed for all factorial groups (Shapiro-Wilk’s W-Test) and did not meet the criterion of homogeneous variances (Bartlett’s Test). Therefore, we used the non-parametric Mann-Whitney U-Test to test for differences between all suction plate samplers and all wick samplers with respect to transport parameters and recovery of applied water volume. The same test was applied to compare the recovery of water and Cl⁻ with samplers of one type that collected drainage at different distances from the trench. We tested the effect of sampler type on the Cl⁻ recovery by the
Fig. 3. Arithmetic means of water and Cl\(^{-}\) balances at the two irrigation regimes. Error bars indicate standard deviations. Different upper case letters indicate significantly different recoveries of Cl\(^{-}\) (Kruskal–Wallis \(H\)-test and post hoc Nemenyi test). Different lower case letters denote significantly different recovery of water during high intensity and low intensity irrigation (Wilcoxon test).

Results and Discussion

The suction plate samplers recovered 115% of the applied water and 118% of the Cl\(^{-}\) during high intensity irrigation and 107% of the applied water during the low intensity irrigation (Fig. 3). The positive bias apparent in suction plate flux measurements may have resulted from stagnant water above the steel box girder, which reduced the soil suction in the direct vicinity of the porous plates (Fig. 1A). Measurements from a tensiometer we installed 1 cm above one girder for 1 d during high intensity irrigation verified that the soil suction there was 0.55 kPa smaller than the suction in freely draining soil. Because the suction applied to the porous plates was adjusted to the matric potential of the freely draining soil, a lateral flow of water to the suction plate probably occurred despite the small surrounding steel rings. The fact that the water recovery decreased to 107% at low flux rates supports the hypothesis that stagnating water streamed laterally to the suction plates. The magnitude of the average systematic error that is caused by the lateral flow of water to the plates was 7 to 18%.

This average error of our suction plate samplers was slightly greater than the error (<10%) that van Grinsven et al. (1988) found. While van Grinsven et al. (1988) controlled one suction plate with three tensiometers, we controlled 10 suction plate samplers with three tensiometers simultaneously. The difference between the maximum and the minimum soil suction measured by the three tensiometers during high intensity irrigation averaged 0.3 kPa and never exceeded 1.1 kPa. This difference reduced to an average of 0.2 kPa (maximum: 0.4 kPa) at low intensity irrigation. Due to the comparably small spatial variability of the soil matric potential, the decision to control all suction plates with three tensiometers did not lead to an unacceptable reduction of accuracy, which allows for cost savings.

The recovery of water and Cl\(^{-}\) with the wick samplers did not differ significantly from the recovery with suction plate samplers (water recovery: Mann-Whitney \(U\)-test; Cl\(^{-}\) recovery: Kruskal–Wallis \(H\)-test; Fig. 3). At high irrigation rate, the soil tension was approximately 3 kPa and the wick samplers captured on average 111% of the applied Cl\(^{-}\) and 103% of the applied water. Unfortunately, the recovery of water with the wick samplers decreased significantly to 70% during the lower intensity irrigation (Wilcoxon test; Fig. 3). We assume that a fraction of drainage water was diverted from the wick samplers because the ambient soil suction was smaller than 30% for soil suction <6 kPa. The average water recovery of 70 to 103% compares well to the collection efficiencies of 66 to 103% that were determined for loamy soils by Boll et al. (1991), Brandi-Dohrn et al. (1996), and Zhu et al. (2002).

The wick samplers collected Cl\(^{-}\) more efficiently in this sandy Plaggept (111%) than Br\(^{-}\) in loamy soils where recoveries were reported to be 29 to 63% (Brandi-Dohrn et al., 1996; Boll et al., 1991). The good recoveries of applied water and Cl\(^{-}\) indicate that the distance of 60 to 100 cm that the wick extended horizontally to the trench did not constrain the collection of drainage.

Transport parameters determined with suction plate samplers and wick samplers did not differ significantly (Mann-Whitney \(U\)-test; Table 2). The fact that two different sampler systems measured similar BTCs shows that the wicks did not induce a significant retardation or dispersion of the tracer pulse. This agrees with the findings of Holder et al. (1991), Poletika et al. (1992), and Knutson and Selker (1996) who found only little...
effects of the wick on travel times and dispersion coefficients.

Water recoveries, Cl\textsuperscript{–} balances, and transport parameters derived from samplers collecting drainage at different distances from the trench did not differ significantly (Mann-Whitney U-test; Table 2). Therefore, collecting drainage at a horizontal distance of 60 cm from a pit or trench should ensure the measurement of representative fluxes in the sandy soil at the research site.

The resin box samplers recovered only 6% of the applied Cl\textsuperscript{–}, which was significantly less than the recovery with suction plate samplers and wick samplers (Kruskal–Wallis H-tests; post-hoc Nemenyi test; Fig. 3). This result differs from the recovery of 60 to 120% that was found by Bischoff et al. (1999) for applications in a variety of soils including sandy soils. In contrast to our experiment in Münster, Bischoff et al. (1999) installed their resin boxes into small caves in the sidewalls of pits without fiberglass pads in direct contact with the soil. Therefore, the fiberglass pads are probably the main reason for the low recovery of Cl\textsuperscript{–}. We assume that the additional interfaces of different materials in the system might have impeded the flow of water through the resin box. It is unlikely that a lack of contact between resin box samplers and soil is the reason for the low recovery of Cl\textsuperscript{–} because we visibly confirmed good contact during the deinstallation of the samplers.

We cannot recommend the installation of resin boxes between pads of fiberglass for future studies. The wick samplers were a good alternative to costly systems for sandy soils where matric potentials exceed \( -5 \) kPa. Extending the wick horizontally to a trench did not constrain the collection of drainage under these conditions. However, the collection efficiency of the wick samplers was not independent of the flux rate and decreased significantly with increasing soil suction. Irrespective of the irrigation regime and the soil suction, the tensiometer-controlled suction plates allowed the estimation of water and Cl\textsuperscript{–} leaching with acceptable accuracy. We conclude that suction plates are the best method for field measurements of solute leaching in the sandy Münster soil. The positive bias in measured fluxes could probably be reduced by minimizing the no-flow boundaries around the porous plates for example, by fusing the plates to small glass sockets equipped with connections to the vacuum source (Siemens and Kaupenjohann, 2003).

The results of this experiment are specific for the soil at the research site and the irrigation regimes that we chose. The application of a two- or three-dimensional process-based model of water flow in the soil-sampler system could support the generalization of our results. Such a model would also support the quantitative interpretation of the processes that caused the systematic errors we observed.

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References


