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LEACHING FROM A TROPICAL ANDEPT DURING BIG STORMS: A COMPARISON OF THREE METHODS

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We measured water and nutrient (Ca, Mg, K, and NO_3) leaching in the field using three methods: (1) estimates of flux using the Darcy flow equation, (2) a water balance, and (3) zero-tension lysimeters. The methods were compared in an Andept near Turrialba, Costa Rica, during two large storms (33 and 22 cm wk^{-1}), at two soil depths (25 and 110 cm), and in four kinds of 1- to 2.5-yr-old vegetation. The water balance was the most accurate method, because the other two techniques sample only parts of the flow. Zero-tension lysimeters were evaluated for use in measuring channeled flow under certain conditions.

Mean water flows calculated by the flux and water balance methods were significantly different: 28.5 and 31.5 cm, respectively, at 110 cm during the 33-cm storm. The flux method overestimated water flow during the 22-cm storm: 51.7 cm compared with 21.7 cm determined by the water balance. Mean water flow determined from zero-tension lysimeter data during both storms was substantially lower than that estimated by the other two methods: 2.1 cm for the 33-cm storm and 2.5 cm during the 22-cm storm.

Nutrient leaching was determined two ways. First, nutrient concentrations measured using porous cup samplers were multiplied by water flows derived from water balance data. Second, nutrient concentrations of leachate collected by zero-tension lysimeters were multiplied by water flows from the lysimeters. In general, nutrient losses determined by the first method were greater than those measured by zero-tension lysimeters, but in some of the vegetations, nutrient losses were so low that there was no difference between the two methods.

A few zero-tension lysimeters collected large amounts of leachate even though the soil did not reach saturation during the storms. Solution collection in the lysimeters was mostly a large-storm phenomenon; of the solution caught annually by the lysimeters at 110 cm, 84% was collected during two, week-long storms. One lysimeter (of 96 monitored) consistently collected leachate in excess of the rainfall and low in nutrient concentrations. It is likely that this lysimeter sampled channeled flow. In this soil, where lateral flow is relatively unimportant and impeding layers do not occur, the lysimeters provide a measure of the occurrence and quality of rapid channelized flow.

Over the last few decades soil scientists, hydrologists, foresters, and ecologists have become increasingly interested in monitoring downward water and nutrient fluxes in soils. However, problems with various methods for measuring these fluxes, especially in field studies on small plots, remain unresolved.

Methods based on soil physical principles have provided valuable information concerning fluxes through plowed, homogeneous soils (Kelley et al. 1946; Richards 1949; Robins et al. 1954; Black et al. 1965; Hagan et al. 1967; So et al. 1976; Libardi et al. 1980). Recently, application of these methods to unplowed and highly structured soils has been questioned (DeVries and Chow 1978; Bouma 1980; Beven and Germann 1982).

Difficulties have also been encountered when a collection device is used to capture leachate (Cochran et al. 1970). In some studies, results obtained using the zero-tension lysimeter described by Jordan (1968) did not correspond with those obtained by other methods, and the reasons for the discrepancies were unclear (Haines and Waide 1979; Haines et al. 1982). Downward water flow under unsaturated conditions cannot be measured accurately using pan-type lysimeters, because capillary forces in the soil surrounding the lysimeter may cause soil solution to pass around the soil directly above the lysimeter (Colman and Hamilton 1947). However, nutrient concentrations of

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leachate collected by zero-tension lysimeters have been assumed to be representative of leachate in the soil profile (Jordan and Kline 1972). Despite the frequent use of zero-tension lysimeters, it has not been determined just what the device actually measures under unsaturated soil conditions.

The objectives of this study were to estimate water and nutrient flows during large storms, using the Darcy flow equation and zero-tension lysimeters, and to compare these estimates with a water balance. Although there may be some overlap in the water sampled by the two techniques, Darcy flow estimates the movement of all water through the soil except that which moves freely through macropores or low-resistance channels. Most of the water captured by zero-tension lysimeters, however, is free-flowing, either because the soil is saturated or because the water is flowing through a macropore or channel.

MATERIALS AND METHODS

Study site

The study site is located near Turrialba, Costa Rica, in the Florencia Norte forest of the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) at 9°53′ N, 83°40′ W. Turrialba is ~60 km from the Atlantic coast. The 2.4-ha study site is situated at an altitude of ~650 m.

The warm, humid climate is classified as Afi in the Koppen system (Morrison and Leon 1951). Tosi (1969) classified the area as tropical premontane wet forest *sensu* Holdridge (1967). According to CATIE's meteorological data, mean annual precipitation (1944 to 1979) is 264 cm and the mean monthly temperature (1959 to 1979) is 22.3°C.

The study site soil (of the Colorado series) has been most recently classified as a Typic Dystrandept (Martini 1969; Harris et al. 1971). It overlies upper Miocene or lower Pliocene age bedrock (Hardy 1961). Through recent times, ash showers have contributed fresh ash to this soil, which is derived from older lava. Physical structure of the soil is highly aggregated and stable (Hardy 1961). The soil is deep (> 6 m to bedrock) and freely drained. Biotic activity in the soil is high. Animal tunnels, especially those of the leaf-cutter ant *Atta cephalotes*, extend to a depth of > 2 m (Alvarado et al. 1981). The soil, like many Andepts, has unusual physical properties, including a high water-holding capacity; at tensions as high as ~15 bar, the moisture content by volume is ~30%. Soil losses by erosion are low (Ives 1951).

In early 1979 the second-growth vegetation at the study site was felled and burned (Ewel et al. 1981). Immediately after the burn, four kinds of vegetation were initiated as part of a broad research project intended to explore the feasibility of using complex vegetation as models for tropical agroecosystem design. The experimental vegetation types (described in Ewel et al. 1982 and Blanton and Ewel 1985) consisted of the successional vegetation that regenerated following the burn, plus three experimental ecosystems that ranged from a 1-yr-old monoculture of trees (*Cordia alliodora*) to three 2.5-yr-old communities that contained > 50 species on each plot. Mean canopy height in the vegetations ranged from 3.9 to 5.2 m, and the tallest tree at the site was 13.0 m. Six plots of each of the four kinds of vegetation were established; each of the 24 study plots was 14 m on a side (196 m^2), plus a 1-m-wide buffer strip.

Water flow

Water flows were determined during two large storms and at two depths, 25 and 110 cm. The first storm, of 32.62 cm, occurred during the week of 7–13 November 1981. The second storm, of 22.24 cm, took place from 22–27 November 1981. Soil water flows during the two large storms were calculated by three methods: (1) Darcy flow (referred to hereafter as *flux*), (2) water balance (referred to as *balance*), and (3) zero-tension lysimetry (referred to as *lysimetry*). The first two methods involved measurements of soil moisture tension.

Mercury manometer tensiometers, described by Richards (1949) and Slavik (1974), were used to measure soil moisture tension (also known as pressure potential, matric potential, suction, pressure deficiency, and capillary tension). One tensiometer was installed at each of four depths, 15, 45, 75, and 115 cm, in each of the plots. During installation we attempted to minimize soil compaction and smearing around the cup, while maintaining good soil contact. We excluded microsites that obviously received channeled flow (e.g., at the bases of trees and within ant tunnels). Insofar as possible, the 96 tensiometers were read at the beginning and end of each of the several rain events that comprised the week-long storms: 15 times during the 33-cm storm and 7 times during the 22-cm storm.

By the flux method, a water flux (q) was calculated for each study plot at the beginning and end of each rain event during the two storms. The fluxes, integrated over the storm times, estimated the downward water flow during the storm. Fluxes were calculated using Darcy's law

$$q = K(\theta)\, dH/dz$$

where K is the hydraulic conductivity at the volumetric content θ, and dH/dz is the rate of change in total hydraulic potential (H) with respect to depth z. Two sets of relationships were determined experimentally to calculate a flux: (1) soil moisture retention, the relationship between soil moisture tension (measured using tensiometers) and volumetric water content; and (2) the relationship between volumetric water content and hydraulic conductivity. To determine soil moisture retention, one intact sample core, 3.5 cm in diameter and 1 cm deep, was taken from three of the replicates of each of the four types of vegetation, at four depth intervals (0 to 15, 15 to 45, 45 to 75, and 75 to 115 cm), and for each of the seven soil moisture tensions for which a gravimetric water content was to be measured, yielding a total of 336 samples. Pressure-plate and pressure-membrane apparatuses produced the seven tensions used to create the moisture retention curves: 0.01, 0.05, 0.10, 0.20, 0.33, 0.50, and 1.00 bar.

Hydraulic conductivity was measured in situ in the 11-yr-old second-growth forest between study plots, using the internal drainage method reviewed by Hillel (1980). A 1.4-m-diameter soil core, trenched to a depth of 120 cm and encased in plastic, was brought to saturation. Soil moisture was monitored as a function of time as water drained from the core, using eight tensiometers (two sets at four depths: 15, 45, 75, and 115 cm).

Because this study concerned water flow during large storms, three assumptions were made that simplified calculation of a water balance. The first was that, during large storms, the proportion of rainfall intercepted by the vegetation was small relative to the total rainfall and could be ignored. The second assumption was that all water flow was vertical and downward through the profile. Overland flow of water was not observed on the study plots during the storms. Lateral flow along the interface between horizons was not investigated, but was assumed not to occur because a hardpan or other impeding layer does not occur at the study site. Third, water losses via evapotranspiration were assumed to be small and could be ignored. Therefore, a water balance could be calculated as the difference between total rainfall and the change in soil water storage resulting from the rainfall. Amount and timing of rainfall were measured using a tipping-bucket rain gauge that recorded rain in 0.25-mm increments. As in the flux methods, the measurements of soil moisture tension before and after the individual rain events during the storms were converted to a volumetric water basis using the experimentally derived soil moisture retention curves.

In the lysimetry method, the volume of leachate collected as outflow from zero-tension lysimeters was measured daily during the two storms. The apparatus, described by Jordan (1968), is a stainless-steel trough, 5 cm wide, 30 cm long, and 4 cm deep. The top is fitted with a fiberglass screen that supports glass wool. Stainless-steel drain rods and tubes are situated beneath the screen. A pit 1.5 m deep was dug in the topographically lowest quadrant of each of the 24 study plots. On the upslope side of the pit, a tunnel ~1 m long was excavated such that it sloped slightly upward from the wall of the pit. The lysimeter was inserted in the tunnel and pressed upward as the space below the trough was backfilled. Tygon tubing was used to connect the outflow tube on the downslope side of the lysimeter to a vented collection bottle. Two sets of lysimeters were installed at each of two depths, 25 and 110 cm, in each of the 24 plots.

Nutrient flows

Nutrient flux was calculated by multiplying the water flux by the nutrient concentration of the soil solution (Hillel 1980). Soil solution concentrations of the following nutrients were determined: Ca, Mg, K, and NO_3. Soil solution was sampled two ways and at two depths (25 and 110 cm) in all 24 study plots.

For the flux and balance methods, soil solution nutrient concentrations were determined using large-diameter (4.8 cm) porous cup samplers. They were first described by Briggs and

McCall (1904) and recently evaluated by Hansen and Harris (1975) and Silkworth and Grigal (1981). Two sets of porous cup samplers were installed at two depths, 25 and 110 cm, in each of the 24 plots. Samples were taken once during the 33-cm storm, over a 48-h period at a tension of 600 mbar. Samples were also routinely taken at the study site once a month; thus nutrient concentrations over time and under different soil moisture conditions were monitored. Samples from the two samplers at the same depth within a study plot were pooled.

The leachate collected from the zero-tension lysimeters was also analyzed for nutrients. Two sets of samples, one for each storm, were collected. Samples were collected daily, but were pooled for chemical analyses over the entire week-long storm. Samples were filtered through no. 40 Whatman paper, preserved with boric acid if destined for NO_3 analysis, and refrigerated until analyzed. Concentrations of cations were determined by atomic absorption. For NO_3 analysis, $AgSO_4$ was added to eliminate interference by Cl^- ions; samples were analyzed with an NO_3-sensitive electrode.

RESULTS

Water flows

Hydraulic conductivity, as measured in situ with the giant soil core, varied linearly over a range of volumetric moisture contents from about 58% to saturation (76%). This corresponds to a range of soil moisture tensions of 0.01 to 0.00 bar. At a soil depth of 15 cm, it ranged from 14.0 to 42.7 cm h^{-1}. The infiltration rate, which was measured as water was supplied to the core, was 35.4 cm h^{-1} at saturation.

Mean (standard error, SE) soil moisture tensions, averaged over all plots and depths, were highest prior to the onset of storms: 0.112 (0.008) bar before the 33-cm storm and 0.105 (0.005) bar before the 22-cm storm. When the soil was wettest, mean (SE) soil moisture tensions were 0.025 (0.002) and 0.028 (0.002) bar during the 33- and 22-cm storms.

Mean hydraulic gradients at the 110-cm depth prior to the onset of the 33- and 22-cm storms were −0.60 (0.14) and −0.76 (0.10), respectively. Even when the soil was wettest during the two storms, mean (SE) hydraulic gradients were −0.70 (0.06) and −0.62 (0.07), respectively, indicating that flow was not steady state but transient.

Two sets of ANOVAs were performed to test for differences in (1) water flows between the two tensiometric methods, and (2) water and nutrient flows in the balance and lysimetry methods. In both cases, ANOVAs were carried out separately for each storm, and the model included terms for the depth at which the measurement was made, the type of vegetation, and all possible interactions.

Water flows determined by the two tensiometric methods were significantly different at both depths and during both storms ($p > F = 0.001$). During the 33-cm storm, mean water flows calculated by the flux and balance methods were 28.5 and 31.5 cm, respectively, at 110 cm, and 7.1 and 28.4 at 25 cm. During the 22-cm storm, the difference between the two means was more striking: 51.7 cm determined by the flux method compared with 21.7 cm calculated by the balance method at 110 cm, and 21.9 and 20.9 cm, respectively, at 25 cm. Mean fluxes past the two depths were not different as determined by the balance method, but were different as calculated by the flux method. The flux method predicted a high frequency of near-zero values and a broader range of water flows, whereas the balance method predicted means that closely approximated the rainfall received (Fig. 1). Because the flux method predicted some unlikely water flows, only balance method water flows were used to calculate nutrient flows. Lysimeters at 110 cm captured only 2.1 cm of water during the 33-cm storm and 2.5 cm during the 22-cm storm. There were no significant differences in water flows into lysimeters past the two depths or among the four vegetations.

Nutrient flows

Mean nutrient losses determined by water balance/porous cup sampler data were substantially greater than those determined by lysimetry (Table 1). However, due to the influence of vegetation on soil-solution nutrient concentrations (especially solution sampled using porous cups) and high variability among samples, nutrient losses estimated by the two methods did not always differ significantly, even though they probably reflect different phenomena.

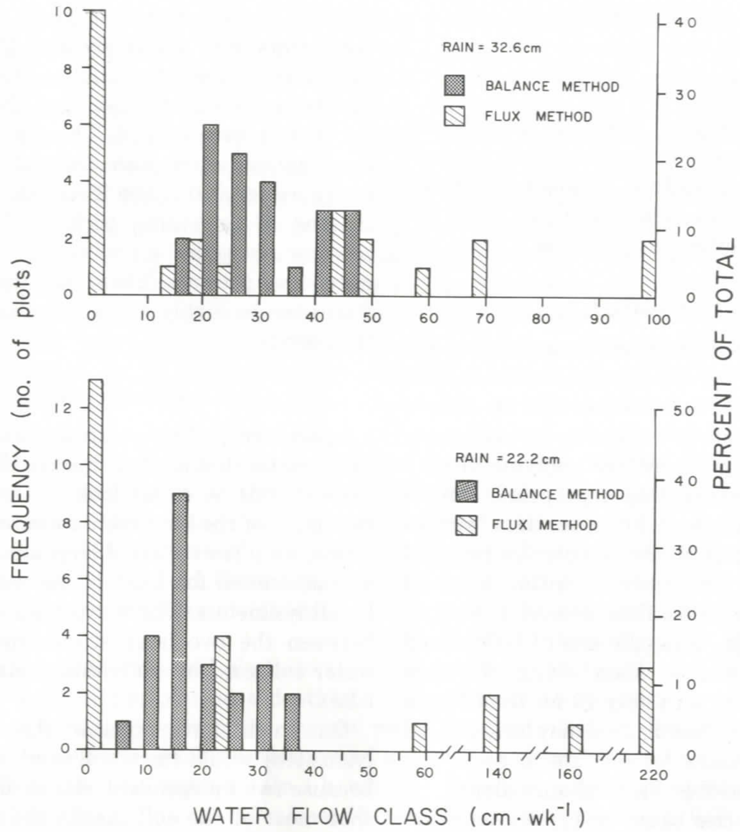

FIG. 1. Water flow calculated by two methods.

TABLE 1

Comparison of methods of determining water and nutrient flow

Depth, cm	Storm size, cm	Method	Water[a]	Ca	Mg	K	NO_3
25	33	Balance	28.36	3.78	2.10	3.16	4.14
			(24.72–30.53)[b]	(2.29*5.03)	(1.44*3.24)	(0.52*7.26)	(0.83*7.48)
		Lysimetry	2.43	0.27	0.11	0.20	0.19
	22	Balance	20.89	2.98	1.57	2.19	3.20
			(19.75–22.79)	(1.55*4.23)	(0.94*2.40)	(0.33*4.98)	(0.46*5.53)
		Lysimetry	1.13	0.08	0.04	0.09	0.07
110	33	Balance	31.52	3.46	1.71	1.34	3.24
			(26.95–37.26)	(1.02*6.46)	(0.76*3.24)	(0.34*3.58)	(0.20*7.20)
		Lysimetry	2.10	0.23	0.04	0.01	0.31
	22	Balance	21.68	2.41	1.21	0.99	2.27
			(19.40–26.58)	(0.80*3.80)	(0.58*2.43)	(0.23*2.86)	(0.15*4.28)
		Lysimetry	2.53	0.04	0.03	0.06	0.06

[a] Water is in cm, all others are kg ha^{-1}.

[b] Parenthetical values are ranges of means corresponding to different vegetation types. Means separated by – did not differ significantly; means separated by * indicate that there were significant differences among vegetation types. None of the lysimetry data differed significantly among vegetation types.

DISCUSSION

Balance method

The water balance method consistently yielded water flux estimates that closely approximated rainfall. Therefore, estimates obtained by this method were used to evaluate flows determined by the other two methods.

Flux method

The flux method predicted some unlikely water fluxes. The most obvious explanation in such a heterogeneous environment is that the sample size was too small to enable us to accurately estimate the true mean. By applying Stein's procedure for determining appropriate sample size (Steel and Torrie 1960) to our data from all 24 plots, we calculated the sample size required to estimate the true mean to within 5 cm of water flow at a 95% confidence level. For water flows past 110 cm, a sample size of 1093 would have been necessary when using the flux method, compared with only 10 for the balance method. Thus, the flux method may have yielded reasonable estimates for one storm or at one depth but not another due to chance alone.

Calculating fluxes based on (1) soil moisture tensions averaged over depth as well as over time and (2) our lowest estimates of hydraulic conductivity (the equations for the 15 cm depth) did not yield a more realistic flux for the 22-cm storm. A more reasonable mean water flow (past 110 cm) of 28 cm for that storm is obtained if three plots with extremely high fluxes are excluded from the calculations. However, there was no reason to believe that the data from these plots were invalid. The microsites where these tensiometers were located were consistently wetter during the 22-cm storm than during the 33-cm storm, perhaps due to subtle changes in vegetation structure or below-ground water-flow patterns. These data emphasize that fluxes can be highly variable both spatially and temporally.

Lysimetry study

Lysimeters probably trap only a small fraction of the water that leaches through the soil during large storms. A closer look at the data shows that most of the lysimeters collected little or no water, but a few collected large amounts (Fig. 2) and accounted for most of the water collected by all lysimeters. There was a good correlation between the two large storms in amounts of water collected by individual lysimeters (r^2 = 0.99).

One might have expected that none of the lysimeters would have collected any leachate, because two independent sets of data indicated that most of the soil matrix did not saturate during the storms. First, soil moisture tension, as determined by > 90 tensiometers, did not reach zero. Second, the infiltration rate of the soil is high (35.4 cm h^{-1} at saturation) and far exceeds the highest rainfall intensity (2.1 cm h^{-1} during the 33-cm storm). Thus, the results bring up an interesting question: How did water get into any of the zero-tension lysimeters if the soil matrix was unsaturated? One possibility is that less permeable layers at any point above the zero-tension lysimeter would cause water arriving via unsaturated flow to pond up until sufficient pressure built up and overcame the soil-air interface at the soil-lysimeter junction. However, this does not explain how one lysimeter collected an amount that exceeded the rainfall (58.7 cm during the 33-cm storm and 50.7 during the 22-cm storm). Most of the flow from that lysimeter occurred on 11 and 12 November when daily rainfalls were 10.0 and 2.8 cm, respectively. Clearly, that lysimeter was collecting water funneled from an area larger than that intercepted by the lysimeter. The question of how rainfall could be channeled was not addressed in this study; however, some field observations, plus results of other researchers provide insight into the problem.

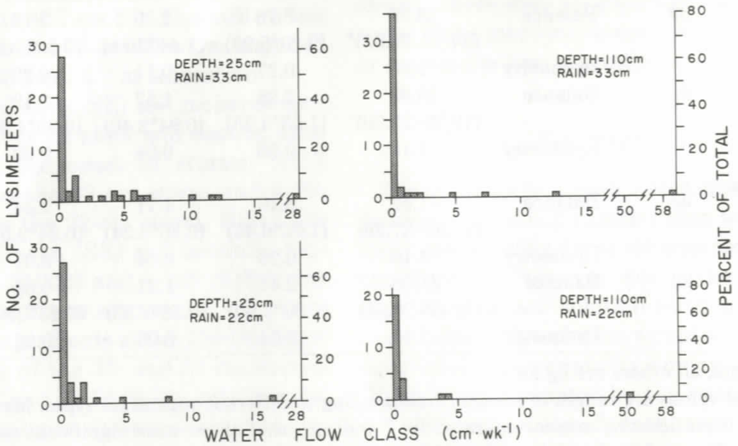

FIG. 2. Frequency distribution of water flow as determined by zero-tension lysimeters.

The face of one of the soil pits intersected a channel ~3 cm in diameter, at a depth of ~40 cm. Faucetlike water flow from the channel was steady and rapid during peak rainfall; the 3.6 m^3 soil pit filled with clear water within 1 h, which would have required a flow rate of at least 60 000 cm^3 min^{-1}. This demonstrated the existence of preferential pathways of water flow at the study site and their capability of conducting large amounts of water.

Over 100 yr ago, Lawes et al. (1882) discovered that water added to soil profiles can move immediately through open channels and interact only slightly with water in the soil matrix. More recent work has verified that channels formed by roots and animals can be quite effective in conducting water through soils, even when the soil is unsaturated (Aubertin 1971; Beasley 1976; Quisenberry and Phillips 1976; Mosley 1979, 1982). Bouma et al. (1982) monitored the volume of water that had to be applied to individual channels to keep them filled. For continuous, more or less vertical worm channels < 6 mm in diameter and extending to a maximum depth of 1.6 m, they measured infiltration rates of 140 ± 30 cm^3 min^{-1}. Flow rates into mole burrows extending to a depth of 50 cm were 400 ± 100 cm^3 min^{-1}.

Collection of leachate in the lysimeters at a depth of 110 cm is clearly a large-storm phenomenon. Data taken during the two, week-long storms were compared with the data taken during the 50 wk of the year when large storms did not occur. Of the water collected by lysimeters at 110 cm over a 1-yr period, 84% was collected during the two storms. Nutrient concentrations (excepting K) were especially high in the leachate captured during the first storm, which accounted for 86% of the Ca, 67% of the Mg, and 77% of the NO_3 caught during the entire year by lysimeters at 110 cm. The second storm yielded leachate at 110 cm that was much lower in nutrient concentration; it accounted for only 5, 15, and 13% of the annual amounts of Ca, Mg, and NO_3 picked up by lysimeters at 110 cm.

There is further evidence that these lysimeters sample different flow than do porous cup samplers. In general, cation concentrations of soil solution collected by the two apparatuses were different. Although there was no consistent trend in nutrient concentrations with respect to water flow rate from the lysimeters, the leachate from the lysimeters that collected amounts of water in excess of rainfall tended to have extremely low nutrient concentrations (Table 2). In particular, the leachate from the lysimeter that yielded flow rates of > 50 cm wk^{-1} during the storms had consistently low nutrient concentrations (mg L^{-1}): 0.05 to 0.09 Ca; 0.05 to 0.09 Mg; 0 to 0.05 K; and 0.11 to 0.25 NO_3. These concentrations were almost as low as those of the incoming rainwater at the site (Hendry et al. 1984).

TABLE 2

Nutrient concentrations of water sampled by lysimeters and porous cups during large storms

Nutrient	Lysimeter catches[a] (mg L^{-1})		Porous cup samplers
	Volumes ≥ rain	Volumes < rain	
Ca	0.30	2.06	1.27
	(0.15)	(0.46)	(0.21)
Mg	0.13	0.56	0.64
	(0.07)	(0.07)	(0.07)
K	0.10	1.29	0.81
	(0.10)	(0.56)	(0.26)
NO_3	0.14	2.16	1.16
	(0.11)	(0.59)	(0.28)

[a] For both lysimeter catches and porous cup samplers, means (standard errors) are based on data from both depths (25 and 110 cm) and all four types of vegetation during the 33-cm storm.

It is likely that under unsaturated conditions in soils with equally permeable layers, zero-tension lysimeters measure channeled flow. Certainly this must be true for lysimeters that collect water in excess of the incoming rain. Whether this is the case for lysimeters that collect smaller amounts of rain could be demonstrated only by verifying the existence of channels in the soil or saturated microsites and by ensuring that the installation procedure did not cause local ponding above the lysimeters. Where lateral flow is negligible and impeding soil layers do not exist, the zero-tension lysimeter may provide a measure of the occurrence and quality of rapid channelized flow under unsaturated soil conditions.

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