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Evaluation of ceramic cup samplers to measure nitrate leaching

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Summary

Three types of ceramic samplers were used to study solute transport in the root zone of a wheat crop. Soil solution was collected by applying either a suction (Coinda and Soilmoisture) or by diffusion through the ceramic wall (Tensionic). The Tensionic instrument allowed sample collection to -60 kPa, whereas the suction cups could sample only to -40 kPa. The hydraulic conductivity of the ceramic had little influence on the volume of sample collected by suction. The Tensionic provided an integrated estimate of soil solution composition over several days, whereas the suction cups effectively characterized the daily composition. No significant differences in nitrate concentrations were observed between the two suction samplers. The Tensionic instrument gave smaller nitrate concentrations than those collected by suction because it integrated over time. However, the change in soil nitrate was similar from the two types of samples to that extracted from soil by KCl, thus making them both suitable for monitoring nitrate leaching under field conditions with acceptable accuracy. The amount of nitrate lost below 25 and 90 cm was determined as 29.3 and 3.3 kg NO₃-N ha⁻¹ respectively when 75% of the annual leaching occurred.

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Introduction

The reliable assessment of leaching through unsaturated soil is important in tracing the fate of nitrate and other potential pollutants of groundwater. The traditional use of lysimetry for determining leaching has often proved to be inappropriate because of preferential flow along the lysimeter walls and changes in water potential at the base of the lysimeters (Haines *et al.*, 1982). Ceramic cups are now commercially available for sampling soil solutions, and have been justified for accurate evaluation of nitrate leaching in certain experimental conditions (Lord & Shepherd, 1993; Webster *et al.*, 1993).

In studies involving suction applied to collect soil solutions the potential for preferential sampling from macropores has raised questions of bias (Grossman & Udluft, 1991; Webster *et al.*, 1993). In circumventing this possibility of bias, Moutonnet *et al.* (1993) devised a passive diffusion technique which allowed soil solution to equilibrate with distilled water contained in a ceramic cup. The technique, termed Tensionic, has provided encouraging correspondence with suction-based samplers in preliminary evaluations. The Tensionic technique is easy to use, as the sample is extracted with a syringe, and

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affords simultaneous measurement of soil-water potential. It remains to be determined if, in common with suction application, differential movement of ions through various ceramic materials introduces artefacts in sampling to measure chemical composition of soil solution.

The performances of three different ceramic cup samples were compared in this field evaluation for which an independent appraisal of the nitrate content of soil water was included. This study involved two suction cups of different manufacture (Coinda and Soilmoisture) and the Tensionic device. The efficacy of these devices for deriving nitrate leaching fluxes was studied over a period approaching 2 months. Transfers into and from the soil layer were evaluated from soil solution samples together with the respective soil water drainage fluxes.

Materials and methods

Samplers

The ceramic cups used to extract soil solutions under suction (Soilmoisture 1 bar high flow ref B1M3 (Soil Moisture Equipment Corp., PO Box 30025, Santa Barbara, CA 93105, USA), outside diameter 4.8 cm and Coinda (Coinda Ceramics



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Pty. Ltd., PO Box 156, Bayswater 3153, Australia), outside diameter 4.0 cm) were glued to the lower ends of PVC pipes (Fig. 1a), closely emulating the design described by Wagner (1962). The length of the PVC pipe was selected to allow a projection of approximately 20 cm above ground level when the cup was located at its reference depth. Two capillary tubes of differing length were forced through the rubber stopper ensuring an airtight seal. The longest tube extended to the bottom of the sampler cup and was used to apply suction as well as withdraw the soil solution sample. The short tube allowed for venting of the sampler after a suction had been applied.

The Tensionic device (Fig. 1b) (SDEC France, 19 rue Edouard Vaillant, 37000 Tours, France) used a fast-flow ceramic cup (similar to that of the Soilmoisture suction cup) 2.2 cm in diameter and was sealed to a cap in which three capillary tubes were inserted. In contrast to the Soilmoisture and Coinda samplers, the ceramic cup cavity in the Tensionic remains filled with approximately 12 cm³ of water during the sampling period. One of the capillary tubes extending to the bottom of the cup is used to remove the sample and to refill the cup with distilled water. The capillary tube at the top of the cup is used to pump air into the cup during sample extraction as well as to purge the cup of air when replenishing with water. The third tube reaching the bottom of the cup is connected to a sealed cavity at the top of the sampler thereby allowing the measurement of water potential at the depth of the ceramic cup. Concentrations of ions in solutions extracted from the Tensionic device were corrected to account for the volume of the capillary tubes (where diffusion was assumed to be negligible) by multiplying the actual values by the ratio of the total volume of the cavity and tubes/volume of the cavity. All the samplers were pre-treated using 1 M HCl as described by Debyle et al. (1988).

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Nitrate screening by the ceramic wall

The effect of the ceramic cups on solution composition was evaluated using four Coinda samplers that had previously been used in the field study. On removal from the field the samplers were cleaned of excess soil adhering to the cup, washed several times in M HCl, and rinsed in distilled water. Samplers were then placed in 800 cm³ of a solution of known concentration, and a -66 kPa suction was applied for 10 min. The sample collected was discarded. Fresh solutions were placed in each beaker and a similar suction was applied for 20 min. The bathing (outer) and extracted (inner) solutions were collected for each cup and analysed for NO₃. This process was repeated using fresh solutions. The maximum interval between extractions was less than 5 min. The bathing solution was prepared by dissolving analytical grade KNO3 in distilled water. The concentration of NO₃ was determined by autoanalyser and colorimetric methods of Hendriksen & Selmer-Olsen (1970).

Field experiment

The samplers were tested in a 15-ha field at Charles Sturt University, near Wagga Wagga, New South Wales (35°4'S, 147°21'E, altitude 219 m). The soil is a chromic Luvisol (FAO-UNESCO, 1989) and was remarkably uniform in profile characteristics across the field (Table 1). The mineralogy of the clay fraction was dominated by kaolin (50-60%) and mica (25-30%), with minor interstratified kaolinsmectite, quartz and hematite.

The field was sown to wheat (Triticum aestivum cv. Janz) at a rate of 78 kg ha⁻¹ on 6 June, 1993. Diammonium phosphate (17 kg N ha⁻¹, 25 kg P ha⁻¹) was drilled at sowing. Within the field two adjoining areas of 5 ha were designated for study (Fig. 2), each having centrally located weighing lysimeters (1.1 m \times 1.3 m horizontally and 1.8 m deep) equipped for continuous monitoring of evapotranspiration. Urea was applied to the northern-most plot at a rate of 140 kg N ha⁻¹ as a surface application on the 6 August 1993.

> able 1. Physical and chemical properties of e soil in the study.

Depth /cm	рН /0.01 м CaCl ₂	C /g kg ⁻¹	Clay /g kg ⁻¹	CEC /cmol _(c) kg ⁻¹	K_s /mm h ⁻¹	Ta the
0-5.	5.8	- 13.1	230	6.66		
10-15	4.5	. 5.5	330	4.71	6.4	
15-25	5.1	4.3	370	5.88		
70-90	5.8	1.2	550	7.22	6.0	



Fig. 2. Field plan and positioning of soil solution samplers.

Field installation and operation of the soil solution samplers

The samplers were installed when the soil was moist at eight locations in each plot, approximately 40 m apart on a transect parallel to and displaced by 50 m from the boundary between plots (Fig. 2). At each location Coinda ceramic cups were inserted at depths of 12, 25, and 90 cm, and Tensionics and Soilmoisture ceramic cups were placed at 25 cm depth. Soilmoisture cups were installed on the northern plot only.

Holes slightly larger than the samplers were augured to 10 cm above the final position of the cup. The remaining 10 cm was augured to the same diameter as the sampler. As a precaution against concentrated flow of water around the sides of the sample tube, the holes were drilled at 45° to the surface for samplers positioned at 15 and 25 cm. All other sampling holes were vertical. The samplers were forced into their final position ensuring a tight fit.

Samples of solution were extracted by applying a -70 kPa suction for 24 h to each of the Soilmoisture and Coinda samplers using a portable pump. Samples were extracted from the Tensionic by withdrawing the solution with a 25-cm³ syringe. Solutions were extracted every 2 weeks between the 6 July to the 26 November 1993, after which the soil was too dry. Samples were placed in polyethylene vials and stored frozen until analysed.

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The volume of solution collected from the cups was recorded for the Soilmoisture and Coinda cups at the 25-cm depth on the northern plot along with the soil water potential from the Tensionic devices. A relationship between matric soil water potential and volume extracted was based on these data.

Input-output budget

A nitrate budget for the depth interval 25–90 cm was established for the period 6 June to 4 August by taking into account leaching from 25 cm as input and leaching beyond 90 cm as output. Inputs of nitrate through mineralization of the organic matter were assumed to be negligible because the mean soil temperature was 8°C at 10 cm during this period. Loss of nitrogen through denitrification in the 25–90 cm was also assumed to be negligible because the carbon content was small, and the profile was never saturated. Uptake of nitrate from this depth interval could be dismissed because roots extended to 25 cm were only observed at the end of the period.

Drainage at 25 and 90 cm was calculated by difference using rainfall, actual evapotranspiration, and change in water content in the 0-25 cm and 0-90 cm layers. Runoff was negligible on this porous soil under light rain. For the suction cups leaching was calculated using data from the Coinda cups by multiplying the average concentration in the soil solution over two consecutive sampling dates by the volume of drainage during this period. For the Tensionic device, leaching below 25 cm was calculated by multiplying the soil-solution concentration extracted at the end of the period (presumed to be an integrated sample) by the volume of drainage during the period.

Chemical analysis

Soil samples were collected fortnightly for water content and inorganic nitrogen determination along a transect on each of the two sites. Four soil cores were extracted from each transect using a tractor-mounted hydraulic corer with an internal diameter of 5.1 cm. Cores were sectioned into increments of 0-5, 5-10, 10-15, 15-25, 25-50, 50-70 and 70-90 cm and bulked for each plot. Four extra samples were collected in each plot from 0-10 cm depth interval and bulked. Samples were refrigerated in sealed polyethylene bags and transported to the laboratory for analysis. The water content at each depth interval was determined by drying at 105°C and the volumetric water content calculated using bulk-density measurements. Inorganic nitrogen was extracted from samples at field moisture content using 2 M KCl (1:5 soil: extractant) on a vibrating shaker for 1 h. Nitrate and ammonium N concentrations were determined on the supernatant using an autoanalyser and colorimetric methods of Hendriksen & Selmer-Olsen (1970) and Markus et al. (1985) respectively. On the 3 and 16 June samples were not bulked so that an estimate of the variability in sampling could be assessed.

At the initiation of the study soil chemical characteristics were determined on air-dried samples ground to pass a 2-mm



Fig. 3. Influence of soil matric potential on the volume of solution collected per day for the Coinda (O) and Soilmoisture (D) ceramic cups (-70 kPa for 24 h).

sieve. The pH was determined in 1:5 soil:0.01 M CaCl₂ suspension. Cation exchange capacity was determined by compulsive exchange (Gillman & Sumpter, 1986). Nitrate sorption isotherms for selected depth intervals were measured at soil solution concentrations similar to those observed in the field. Batch equilibrium was undertaken on duplicate samples at NO₃ solution concentrations of 0, 0.19, 0.37, 0.52, 0.70 and 1.41 mmol dm⁻³ using the methodology of Cahn *et al.* (1992).

Results and discussion

Screening of nitrate through the cup walls

The mean internal and external concentrations of nitrate, collected over two consecutive samplings, from the four Coinda samplers in the laboratory study were 4.65 mg dm⁻³ with a standard error (SE) of 0.05 and 4.75 mg dm⁻³ (SE 0.41) respectively. Approximately 2% of the external NO₃ was retained by the ceramic wall after passing through. Thus for NO₃ concentrations of >5 mg dm⁻³ retention by the Coinda ceramic was negligible. Prior to the installation of cups in the field a similar assessment was undertaken on acid washed Coinda cups. In this case the percent retention by the cup was 11% with mean internal and external concentrations of and 3.16 mg dm⁻³ (SE 0.05) and 3.56 mg dm⁻³ (SE 0.03) respectively.

Field performance of samplers

Field performance of the samplers was characterized by small failure rates in moist soil in which the lower limit of sample extraction ranged between matric potentials (ψ) of -40 kPa for the suction cups and -60 kPa with the Tensionic device. The Tensionic device was the most reliable (failure rate of 2% compared to 6% with suction cups when $\psi < -30$ kPa), and its sampling period was extended by 2 weeks under the soil water conditions that prevailed. The overall reliability of the samplers in this study compared favourably with other undertakings involving a similar protocol for sampling (10%)

for Saragoni *et al.*, 1990). Care in ensuring non-disruptive insertion of ceramics and in avoiding leaks are reflected in the reliable performance of samplers in this study.

The amount of solution collected by suction samplers followed an exponential relation with a decrease in matric potential (Fig. 3), this being consistent in form with other findings (Saragoni et al., 1990). A systematic increase in flux of approximately 50% was apparent for the Soilmoisture over the Coinda cups across the range of matric potential. This was associated with an eight-fold difference in hydraulic conductivity (data not presented). The lack of proportionality in differences between volume collected and hydraulic conductivity of the ceramic suggests that hydraulic characteristics of soil are important determinants of the yield by suction cups. This would explain the halving of collection by Soilmoisture cups in the present study compared to that of Saragoni et al. (1990) who used identical samplers (ref. B2M2). The failure to generate differences in sample volumes by suction cups of contrasting flow properties could also be attributed to a predominating role of soil characteristics for sample yield.

With either the Coinda or Soilmoisture suction cups, the volume of soil solution collected per cup was $< 1 \text{ cm}^3 \text{ d}^{-1}$ when the matric suction was less than -40 kPa. However, the failure rates of the cups increased dramatically when the matric suction was < -15 kPa. The use of suction cup solution samplers is therefore restricted to matric suctions of > -15 kPa. In leaching studies this may not be a serious limitation because the hydraulic conductivity of the soil decreases exponentially with matric potential and as a consequence drainage is often small.

Comparison between samplers for nitrate and ammonium extraction

To quantify the amount of nitrate leached from the rooting zone ceramic cups should be positioned below that zone. Most investigators monitoring the movement of leachate have installed cups at 0.9-1 m (Lord & Shepherd, 1993). However, Bailey (1990) indicated that cereals can extract water down to 120 cm and probably deeper. In the current study a depth of 90 cm was considered the limit of effective root growth, because only 3.3% of the total root mass was below 90 cm at maximum elongation.

The mean concentrations of nitrate extracted from the three samplers at 25 cm (Table 2) indicated that the Tensionic samplers had a significantly (P < 0.05) smaller mean concentration of nitrate than the Coinda and Soilmoisture samplers. A possible reason for this is incomplete equilibrium between solution inside and outside the ceramic cup or the dilution by the initial distilled water or both. The coefficients of variation for nitrate extracted from the samplers ranged from 24 to 39% which are less than those reported by Lord & Shepherd (1993). Comparisons of nitrate concentration between samplers over time indicate good agreement between the Coinda and

Soilmoisture suction samplers, while for two sampling dates in July there were significant differences between the Soilmoisture and Tensionic samplers (Fig. 4). With respect to the Tensionic, nitrate values at a particular time were equivalent to the mean of the suction samplers collected at the beginning and end of the Tensionic equilibrium period. The systematic differences in the concentration of the nitrate monitored support the notion that the Tensionic samples represent the flux concentrations, whereas the suction cup samplers approximate the instantaneous composition of the soil solution. This is in agreement with the conclusions of Magid & Christensen (1993).

Concentrations of ammonium in the Tensionic samples were on average three times greater than in the Coinda samples (Fig. 5). Similarly, Moutonnet (personal communications) reported ammonium values eight times larger in Tensionic samplers when compared to suction cup values. Moutonnet interpreted the larger values of ammonium in the Tensionic samplers as evidence that soil water held in micropores was more subject to anaerobic conditions than that in macropores, and therefore the concentration of ammonium in macropores would be smaller. Indeed, suction cups preferentially remove soil solution from the larger macropores with the degree of preference a function of the applied suction (Grossman & Udluft, 1991). Consequently, the ammonium concentration in their samples would be less than that of the Tensionic samples, which equilibrate with the bulk soil. Therefore these discrepancies may be explained on the basis of differences in the concentration of ammonium ions in pores of different sizes and the fact that equilibrium between the soil solid phase and the soil solution would be established more rapidly in smaller pores. This interpretation agrees with the conclusions drawn by Severson & Grigal (1976) who observed that by increasing the extracting time the concentration of calcium and potassium increased in the solutions collected from ceramic cups. They concluded that soil solutions extracted over a short period samples solution moving through the soil macropores, whereas extractions over longer periods include solution held at greater suctions. One can conclude that solutions extracted by

Table 2. Comparison of three soil solution samplers for variability at the 25 cm depth interval and the influence of site on nitrate concentrations.

	4		
Sampler	Coinda	Soilmoisture	Tensionic
Mean /mg N dm ⁻³	16.5	18.9	11.6
^a SE	2.7	3.2	1.5
	North	South	
	(fertilized)	(unfertilized)	
Coinda/mg N dm ⁻³	16.1	17.2	
SE	3.3	4.6	and and a
Tensionic/mg N dm ⁻³	11.6	12.4	
*SE	1.8	2.6	

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Fig. 4. Comparison of nitrate concentrations collected in the soil solution samplers and soil extracts at 25 cm depth (fertilized plot).





Tensionic were equivalent to the mean suction cup samples collected at the beginning and end of the Tensionic equilibrium, but that for the ammonium the values from the Tensionic seemed to be consistently larger than those from the suction cups.

An analysis of the nitrate concentrations collected from the northern (fertilized) and southern (unfertilized) plots using the Coinda and Tensionic samplers showed no significant differences between samples collected on the two plots (Table 2). A lack of response to urea application on 6 August in nitrate and ammonium concentrations could not be attributed to deficient performance of the samplers; soil concentrations of nitrate and ammonium appeared similarly unperturbed to urea application (data not shown). On the basis of a nil statistical difference between the two suction cups, we conclude that both types of ceramic were similar in sample collection for nitrate concentration assessment.

Comparison of nitrate contents from soil extracts and soil solution

In order to determine the variability in nitrate concentrations in 2 M KCl extracts from soil, samples were not bulked on the 3 March 1993 and 16 June 1993. The coefficients of variation

 Table 3. Soil nitrate variation of samples collected on the 3 March and 16 June (Sample size 8).

		Depth /cm			
*	0-10	1025	25-90		
Date: 3 March					
Mean/kg NO ₃ -N ha ⁻¹	10.9	2.8	6.3		
SE	2.8	0.3	0.7		
Date: 16 June					
Mean/kg NO₃−N ha ⁻¹	26.8	8.3			
SE	1.5	1.6			

on these two occasions ranged from 16 to 75%, the greater value being observed for the 0-10 cm depth interval where much mineralization would be expected (Table 3). The greater variation in soil extracts when compared to soil solution may in part be due to the larger volumes of soil sampled by the ceramic cups (Lord & Shepherd, 1993).

A comparison of the nitrate values in soil extracts with those determined in the soil solutions indicated good agreement between the two methods for values $>10 \text{ mg NO}_3$ -N dm⁻³ (Fig. 4). For values of <10 mg NO₃-N dm⁻³, soil extracts contained significantly more nitrate than the soil solution. This discrepancy may in part be attributed to nitrate sorption on the exchange complex of soil. The relation between nitrate in solution and nitrate sorption is shown in Fig. 6 for soil collected from the 10-15 cm depth. Most nitrate sorption occurred at this depth interval. At nitrate concentrations commonly found in the soil solution under field conditions variation in sorption between selected depth intervals was observed, this being a function of pH with sorption decreasing with increasing pH (data not shown). This result agrees with the results of Alberts et al. (1977) who reported concentrations determined by solution sampling generally less than those from soil extracts at small concentrations. A further possible reason for differences between soil extracts and suction samples is that the ceramic cups effectively sample only a





limited range of pore sizes because of the small tension applied (-70 kPa), whereas the soil extraction samples nitrate from the whole range (Webster *et al.*, 1993). Under the prevailing conditions both ceramic cups and soil extracts appear to monitor nitrate leaching adequately for concentrations exceeding 10 mg N kg⁻¹, although the accuracy of soil extracts has been brought into question (Webster *et al.*, 1993). Notwithstanding these discrepancies between the two techniques, simple linear regressions between solutions collected in the Coinda and Tensionic cups and 2 M KCl soil extracts resulted in the following regression equations:

Coinda:

NO₃-N in extract (mg dm⁻³) = $0.72(\pm 3.94) + 1.13(\pm 0.13)$ ×NO₃-N in porous cup (mg dm⁻³)

Tensionic:

$$NO_3 - N \text{ in extract } (mg \, dm^{-3}) = 1.49(\pm 2.99) + 0.48(\pm 0.11) \\ \times NO_3 - N \text{ in porous cup } (mg \, dm^{-3})$$

The regression for the Coinda samplers explained 77% of the variance, and the gradient of the regression line was not significantly different from 1.0. In addition, the intercept term was non-significant. In contrast, the regression equation for the Tensionic samplers explained 61% of the variance, and the gradient was significantly less than 1.0. The smaller gradient can be interpreted as the result of the Tensionic samplers integrating nitrogen contents over time.

Nitrate budget in the 25-90 cm layer

The largest value of nitrate measured at 25 cm on the 13 July 1993 corresponded with the flush of nitrate moving down from the surface horizon (Fig. 4). The amount of nitrate in the 25–90 cm layer was calculated using the nitrate content of the soil (average of both the northern and the southern plot, as both plots were identical in N applications up to 6 August 1993) and the bulk density. The nitrate content in soil extracts increased from 17 kg NO₃-N ha⁻¹ to 38 kg NO₃-N ha⁻¹ over the period; the standard error between nitrate determinations of the various samplers of soil extracts were 3.6 kg NO₃-N ha⁻¹.

Water balance determinations for the series of intervals June 7 to August 4, 1993 indicated greater drainage at 25 cm than at 90 cm by approximately 20 mm (Table 4). Drainage was estimated as starting after 7 July for 25 cm and after 13 July for 90 cm; the small quantities of apparent drainage before these dates were attributed to experimental error, these being less than the nominal uncertainty of 10 mm associated with gravimetric determinations of soil water content. The later and smaller amount of drainage from 90 cm compared to 25 cm resulted from the effect of initial soil water status at 25–90 cm being less than its drainable limit of 25 mm.

Samples collected from the Coinda samplers were used to calculate the amount of nitrate leached below the 25 and 90 cm

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Table 4. Water balance and mean	n nitrate leaching from	7 June to 4 Au	gust. 🦣 🖓 👘 🖉	化型合合 建黄金 化合理性试验	计读号分析	10 in 1
The state of the s	7 June-16 June 8	June-6 July	6 July-7 July	13 July-28 July 77 29	July-4 Augu	st Total
Rainfall/mm	1 (12.500) (12.500) 21.500 7 (10.500) (10.500)	11	37 4	16	22 ···:> 12 //··	125 55
25 cm Water balance/mm		- -				
Change in water content	+2	-7	+8	+3	+1	7
Drainage	4	2	25	24	9	64
Nitrate leaching/kg N ha ⁻¹						
Coinda	-	_	13.4	12.8	2.3	28.5
Soilmoisture	-	-	12.5	12.6	2.8	27.9
Tensionic	-	-	10,6	6.5	1.4	18.5
90 cm Water balance/mm				· .		
Change in water content	+6	-13 ~	+35	. +1	-1	28
Drainage	-1	8	-2	26	11	42
Nitrate leaching/kg ha ⁻¹						
Coinda mean value	-	-	-	2.4	0.8	3.2

depth intervals. It was assumed that the missing value for the Coinda cups at 90 cm on the 12 July 1993 was equal to the value on the 28 July 1993. Estimated nitrate leached below 25 cm between 6 July 1993 and 4 August 1993 was 28.5 kg N ha⁻¹. Evaluation of leaching at 90 cm was 3.3 kg N ha⁻¹, with a confidence interval of 2.4 to 4.2 kg N ha⁻¹. From the 7 June 1993 to the 4 August 1993 the difference between the amount of NO₃ in the soil measured by 2 mm KCl soil extract and that from the sampling cups was <5 kg N ha⁻¹.

Conclusion

The porous ceramic cups have proved to be reliable and accurate for monitoring nitrate leaching on soil that is fairly homogeneous and contains a moderate amount of clay. Sampling strategies and the time-averaging procedures for nitrate concentrations from soil solution seem to provide realistic estimates of transported solute; during this interval soil water composition could be expected to be at its most dynamic. A fortnightly period emerges as optimal for sample extraction from the Tensionic with a reported equilibrium time of 6-10 days (Moutonnet et al., 1993). Similarly, averages of the two discrete values for each fortnightly interval used with suction cups proved to be effective for a solute balance. Clearly, data obtained using ceramic cups accurately described the nitrate budget of soil with acceptable accuracy. Since porous cups can be left in place, changes over time are not confounded with changes due to sampling from differing locations as is the case with successive soil samples.

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