

SOIL SOLUTION NUTRIENT CONCENTRATIONS SAMPLED WITH TENSION AND ZERO-TENSION LYSIMETERS: REPORT OF DISCREPANCIES¹

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Abstract

Lysimeters were used to sample soil solutions in an ecosystem-level study of nutrient cycling in a southern Appalachian deciduous forest watershed. Four lysimeters were installed at each of 16 randomly designated locations. At each location, first at the litter-soil interface and again 30 cm beneath the litter-soil interface, one tension and one zero-tension lysimeter were installed side by side. Samples for 13 time intervals over a 15-month period were analyzed for water volume, H^+ , NH_4^+ , K^+ , Na^+ , Ca^{2+} , Mg^{2+} , NO_3^- , Cl^- , SO_4^{2-} , $H_2PO_4^-$, and dissolved silica. The sums of cations, the sums of anions, and the anion deficit (unmeasured anions) were calculated for each collection. Estimates of soil solution composition and water flow differed according to lysimeter type. At the litter-soil interface the zero-tension lysimeters collected 7 times more water flow which had significantly higher concentrations of H^+ , Ca^{2+} , and SO_4^{2-} and significantly lower concentrations of Na^+ , K^+ , and Cl^- than collections from tension lysimeters. At a soil depth of 30 cm, zero-tension lysimeters collected 2.1 times less water which had significantly higher concentrations of NH_4^+ , K^+ , NO_3^- , Cl^- , SO_4^{2-} , sums of cations, and sums of anions but significantly less silica than collections from tension lysimeters. A testable hypothesis is advanced to account for these observed discrepancies.

Additional Index Words: hardwood forest, cation-anion balance.

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IN studies of nutrient cycling it is often desirable to sample soil water at several depths to determine nutrient concentrations. Among sampling devices there are several types of tension or suction lysimeters constructed with porous ceramic discs or plates (Tanner et al., 1954; Cole et al., 1961), with porous ceramic cups of several sizes (Hansen and Harris, 1975), or with porous Teflon cylinders (Zimmermann et al., 1978). Tension may be applied by means of a hanging water column or by hand-powered or automatic vacuum pumping systems. Zero-tension lysimeters, constructed from metal (Jordan, 1968; Roose and des Tureaux, 1970), have relied on gravity to move water from the soil-air interface to the sample-collecting vessels.

Problems with the use of lysimeters in measuring water quality and quantity are well known. Tension lysimeters collect variable volumes, thus Cochran et al. (1970) recommend their use only for monitoring changes in water quality with respect to time at a particular sampling location. In a theoretical model

study comparing collections from porous ceramic cup lysimeters and tension lysimeters, van der Ploeg and Beese (1977) concluded that there "was no useful relation between extracted amount of soil water and freely percolating soil water . . ."; they thus recommended determining percolation rates in an independent manner. Further, they recommended the use of suction plates of a large cross-sectional area in preference to ceramic cups in order to obtain the most representative soil solution samples. Validity of water collections from two sizes of porous cup lysimeters were investigated by Hansen and Harris (1975) who reported problems including variability in intake rates, in total volume collected, and adsorption of P to the ceramic. Porous ceramic cup lysimeters were compared to porous Teflon by Zimmermann et al. (1978). They found that porous ceramic lysimeters collected 11% of the NH_4^+ and 43% of the PO_4^{3-} from test solutions, while Teflon lysimeters recovered between 102 and 106% of these ions in initial solutions. We are not aware of studies comparing tension lysimeters and zero-tension lysimeters.

In the planning of a study of nutrient cycling it was not clear which type of lysimeter would be most suitable for monitoring changes in the quantity and quality of soil solution that might result from a clear-cut logging operation. Thus we installed both tension lysimeter and zero-tension lysimeters side by side at 16 locations and at two depths on an experimental watershed. Here we report water flow and 14 chemical properties from 365 samples taken during 13 collection periods.

Methods

Tension lysimeters were made from 15 cm in diameter porous ceramic plates (Pacific Lysimeter, Seattle, Wash.) which were fitted with fiberglass resin backing and plastic drain tubes. Lysimeters were leached with 2 liters of 1N HCl (Grover and Lamborn, 1970) and then with deionized water until the electrical conductivity of the leachate was

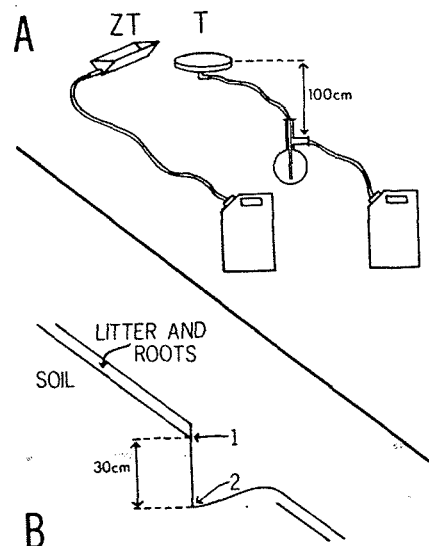


Fig. 1—Lysimeter elevations (A) lysimeters: zero-tension (ZT) drain by gravity, while tension (T) was fitted with 100-cm-hanging water column. Water accumulated in 20-liter carboy; and (B) elevations: one each ZT and T lysimeters placed at each level 1 and again at level 2. Not drawn to scale.

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Table 1—Monthly means for properties of lysimeter collections before clearcut of hardwood forest W. S. 7, Coweeta Hydrologic Laboratory, from February 1975 to April 1976.

Property	Litter				Soil			
	Tension		Zero tension		Tension		Zero tension	
	\bar{X}	SD*	\bar{X}	SD*	\bar{X}	SD*	\bar{X}	SD*
Mean flow, cm	3.56	5.91 ac	26.56	25.72 ad	6.68	11.85 bc	3.19	6.07 bd
Sample numbers								
Flow	208		207		208		207	
Chemistry	57		170		86		52	
Mean $\mu\text{eq/liter}$								
H ⁺	5.59	10.15 ac	13.86	23.66 ad	1.17	2.24 c	1.04	1.41 d
NH ₄ ⁺	3.35	9.47	5.14	16.11	1.71	4.52 b	8.72	24.29 b
K ⁺	75.04	32.88 ac	63.09	40.16 ad	28.28	23.54 bc	39.03	33.09 bd
Na ⁺	13.71	7.98	11.16	9.09 d	21.12	31.94	19.10	13.42 d
Ca ²⁺	71.11	35.95 c	99.43	111.72 d	34.42	29.88 c	46.37	45.63 d
Mg ²⁺	56.75	35.04	73.14	61.63	57.23	24.79	65.52	30.26
NO ₃ ⁻	0.87	1.89	1.33	2.65	0.61	1.84 b	2.11	3.65 b
Cl ⁻	45.38	48.12 c	35.96	27.35	24.57	25.49 bc	39.84	28.50 b
H ₂ PO ₄ ⁻	0.95	1.70	0.96	4.05	0.96	1.63	1.19	1.18
SO ₄ ²⁻	102.51	53.25 ac	124.23	72.94 ad	67.49	23.66 bc	100.58	39.34 bd
Cation sum	225.57	93.44 c	265.83	181.61 d	143.94	64.72 bc	179.79	80.92 bd
Anion sum	149.71	85.31 c	162.47	83.63	93.64	33.26 bc	143.73	59.01 b
Cation sum - anion sum	75.86	75.48 c	103.35	172.17 d	50.30	64.76 c	36.05	77.97 d
Dissolved silica, $\mu\text{g/liter}$	2024.0	1822.6 a	618.72	393.87 ad	2519	1455 b	1472 b	1020 bd

* Difference between (a) tension and zero-tension lysimeters in litter significant at 0.05 level; (b) tension and zero-tension lysimeters in soil significant at 0.05 level; (c) tension lysimeters in litter and soil significant at 0.05 level; and (d) zero-tension lysimeters in litter and soil significant at 0.05.

indistinguishable from the initial deionized water of about 0.15 mS/m. Zero-tension lysimeters were constructed according to Jordan (1968). Briefly, they consisted of stainless steel troughs, 5.2 cm by 30 cm by 4.0 cm-deep, fitted with fiberglass screen supporting glass wool and stainless steel drain rods and tubes beneath the screen. Tension and zero-tension lysimeters were installed, one each at the litter-soil interface such that lysimeter collecting surfaces were flush with the soil surface (Fig. 1). One tension and one zero-tension lysimeter were also placed against the ceilings of tunnels located 30 cm beneath the soil surface. Access holes were back filled. Buried plastic tubes drained percolates from lysimeters to 25-liter-vented plastic carboys. Drains from tension lysimeters were inserted within a few millimeters of the bottoms of 500-ml sidearm flasks. The elevations of flask drain spouts were adjusted to lie 100 cm below the surface of a particular lysimeter plate. When filled with water, this assembly provided a 100-cm-hanging water column as well as a 500-ml reservoir of water. When soil suction exceeded 100 cm, water in the flask would, for some time at least, keep the lysimeter plate wet and in hydraulic contact with the soil. Flasks were vented above the drain spouts. Spouts were drained by plastic tubing to individual 25-liter carboys. Identical installations were made at 16 locations, randomly designated, on a hardwood forest watershed at the Coweeta Hydrologic Laboratory, Otto, N.C. A percent water collection efficiency term was calculated for each lysimeter type as the number of samples of sufficient volume for chemical analyses divided by the product of locations and monthly sampling intervals ($16 \times 13 = 208$) $\times 100$.

Water flow in centimeters was calculated as the volume collected during each sampling interval divided by the area of the collector.

Water samples were analyzed for Na⁺, Ca²⁺, Mg²⁺, and K⁺ with a Perkin-Elmer model 305 atomic absorption spectrophotometer (Perkin-Elmer Co., Norwalk, Conn.) while NH₄⁺, NO₃⁻, PO₄³⁻, Cl⁻, SO₄²⁻, and silica were determined colorimetrically with a Technicon Autoanalyzer (Technicon Co., Tarrytown, N.Y.). Because sample pH values ranged from 4.0 to 6.0, the P in solution is assumed to be H₂PO₄⁻ (Lindsay, 1979). The pH was determined with a glass

electrode and a Beckman Zeromatic SS-3-pH meter. The H⁺ was calculated from pH.

Means, standard deviations, analysis of variance, and correlations were computed with the statistical analysis system of Barr et al. (1976).

Results and Discussion

Results show that tension and zero-tension lysimeters sample both soil water fluxes and ions differently.

Sample volume was not always sufficient to complete analyses for all elements. Thus, 19 out of the 384 samples have been omitted from statistical analysis of chemical constituents given in Table 1. The number of completely analyzed samples was used to calculate collection efficiency. Water sample collection efficiencies for tension lysimeters were 27% beneath the litter and 41% at the 30-cm depth in the soil. The zero-tension lysimeter values were 82% for litter and 25% for soil, respectively.

Zero-tension lysimeters collected 7 times more water than the tension lysimeters beneath the litter. This pattern was reversed at the 30-cm depth in the soil where the tension lysimeter collected 2.1 times more water than the zero-tension lysimeter.

If the two lysimeter types were sampling the same soil water fractions, we would expect significant positive correlations between the two lysimeter types in terms of element concentrations in and volumes of samples collected. If there were a dilution effect of large storm volumes on elements mineralized out of litter, a negative correlation between element concentration and sample volume in the litter solution might be expected. Correlations calculated for collection volume and for the 14 chemical properties of the water sampling were generally quite low. At the litter-soil interface, the correlation between the volumes collected by the two lysimeter types was 0.031, while

for the chemical properties, the values ranged from a low of 0.005 for Na^+ up to 0.79 for NO_3^- . At the 30-cm depth in the soil the correlation for collection volume was higher at 0.38, while values for chemical properties ranged from a low of -0.012 for Cl^- to highs of 0.32, 0.33, and 0.53 for H_2PO_4^- , SO_4^{2-} , and silica, respectively.

Samples from zero-tension and tension lysimeters beneath the litter differed significantly with respect to four chemical constituents (Table 1). For those differing significantly, the concentration ratios in zero-tension/tension lysimeters were: H^+ , 2.4; SiO_2 , 0.31; K^+ , 0.53; and SO_4^{2-} , 1.36. At the 30-cm depth there were significant differences between water samples from the two types of lysimeters for eight chemical constituents (Table 1). The concentration ratios of zero-tension/tension lysimeters for those properties were: NH_4^+ , 5.1; K^+ , 1.4; NO_3^- , 3.4; Cl^- , 1.6; SO_4^{2-} , 1.5; cation sum, 1.3; anion sum, 1.5; and silica, 0.58.

For each lysimeter type there were significant differences between concentrations sampled in the litter and in the soil (Table 1). For zero-tension lysimeter's eight chemical constituents differed significantly between the litter and soil collections. The ratios of concentration in litter/soil were: H^+ , 13.3; K^+ , 1.60; Ca^{2+} , 2.14; SO_4^{2-} , 1.2; cation sum, 1.5; anion sum, 1.1; anion deficit, 2.8; Na, 0.59; and SiO_2 , 0.4, indicating a removal of all of these elements except Na^+ and SiO_2 from water as it percolated from litter to soil. The tension lysimeter's eight properties also differed significantly between water samples from the litter and from the soil. The ratios of concentrations in litter/soil were: H^+ , 4.7; K^+ , 2.6; Ca^{2+} , 2.1; Cl^- , 1.8; SO_4^{2-} , 1.4; cation sum, 1.6; anion sum, 1.6; and anion deficit, 1.5. These elements were significantly removed from the soil solution as it passed from the litter-soil interface to the 30-cm depth in the soil.

Discrepancies in collection volume between the types of lysimeters or great variability of collection volume for a given type of lysimeter are less a problem than are discrepancies in solution chemistry. Zero-tension lysimeters were designed to sample chemical properties of the soil solution (Jordan, 1968). The variability of sample volume obtained with tension lysimeters is well known (Cochran et al., 1970; van der Ploeg and Beese, 1977; Hansen and Harris, 1975). Element concentration data from either type of lysimeter can be multiplied times water fluxes estimated by a number of hydrologic methods in order to obtain estimates of downward element flux.

Our current testable working hypothesis to account for differences in water quality sampled by the two devices follows. The observed pattern of lysimeter collections might result from interactions of real soil nutrient concentrations, soil water volumes, and lysimeter tension and resistance characteristics. Instantaneous real soil solution nutrient concentrations are likely to be interacting functions of microbial oxidation rates, nutrient uptake rates by plants, and soil water content. Magnitudes of each of these factors and the amounts of soil water are expected to vary with elapsed time since the most recent storm and to show broad seasonal trends. Maximum quantities of min-

eralized and leachable elements might occur in decomposing litter after several days without rain. During the first few hours of a new rain episode, these accumulated mineralized elements could increase element content of soil solution at the litter-soil interface. The amount of soil water collected by a given lysimeter will also change with time. Using the Ohms law analogy in which flux is a function of a gradient in potential energy divided by the sum of the resistance terms (e.g., Campbell, 1977, p. 7), we can say that the amount of water collected will approximately equal

$$\frac{(\text{soil water tension} - \text{lysimeter tension})}{(\text{soil hydraulic resistance} + \text{lysimeter resistance}),}$$

where hydraulic resistivity is the path length divided by hydraulic conductivity. The zero-tension lysimeter is a low tension, low resistance device. It is thus expected to most efficiently sample a pulsed element input to saturated flow beneath the litter. The tension lysimeter has a higher tension term but this is achieved by use of small pores which confer upon it a higher resistance term. It is expected to sample saturated flow less efficiently, and to sample nonsaturated flow more efficiently.

We believe that the excess of measured cations over measured anions, or the anion deficit (Table 1), results from some combination of HCO_3^- and organic acid anions. The anion deficit in water from lysimeter samples from a New Hampshire subalpine forest ranged from 0 to 31% of the total measured cations with an overall average of 11% (Cronan et al., 1978). Their samples contained no HCO_3^- because of low pH. Using gas chromatography and ultraviolet light oxidation, they determined the unmeasured anions to be organic acids. They reviewed other studies in which the anion deficits in samples from springs and lysimeters ranged from 62 to 77% of the sums of measured cations. During our study we did not measure either HCO_3^- or organic acids.

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