CONSTRUCTION AND PERFORMANCE OF RUGGED CERAMIC CUP SOIL WATER SAMPLERS

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Abstract

To assess solute concentration changes associated with soil compaction and organic matter removal resulting from forest harvesting, we constructed and field tested ceramic cup soil water samplers designed to withstand the forces of compaction by heavy equipment. They were installed with the cup at either the 30-or 60-cm depth; the vacuum and collection tubes rested on the soil surface during treatment. Moderate compaction consisted of a double pass across the plots with a 19 400 kg crawler tractor (60 kPa ground pressure), advancing one track width (61 cm) each pass. Severe compaction included the moderate treatment followed by a double pass with a 20 455 kg rubber-tired, front-end loader (110–120 kPa), advancing one tire width (52 cm) each pass. Cleats on the tracks of the bulldozer pinched the polyethylene tubes on 25% of the samplers, but they were easily repaired. Severe compaction apparently damaged the ceramic cup on one of the 18 samplers installed at the 30-cm depth. Sample acquisition averaged 86% without reestablishing the vacuum during 3- to 4-wk intervals between collections. The samplers appear well suited for use in studies involving soil compaction by heavy equipment.

DURING MUCH OF EACH YEAR, heavy equipment used for logging and site preparation can compact soils. Forest management activities that decrease soil porosity and remove organic matter frequently are associated with declines in site productivity (Powers, 1990). A nationally coordinated study is underway (Powers et al., 1990) to evaluate these effects on long-term soil productivity (LTSP). In the northern Lake States region, research has been initiated in the aspen (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) forest type (Alban et al., 1994). In conjunction with that work, we designed a study to determine the effects of harvest intensity, organic matter removal, and compaction on soil nutrient leaching. To evaluate these treatment effects, the soil water samplers had to be installed before the treatments were applied; thus, they had to withstand compaction without serious damage. This note reports the construction and field performance of porous ceramic cup soil water samplers designed to withstand the forces of soil compaction by heavy equipment.

Materials and Methods

The samplers were constructed after the design described by Knighton and Streblow (1981) for an inverted sampler, with the reservoir located below the ceramic cup. We modified the design by using 7.6-cm (i.d.), Schedule 40, PVC pipe and end caps (part no. 85075, Cresline Co., Evansville, IN)[1] for the body of the samplers; thick-wall, 100 kPa (1.0 bar), high-flow ceramic porous cups (part no. 0653X02-B1M3, SoilMoisture Equipment Corp., Santa Barbara, CA); and 4.8-mm (i.d.), 2.4-mm wall, black latex tubing (Curtin Matheson Scientific, Houston, TX) to connect the sample collection and vacuum tubes (Fig. 1). The wall of Schedule 40 pipe is 6.4 mm, double that of the previous design. The ceramic cups have a 4.0-mm wall, compared with the 2.4-mm wall of those used previously. Black latex tubing was selected because it resists collapse under vacuum and is more resistant to chemicals, and presumably, to solar radiation than the amber formulation. We used high-density polyethylene for the vacuum and collection tubes.

We used the following procedures to construct the samplers, completing each step for all samplers before beginning the next step. We cut the PVC pipe into 14.6-cm lengths; this yielded 20 pieces from each 3.05-m (10-foot) length of pipe, and the completed samplers have a capacity of more than 700 mL. Next we drilled a 44-mm (1.75-inch) hole in the center of each top cap for the ceramic cup and a 19-mm (0.75-inch) hole for the rubber stopper near the edge of the cap, 3 to 4 mm from the center hole, and about 30° from vertical (Fig. 1). We then used a reamer to enlarge the inner diameter of the hole to about 20 mm and the outer diameter to 22 mm to approximate the taper of the rubber stopper; and inserted a no. 3, two-hole rubber stopper into the tapered hole until it extended through the cap, inverted the cap, and pulled the stopper inward until the larger end was nearly flush with the outer surface of the cap (pulling them through the hole provided a more secure fit than is possible by pushing them in). We applied epoxy cement (PC-7 Waterproof Epoxy, Protective Coating Co., Allentown, PA) to the inside of the hole in the cap and the outside neck of the ceramic cup, inserted the cup with a slight twist, and smoothed it off to form a uniform, air-tight bead.

We determined the length of polyethylene tubing required based on sample depth, and allowed an additional 50 to 60 cm to extend above the soil surface. Each sampler required two pieces of tubing, one about 15 cm longer than the other to extend to the bottom of the sampler (Fig. 1). We cut the tubing and marked each sample tube with plastic tape 4 to 5 cm from one end, trimming the other end at a 30 to 45° angle and applying liquid silicone lubricant (part no. RW206, Raingo, Genova Co., Davison, MI) to the end 2 to 3 cm of the tube before inserting it into the rubber stopper until it extended to the bottom of the sampler. We trimmed and lubricated the vacuum tube and inserted it into the other hole the full length of the stopper. We then connected the opposite ends of the tubes with two 5-cm lengths of black latex tubing attached to a 5-cm length of polyethylene tubing (Fig. 1).

Each completed sampler was numbered, flushed with 300 to 400 mL of 0.1 *M* HCl followed by three volumes of deionized water (Linden, 1977), and checked for flow rate under a 65 to 70 kPa declining tension. Of the 100 samplers constructed,

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[1] Trade names are provided for the convenience of the reader and do not imply endorsement or approval of any product by the U.S. Department of Agriculture.

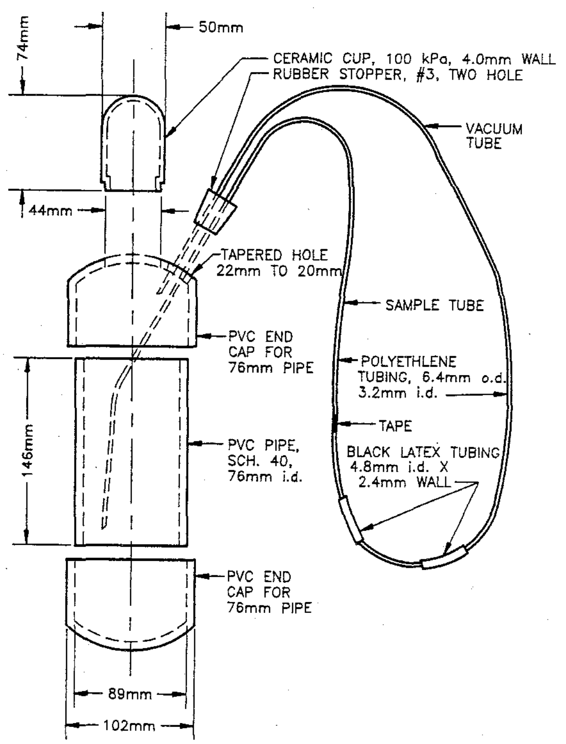

Fig. 1. Soil water sampler components.

the 88 with the most similar flow rates were selected for the study.

The thick-wall ceramic cups cost $15.00 each (September 1993), the Schedule 40 end caps $1.15 each, and Schedule 40 pipe cost $6.64 per 3.05-m length, or about $0.33 per sampler. Miscellaneous costs for tubing, epoxy cement, PVC primer and cement, rubber stoppers, etc. brought the total cost of materials to about $20.00 per sampler. Construction time was about 0.5 h each.

The study was installed on the Chippewa National Forest in Cass County, north-central Minnesota. The site is on the Guthrie till plain, a ground moraine deposited about 12 000 yr ago (Wright, 1972). The till is comprised of calcareous, grayish-brown, loamy, shaley materials overlain by a silt-loam loess cap about 40 cm thick. The predominant soil series is Warba silt loam (fine-loamy, mixed, frigid, Glossic Eutroboralfs, Soil Survey Staff, 1975). The soil becomes calcareous at about 100 cm and is highly productive; site index for aspen is 24.4 m (80 feet) at age 50 (Alban et al., 1991). The area supported fully stocked stands of predominantly 75- to 80-yr-old aspen with a minor component of other hardwood species.

The main LTSP study design is a complete 3 × 3 factorial with three replications; uncut control plots are located around the perimeter of the harvested blocks, for a total of 10 treatment combinations. The objectives are to evaluate effects of three levels of biomass and organic matter removal and three levels of compaction on subsequent soil conditions and vegetation development (Alban et al., 1994). The compaction treatments increased bulk density of the surface 25 cm of soil from 1.31 g cm^{-3} on noncompacted plots to 1.45 and 1.60 g cm^{-3} with moderate and severe compaction, and increased soil strength from 1000 kPa to about 1500 and 2000 kPa.

The stands were harvested during January and February 1993 when there was a 30- to 46-cm snowpack. On the noncompacted plots, the trees were felled with chain saws and winched off the plots with a cable skidder located outside the plot boundaries. On all other plots, the trees were cut with a feller-buncher and placed outside the plot boundaries; skidders did not enter any of the plots. Seven of the 10 treatment combinations were selected for sampling: (i) uncut control (NC); (ii) conventional (bole only) harvest (CH); (iii) CH plus compaction (CH+C); (iv) total tree harvest (TTH); (v) TTH plus compaction (TTH+C); (vi) TTH plus forest floor removal (TTH+FFR); and (vii) TTH+FFR plus compaction (TTH+FFR+C).

In early May, before the forest floor removal and compaction treatments were applied, samplers were installed with the cup at either the 30- or 60-cm depth at two locations on each of 18 harvested plots and four uncut control plots, a total of 88 samplers. At each sample point, a power-driven auger was used to bore a 10.2-cm-diam. hole at about a 45° angle to the soil surface; thus, the soil located vertically above each cup was essentially undisturbed. The sampler was inserted with the ceramic cup oriented upward and the rubber stopper on top. The soil from the hole was then replaced carefully to approximate the original profile. During backfilling, the soil was packed with a wooden stake every 5 cm to minimize percolation of water through the backfilled soil to the porous cup. After a 5- to 7-d equilibration, a 65 to 70 kPa vacuum was applied to each sampler, using a vacuum test hand pump (Model 2005G2, SoilMoisture Equipment Corp., Santa Barbara, CA).

The aboveground portion of the collection and vacuum tubes rested on the soil surface while the forest floor removal and compaction treatments were applied. The forest floor removal treatment consisted of first manually removing all undecomposed coarse woody debris, and then removing the forest floor materials, using a power-driven sidewalk sweeper with a revolving wire brush head 45 cm in diameter and 90 cm wide. The moderate compaction treatment consisted of a double pass across the plots with a Model D-7 Caterpillar tractor, advancing one track width (61 cm) each pass. Total weight of the tractor with bulldozer blade was 19 400 kg, providing a static ground pressure of about 60 kPa. The severe compaction treatment included the moderate treatment followed by a double pass with a rubber-tired, front-end loader with 52.1 by 63.5 cm (20.5 by 25 inch) tires, advancing one tire width each pass. It weighed 20 455 kg and applied 110 to 120 kPa of ground pressure. Four of the nine compacted plots received moderate compaction (16 samplers), and the other five received heavy compaction (20 samplers).

Soil solution samples were collected seven times between 9 June and 28 Oct. 1993. The samples were collected and the vacuum reestablished simultaneously by placing a pinch clamp on the latex tubing connected to the vacuum tube while the water was withdrawn from the sample tube (Fig. 1). The vacuum was not reestablished during the 3- to 4-wk intervals between sample collections. Variation in sample volume by collection date, sample depth, and compaction treatment each was evaluated by one-way analysis of variance; differences between means were tested using Tukey's Honestly Significant Difference procedure (Systat, 1992). Differences in sample volume between the noncompacted and severe compaction treatment were evaluated by a two-sample *t*-test for each depth.

Results and Discussion

The samplers withstood the forces of the compaction treatments with little serious damage. The polyethylene

Table 1. Sample acquisition and mean sample volume, Chippewa National Forest, 1993.

Collection date	Sample acquisition	Sample volume
	%	mL
9 June	70	338 a†
12 July	82	411 b
3 August	99	399 b
25 August	94	408 b
15 September	91	397 b
5 October	84	346 a
28 October	81	347 a
Mean	86	381

† Means followed by the same letter do not differ significantly at the P = 0.05 level; one-way analysis of variance.

collection or vacuum tubes were pinched on nine of the 36 samplers installed on plots that were compacted. The tubes were pinched if they were located above a sizeable tree root near the soil surface that provided sufficient resistance to the force exerted by the cleats on the tracks of the bulldozer. The damage was simple to repair; if the constriction was near the end of the tube, it was cut off. Otherwise, the tube was cut, the 2- to 3-cm damaged section was eliminated, and the pieces were spliced with a 5-cm length of latex tubing. Detection and repair of damaged tubing required 2 to 3 min per sampler. No damage to the tubes occurred from compaction by the rubber-tired, front-end loader. However, the additional pressure of the severe treatment damaged one sampler installed at the 30-cm depth, apparently by a slight fracture of the ceramic cup. Before the severe compaction treatment, the samples were clear; after the final treatment the sampler held a vacuum and collected water, but the samples were turbid, containing clay-size particles.

Tension lysimeters require continuous capillary contact between water in the surrounding soil and that within the porous wall of the sampler. With relatively infrequent (3- to 4-wk) sample collection and sampler evacuation, some samplers can be expected to lose the vacuum and not acquire a sample during each interval, particularly soon after installation. Sample acquisition increased from 70% at the first collection to 99% by the third collection, then gradually declined to 81% as rainfall decreased and the soils became drier later in the season (Table 1). Mean sample volumes of the first collection and last two collections were significantly lower than the intervening collections. Reestablishing the vacuum at more frequent intervals probably would have increased sample acquisition whenever water was readily available. Our laboratory protocol for this study includes determination of 24 chemical parameters and requires a minimum 50-mL sample. Between 12 July and 3 August, when water was readily available, all 88 samplers acquired water except one installed at the 30-cm depth in an uncut control plot. Individual sample volumes ranged from about 60 mL to >600 mL, and averaged 399 mL. During this period, only seven of the 87 functioning samplers acquired <100 mL of solution; all seven were at the 60-cm depth, and two were in uncut plots where evapotranspiration undoubtedly was higher than on plots occupied by first-year aspen suckers.

Table 2. Mean sample volume by depth and degree of compaction (number of samples in parentheses).

Compaction	Sample depth 30 cm	Sample depth 60 cm
	mL	
None	431 (162)	345 (145)
Moderate	430 (50)	338 (43)
Severe	386 (62)	313 (55)
Mean	420† (274)	337 (243)

† Difference between means is highly significant ($P < 0.01$); one-way analysis of variance.

Mean sample volumes varied significantly by depth for each compaction treatment (Table 2). Samplers installed at the 30-cm depth, near the base of the loess cap, acquired an average of 83 mL more water than those in the clay till at 60 cm. Moderate compaction had no effect on sample volume at either depth. At the 30-cm depth, mean sample volume of the severe compaction treatment was 45 mL less than on noncompacted plots (t-test, P = 0.045); at 60 cm the difference was about 30 mL, not statistically significant (P = 0.168).

Knighton and Streblow (1981) compared the chemical parameters of soil water samples collected with conventionally designed and inverted samplers and found no significant difference in N, P, K, Ca, or Mg concentrations nor in specific conductance. Samplers constructed by our modified design withstood soil compaction treatments with only minor damage; sample acquisition averaged 86% without reestablishing the vacuum during 3- to 4-wk intervals between collections. The samplers appear well suited for use in studies involving soil compaction by heavy equipment.

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FIBERGLASS WICK SAMPLER EFFECTS ON MEASUREMENTS OF SOLUTE TRANSPORT IN THE VADOSE ZONE

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Abstract

Fiberglass wick samplers are being evaluated by scientists to determine their effectiveness as soil pore water samplers. Part of this evaluation requires knowledge of the effects that the sampler itself has on the transport of the chemicals being sampled. Tracer (FD&C Blue Dye no. 1) tests were conducted to determine the dispersivities of clean 55-cm-long fiberglass wicks that could be used for sampling soil pore water. The tracer breakthrough data fit the convective-dispersive equation solution well ($R^2 > 0.984$) and resulting dispersivity estimates ranged from 0.59 to 4.3 cm. A finite difference model was used to simulate chemical transport through a soil and wick sampler system. The simulation results show that, for a 55-cm-long wick that samples 100 cm^2 in soil types with sand or silt characteristics, the additional travel time and dispersion are negligible. This was determined by comparing the chemical breakthrough curve predicted at the bottom of a 100-cm soil column to that predicted at the bottom of a sampling wick (at sample collection bottle). This result is expected since the water flux through a wick is usually much larger than in the soil (a single wick may intercept flow from up to 900 cm^2 of soil and typically has an area under 5 cm^2).

STUDIES of contaminant transport in the vadose zone require soil pore water samples that are representative of solute fluxes to the water table. To accomplish this, pressure continuity must exist between the soil pore water and the sampling device and the area of soil sampled must be known (Knutson and Selker, 1994). It is also important that the effects that the sampling device has on the transport and breakthrough of a chemical can be accounted for if necessary. A new sampler for use in the unsaturated zone is the PCAPS (Holder et al., 1991; Boll et al., 1992; Poletika et al., 1992). A PCAPS (Fig. 1) uses the capillary potential of vertically hanging fiberglass wicks to draw pore water samples from soils across a range of pressures. The sampling potential generated by a wick depends on the moisture content, which varies with the water flux. The water flux in a wick will depend on the area of soil sampled, soil water flux, and wick cross-sectional area. It is possible to design samplers for use at particular sites by matching the pore water pressure at the top of a wick to the matric potential in the soil profile across a range of fluxes (Knutson and Selker, 1994). The objective of the research presented here is to determine the effects that fiberglass wicks may have on the transport of chemicals and, if necessary, how to account for these effects when using capillary wick samplers.

Previous research concerning the effects of fiberglass wicks on solute travel has yielded promising results. Boll et al. (1992) reported an average dispersivity of 1.03 cm and a retardation coefficient of 1.3 with FD&W Blue Dye no. 1 and a 50-cm length of 1.27-cm-diameter wick produced by Pepperell Braiding Co. (Pepperell, MA). No retardation of inorganic or organic chemicals was found by Brown et al. (1986) for a 1.27-cm-diameter Pepperell wick. Poletika et al. (1992) found a typical dispersivity of 1.9 cm and retardation coefficients of 1.07 for Simazine and 1.04 for MS-2 Coliphage virus particles in a 9.5-mm-diameter Pepperell wick. These dispersivities and retardation coefficients are all negligible compared with typical values found in soils and could be caused by measurement error. Knutson et al. (1993) demonstrated that fiberglass wicks received from manufacturers have various types and amounts of organic chemical coatings that greatly affect the exhibited porous media and chemical transport properties. These compounds could cause sorption of solutes, which would also explain the small retardation coefficients reported by Boll et al. (1992) and Poletika et al. (1992). Knutson et al. (1993) also presented data showing that combustion at 400°C effectively removed these contaminants from wick materials with impurities <35 g kg^{-1}.

Materials and Methods

Woven and braided fiberglass wicks were purchased from three manufacturers. Three wicks from Pepperell Braiding Co., six wicks from Amatex Co. (Norristown, PA), and six from Mid-Mountain Materials Co. (Redmond, WA; Table 1). In Table 1, the terms *high*, *medium*, and *low* refer to density designations used by Amatex, *knit* and *matrix* refer to braid types used by Mid-Mountain, and the numbers 1, 1/2, 3/8, and 1/4 are used by all three manufacturers to identify wick diameters. These terms are retained and the product numbers are given for the Amatex and Pepperell wicks to aid interested

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Abbreviations: PCAPS, passive capillary sampler; BTC, breakthrough curve; CDE, convective–dispersive equation.