[illegible]

Reprinted from

GEODERMA

Geoderma 84 (1998) 29–43

Nitrate leaching through oxisols of the Loyalty Islands (New Caledonia) under intensified agricultural practices

C. Duwig [a,c,*], T. Becquer [a], B.E. Clothier [b], M. Vauclin [c]

[a] *ORSTOM, Laboratoire d'Agropédologie, B.P. A5, 98848 Nouméa Cedex, New Caledonia*
[b] *Environment Group, HortResearch, P.B. 11-030, Palmerston North, New Zealand*
[c] *Laboratoire d'étude des Transferts en Hydrologie et Environnement (CNRS-UMR 5514, INPG, UJF), B.P. 53, 38041 Grenoble Cedex 9, France*

Accepted 23 July 1997

ELSEVIER

GEODERMA

AN INTERNATIONAL JOURNAL OF SOIL SCIENCE

Scope of the journal

The primary intention of the journal is to stimulate wide interdisciplinary cooperation and understanding among workers in the different fields of pedology. Therefore, the journal tries to bring together papers from the entire field of soil research, rather than to emphasize any one subdiscipline. Interdisciplinary work should preferably be focused on occurrence and dynamic characterization in space and time of soils in the field.

Publication information

Geoderma (ISSN 0016-7061). For 1998 volumes 81–86 are scheduled for publication. Subscription prices are available upon request from the publisher. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery via SAL is ensured: Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Japan, Malaysia, Mexico, New Zealand, Pakistan, PR China, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request. Claims for missing issues must be made within six months of our publication (mailing) date. For orders, claims, product enquiries (no manuscript enquiries) please contact Customer Support Department at the Regional Sales Office nearest to you:

New York, Elsevier Science, P.O. Box 945, New York, NY 10159-0945, USA. Tel: (+1) 212-633-3730, [Toll free number for North American Customers:1-888-4ES-INFO (437-4636)], Fax: (+1) 212-633-3680, E-mail: usinfo-f@elsevier.com
Amsterdam, Elsevier Science, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Tel: (+31) 20-485-3757, Fax: (+31) 20-485-3432, E-mail: nlinfo-f@elsevier.nl
Tokyo, Elsevier Science, 1-9-15, Higashi-Azabu 1-chome, Minato-ku, Tokyo 106, Japan. Tel: (+81) 3-5561-5033, Fax: (+81) 3-5561-5047, E-mail: info@elsevier.co.jp
Singapore, Elsevier Science, No. 1 Temasek Avenue, #17-01 Millenia Tower, Singapore 039192. Tel: (+65) 434-3727, Fax: (+65) 337-2230, E-mail: asiainfo@elsevier.com.sg

US mailing notice – *Geoderma* (ISSN 0016-7061) is published montly by Elsevier Science B.V. (Molenwerf 1, Postbus 211, 1000 AE Amsterdam). Annual subscription price in the USA US$ 1707 (US$ valid in North, Central and South America), including air speed delivery. Application to mail at periodicals postage rate is pending at Jamaica, NY 11431.
USA POSTMASTERS: Send address changes to *Geoderma*, Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003.
Airfreight and mailing in the USA by Publications Expediting.

Advertising information:

Advertising orders and enquiries may be sent to: *International:* Elsevier Science, Advertising Department, The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK; Tel.: (+44) (0) 1865 843565; Fax: (+44) (0) 1865 843976. *USA and Canada*: Weston Media Associates, Dan Lipner, P.O. Box 1110, Greens Farms, CT 06436-1110, USA; Tel.: +1 (203) 261 2500; Fax: +1 (203) 261 0101. *Japan*: Elsevier Science Japan, Marketing Services, 1-9-15 Higashi-Azabu, Minato-ku, Tokyo 106, Japan; Tel.: +81 3 5561 5033; Fax: +81 3 5561 5047.

ELSEVIER

Geoderma 84 (1998) 29–43

GEODERMA

Nitrate leaching through oxisols of the Loyalty Islands (New Caledonia) under intensified agricultural practices

C. Duwig [a,c,*], T. Becquer [a], B.E. Clothier [b], M. Vauclin [c]

[a] ORSTOM, Laboratoire d'Agropédologie, B.P. A5, 98848 Nouméa Cedex, New Caledonia
[b] Environment Group, HortResearch, P.B. 11-030, Palmerston North, New Zealand
[c] Laboratoire d'étude des Transferts en Hydrologie et Environnement (CNRS-UMR 5514, INPG, UJF), B.P. 53, 38041 Grenoble Cedex 9, France

Accepted 23 July 1997

Abstract

For the uplifted coral atolls of the Loyalty Islands (New Caledonia), the prime source of potable water is the freshwater lenses that underlie the islands. The recent adoption of more-intensive agricultural practices, particularly the use of nitrogeneous fertilizers, may, however, represent a threat for these fragile Pacific ecosystems. To assess the risk posed by nitrate leaching, experiments have been conducted on the permeable oxisols of the island of Maré, using both cropped and bare soil sites. Drainage below the root zone was found to be very important, about 50% of the rainfall, even on the cropped site. The soils are thin and permeable, and the frequent tropical storms have high rainfall intensities. Nitrate fertilizers thus have potential to be leached, in large amounts, even up to 100% of the nitrate supply, especially if fertilizers are not supplied according to weather conditions and in concert with the plant's ability to extract them.

Keywords: coral atoll; hydraulic conductivity; fertilizer; groundwater

---

1. Introduction

The adverse effects of intensified agricultural practices on soil and water quality are well documented (Sumner and McLaughin, 1996). Pollution of our

---

[*] Corresponding author. Tel.: +64-6-3568080; Fax: +64-6-3546731; E-mail: cduwig@hort.cri.nz

0016-7061/98/$19.00
PII S0016-7061(97)00119-5

reserves of drinking water by nitrate leaching from the root zone is a major public concern of increasing intensity. On the other hand, the world's population growth demands that there should be an increase in food production as well as in other agricultural products. The ability to use new arable or pastoral land is limited. Therefore, the use of fertilizers, mainly nitrogen, is often the first means adopted to achieve an improvement in the productivity of agriculture, so as to increase the return from the land (Angé, 1992).

As in many developing countries, the islands of the South Pacific must increase their agricultural production because their population is likely to increase some twofold over the next 30 years (WRI, 1990). Traditional agriculture is still the most important source of food for the people of the Pacific (Brookfield, 1989), and agriculture is generally the main source of national income. Furthermore, the cash-cropping sector is increasing in size (Naidu et al., 1991). However, more and more young people are leaving their rural villages to go to urban areas. Intensification of agricultural practices means that less labour is required relative to traditional practices. Thus, while there is an increasing demand for the potable water by urban dwellers, at the same time in rural areas more agrochemicals are being applied to the soils as agricultural practices become more intensive. Leaching of these agrochemicals from the root zone might compromise the quality of the water being demanded by the city.

The Loyalty Islands in New Caledonia, are no exception to these conflicts. Because of economic and demographic pressure, farmers are using more intensive agricultural practices, rather than traditional procedures. The increased use of nitrogen fertilizers could, however, pose a risk to this fragile ecosystem. Indeed, the freshwater lenses that underlie these uplifted coral atolls often constitute the sole source of drinking water. The primary aim of this current study is to quantify nitrate leaching under intensified agricultural practices. This research stresses the need to understand drainage from the root zone so as to determine the optimal fertilization rate. In this way, the amount of nitrate leaching beyond the bottom of the profile can be reduced, without unacceptably reducing crop production.

2. Materials and methods

2.1. Experimental site

The study was carried out on the island of Maré (New Caledonia), the southernmost island of the Loyalty Islands. Like some other volcanic islands in the Pacific Ocean, Maré is an uplifted coral atoll which is build upon an underlying volcanic structure. Above the basalt substratum, the coral rock is from 50 to 100 m deep and displays many fractures whose complex structure is not yet well known. The freshwater lenses are subterranean, and float upon the underlying salt water. The soil of the study site is an oxidic ferrallitic soil (type

Acorthox, USDA, 1975). This type of soil represents just 19% of the entire surface of the island, but nearly 60% of the cultivated soils. The soil derives from altered volcanic ejecta and ash, and is relatively thin, ranging from nothing to one meter deep. Across the experimental field site on average the depth is 0.4 m. The soil primarily comprises iron and aluminium oxides (Latham and Mercky, 1983), mainly as gibbsite, boehmite and goethite with a very low level of silicates. The main physico-chemical characteristics of the soil for various subplots at the Tawaïnèdre site are presented in Table 1. Here the code *Bush* refers to a profile under bushfallow, and was collected before commencement of field experimentation, while *Corn* and *Grass* are profiles of two plots of the experimental field, collected under corn and grassland, after two years of cultivation.

2.2. Field experimentation

Three plots of 400 m^2 were studied. They were ploughed at the beginning of January 1995. The bare soil plot was kept bare by the application of herbicide. Another plot was sown with corn (Zea mays, cv. Hycorn 90) at 50,000 plants ha^{-1} on the same date. The last plot was a two-year old grassland (Rhode grass, *Chloris gayaha*, cv. Callide). On January 11, 1995, all plots received 104 kg N ha^{-1} as ammonium nitrate. The results presented here relate only to the first half of 1995, between January and June, during the growth cycle of the corn. This period corresponds to the wet season under this tropical climate, during which time leaching is most likely to occur.

2.3. Measurements

The purpose of this study was to monitor both the drainage from the root zone and the leaching of nitrogen under the different plots.

Each plot was instrumented for soil moisture and soil solution concentration measurements. Eight waveguides for water content measurement by TDR (Time Domain Reflectometry; TRASE, Soilmoisture Equipment Corporation, Santa Barbara, CA) were installed horizontally to measure the water content at 10, 20, 30 and 40 cm. Until the month of April, when the TDR became available, soil moisture measurements were made gravimetrically. Nearby, eight tensiometers were installed to record the hydraulic head of water in the soil at 10, 20, 30, 40 and one at 60 cm where the soil was deep enough. Eight suction cups were located at both 10 and 40 cm depth. These allowed measurement of the nitrogen concentration of the soil solution.

Measurements of soil moisture and tensiometers were recorded every two days just after a rainfall, and every week during drying periods. Collection of soil solution samples were made weekly when the soil was wet enough. Temperature, rainfall and micrometeorological data were obtained every hour with an automatic data acquisition system. These data allowed estimation of the

Table 1
Selected properties of soil profiles under bushfallow (Bush), corn (Corn), and grassland (Grass)

Profiles	Depth (cm)	Bulk density (Mg m^{-3})	Particle density (Mg m^{-3})	pH		Organic C (g kg^{-1})	N (g kg^{-1})	Exchangeable bases (cmol kg^{-1}) (a)				CEC (a) at pH 7 (cmol kg^{-1})	Total elements (b)		
				H_2O	KCl			Ca	Mg	Na	K		SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)
Bush-1	0–15	0.62	—	6.8	6.3	76.80	6.77	15.79	10.08	0.26	0.28	26.93	nd	21.05	37.62
Bush-2	15–35	0.73	—	6.3	6.2	24.02	2.10	4.32	3.33	0.18	0.08	10.71	1.06	24.51	42.95
Bush-3	35–60	0.80	—	5.8	6.0	8.44	0.95	0.28	0.30	0.08	0.01	3.48	1.46	25.14	44.00
Corn-1	0–30	0.73	2.60	6.6	6.2	78.60	6.06	16.01	11.60	0.28	0.73	33.06	—	—	—
Corn-2	30–40	0.82	2.75	6.5	6.1	50.85	4.19	8.74	8.33	0.20	0.30	24.08	—	—	—
Corn-3	40–60	0.87	—	5.7	5.9	16.65	1.36	1.21	1.29	0.06	0.12	9.79	—	—	—
Grass-1	0–15	—	2.60	6.6	6.3	75.57	5.62	14.09	10.05	0.23	0.29	29.30	—	—	—
Grass-2	15–25	—	2.85	6.3	6.1	39.20	3.25	5.24	4.83	0.20	0.11	17.00	—	—	—
Grass-3	25–40	—	—	5.8	6.2	11.24	1.12	0.68	0.53	0.14	0.08	4.44	—	—	—

(a) Tucker, 1954; (b) Digestion with perchloric acid; — = no data.

potential evapotranspiration (ETP) with the use of the Penman–Monteith method (Brunel, 1994).

2.4. Methods

The relationship between soil hydraulic conductivity, K, and water content, θ, was determined by two different and complementary methods.

The first method involved the use of the 'zero flux plane' approach and provided values of $K(\theta)$ in the unsaturated range of $\theta \approx 0.3$ cm^3 cm^{-3}. As described by Vachaud et al. (1978), this method is based on an analysis of the soil moisture and soil hydraulic head profiles during periods of drainage in the absence of rainfall, when there are no plants, or plants just having a very shallow depth of rooting.

The use of a tension disc infiltrometer (Clothier and White, 1981; Ankeny et al., 1991) allowed determination of the soil's unsaturated hydraulic conductivity in the region close to saturation. Measurements were made at three different suctions (0.5, 5 and 15 cm of water). These measurements were carried at a depth of approximately 40 cm in the profile, in the third horizon at the base of the root zone.

With the $K(\theta)$ relationship formed by cobbling together these two data sets, and from the measured hydraulic information, the drainage D (m) at a depth of 40 cm was calculated from Darcy's law. Here the cumulative amount of drainage can be found using:

$$D = q \cdot \Delta t = -K(\theta) \cdot \frac{\Delta H}{\Delta z} \cdot \Delta t \qquad (1)$$

where q is the mean volumetric flux density (m day^{-1}) during Δt, $K(\theta)$ is the hydraulic conductivity (m day^{-1}) corresponding to the measured water content at 40 cm, and $\Delta H/\Delta z$ is the hydraulic head gradient measured at this depth.

Nitrate and ammonium concentrations were measured in the soil solution. The rate of nitrogen leaching L_N (kg m^{-2}) below the root zone was thus obtained from the relationship:

$$L_N = D \cdot C \qquad (2)$$

where D (m) is the drainage at depth 40 cm, as calculated above, and C (kg NO_3–N m^{-3}) is the NO_3–N concentration measured by suction cups at this depth (Kengni et al., 1994).

3. Results

3.1. Hydraulic conductivity

Determination of hydraulic conductivity was carried on every plot, below the root zone. Because there are not enough data to characterize individually each site, one curve was fitted to all the data using a power law. Others (Vachaud et

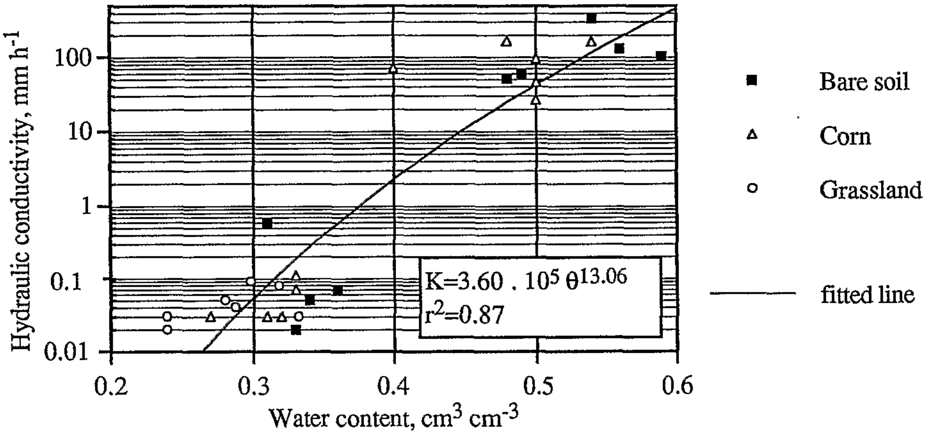

Fig. 1. The fitted relationship between measurements of soil hydraulic conductivity and the volumetric water content.

al., 1981; Poss and Saragoni, 1992) have suggested this approach. In our case, the soil across the entire site is likely to be quite uniform at this depth. The results are presented in Fig. 1.

On this figure, two groups of measured points can be distinguished depending on the method used to obtain the $K(\theta)$ data. As a matter of fact, the infiltrometer gives values near the saturation and the 'zero flux plane method' in the range of the water content mostly found on the field (see Fig. 2). We can note the high sensitivity of the hydraulic conductivity to water content, and more importantly this soil is found to be very permeable at saturation. The two data 'clouds' provide good upper and lower limits to the values of hydraulic conductivity in the range of the water content that is important for drainage (Figs. 1 and 2). The fitted line thus allows interpolation so that Eq. (1) can be used to compute the water flux from measurements of the water content and hydraulic head gradient.

3.2. Soil water content and hydraulic head

As is shown in Fig. 2, the response of the water content, even at 40 cm depth is significant to any important rainfall input. Such a significant response is expected for a soil having such high values of hydraulic conductivity near saturation. However, the temporal variation at 40 cm would not be as large as in the upper horizons. Both these traits lend evidence to our proposed use of Darcy's law at this depth. The fluctuations are muted, and there is a consistency between the various plots, as might be expected due to the greater uniformity at 40 cm.

Likewise, as is shown in Fig. 3, the hydraulic head gradient in this permeable soil also responds quickly to any rainfall input. On bare soil, apart from after the

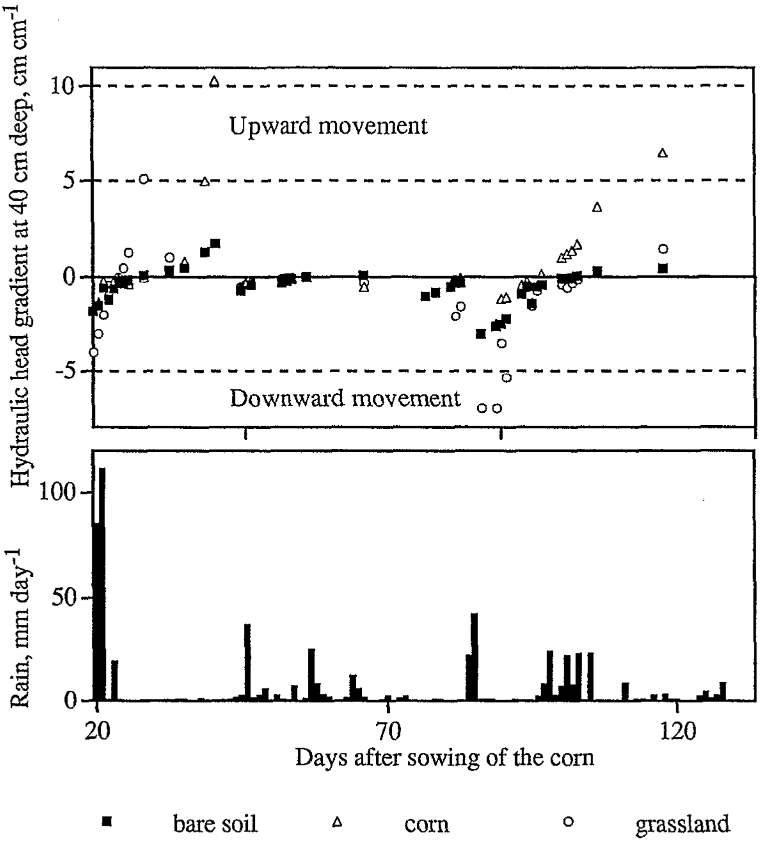

Fig. 2. The water content at 40 cm with time on the different plots.

first important rainfall followed by a 3-week dry period, the hydraulic head gradient is mostly negative. This indicates that the soil is often subject to drainage, and consequently the possibility for nitrate leaching would always exist.

The behaviour of the bare soil plot and the corn plot were similar, at least up until one month after sowing. However, after that, root extraction started to be important at the cropped site. The upwards hydraulic head gradient was sometimes very high, perhaps because of root dry down of the surface soil, with the prospect of capillarity bringing water upwards from below the root zone.

On the grassland plot, the gradient was almost always negative, being similar to the bare soil plot. However, after the first rainfall event, the gradient here became positive sooner than in the two other plots. So even with an active, but shallow-rooted pasture, water can be lost rapidly after any significant rainfall event.

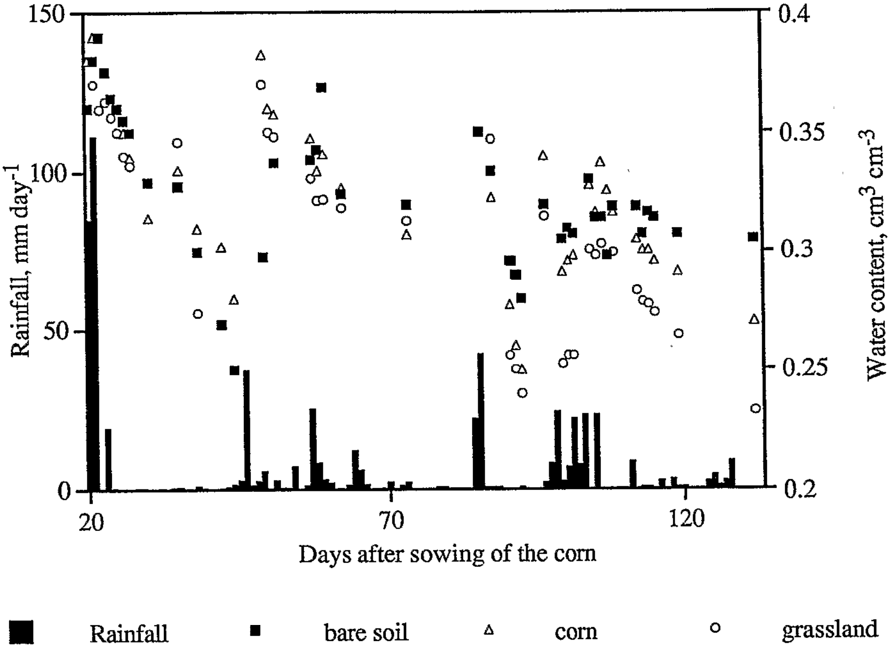

Fig. 3. The hydraulic head gradient at 40 cm during several rainfall events.

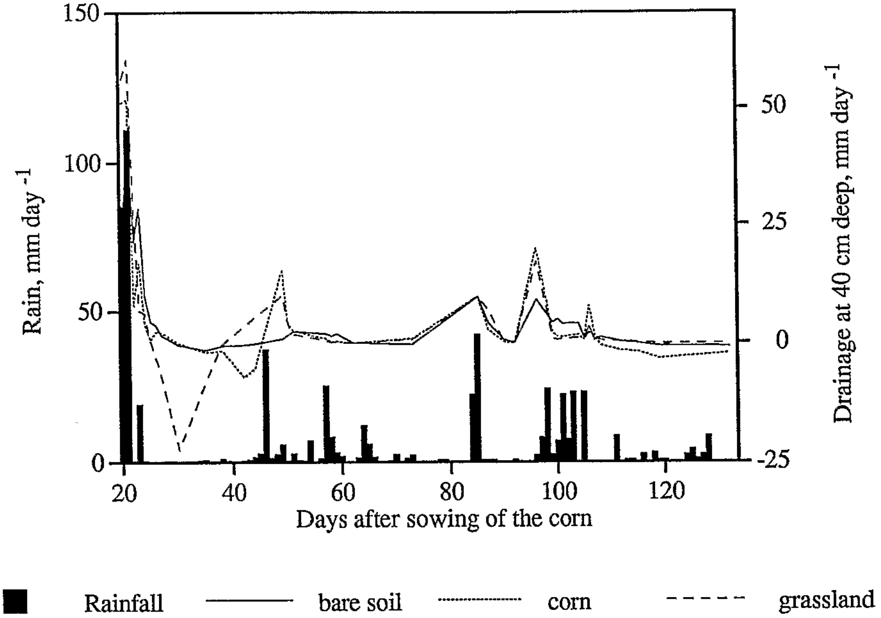

Fig. 4. Calculated drainage at 40 cm for each plot.

3.3. Drainage flux

To calculate the drainage, it was necessary to establish on a daily basis the water flux density by Darcy's law. But because of the dynamic behaviour of this soil, this poses some problems with respect to water content determination. To overcome this, it was necessary that the water content values were interpolated between two measurements far apart using tensiometer data. For this, a water-retention curve was used having being obtained from simultaneous TDR-tensiometer measurements.

The drainage flux at each site is shown in Fig. 4. Drainage was at a maximum the day after rainfall, but it then diminished rapidly, and became negligible after one week. Such peaked behaviour is to be expected for a soil possessing such a steep $K(\theta)$ relationship (Fig. 1). Following the first and intense rain, some 170 mm in 8 h, the total drainage was almost 70–78% of the rainfall. For the following rains, the drainage fraction was much less. These values are nonetheless high because of the high value of the hydraulic conductivity when the soil is

Table 2
Comparison between ETR estimated from ETP (ETR[a]) and calculated by the water balance (ETR[b]). NO_3–N contents in soil solution and standard deviations

	Periods of drainage			
Date:	29/01–08/02	24/02–13/03	03/04–14/04	15/04–5/05
P (mm)	179.4	104.8	65.9	127.0
ETP (mm)	67	82	49	85
ETR[a] (mm)	31	52	21	54
Bare soil				
ΔS (mm)	10	30	10	10
D (mm)	141	25	34	62
ETR[b] (mm)	29	50	22	55
NO_3–N (g m^{-3})	32.5 ± 29.5	24.5 ± 20.7	14.9 ± 15.6	17.4 ± 20.5
Corn				
ΔS (mm)	5	27	10	10
D (mm)	141	37	38	62
ETR[b] (mm)	33	41	18	55
NO_3–N (g m^{-3})	72 ± 39.8	44.1 ± 41.8	12.4 ± 25.2	16.4 ± 16.9
Grassland				
ΔS (mm)	10	38	10	10
D (mm)	132	35	22	63
ETR[b] (mm)	37	31	29	54
NO_3–N (g m^{-3})	10.2 ± 14.2	0.1 ± 0.2	0.0	0.04 ± 0.08

[a] ETR calculated by Chopart and Siband (1988) method.
[b] ETR estimated by the water balance.

close to saturation, as happens during and just after such heavy tropical downpours that result from convective weather systems.

3.4. Water balance

A water balance was only calculated over periods when the hydraulic head gradient was negative, that is to say during each drainage period. There was a lack of data during drying periods to allow this. Integration of the law of mass conservation between the surface and 40 cm deep leads to:

$$\mathrm{ETR} = P - R - \Delta S - D \tag{3}$$

where ETR (mm) is the actual evapotranspiration, P (mm) the amount of rainfall, R (mm) the surface runoff, ΔS (mm) the water storage variation and D (mm) the drainage. All these parameters were determined during drainage periods. Surface runoff did not occur as the highest rainfall intensity recorded was 50 mm h^{-1}, while the hydraulic conductivity near saturation was about 100 mm h^{-1}. The water storage was calculated using water contents in the whole profile.

This calculation of ETR was compared with the estimation of ETR using the potential evapotranspiration (ETP) by Penman–Monteith (Chopart and Siband, 1988). This last estimation as well as the other components of the water balance are presented in Table 2.

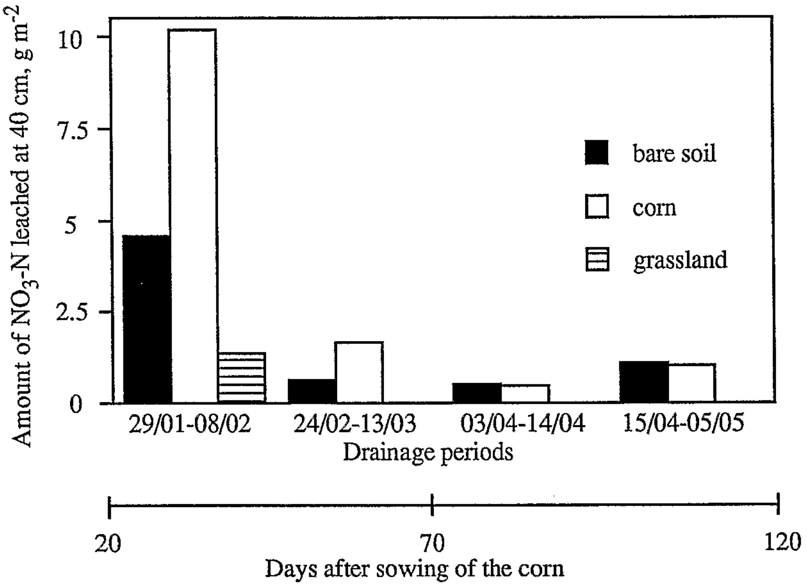

Fig. 5. Amount of NO_3–N leached at 40 cm for various periods.

On the bare soil plot, the two values of ETR were very close, while they were different for the two other plots. This can be explained by the estimation of ETR using ETP. Indeed, this estimation of ETR does not include the effect of a plant and its transpiration but only the state of soil water content.

3.5. Nitrogen leaching

Cumulative drainage was also calculated over each drainage period. An average value of the nitrogen content in the soil solution at 40 cm was determined for each period (Table 2) so that the amount of nitrogen lost below that depth could be calculated using Eq. (2) (Fig. 5). The ammonium content was found to be almost negligible in the soil of each plot, presumably because of a rapid nitrification of ammonium to nitrate in the moist, warm, tropical soils.

In the drainage period after the first rain, just 20 days after the fertilization, the loss of nitrogen was high on all plots. On the bare plot, some 44% of the nitrogen was lost, relative to the total nitrogen supplied. The loss was 98% for the corn and 13% for the grass. Under grassland, the rate of nitrogen leaching then became negligible, whereas losses continued for the other plots.

4. Discussion

4.1. Water fluxes

Our proposed use of Darcy's law is confirmed by the similarity between the two different estimations of ETR for the bare soil plot. The Chopart and Siband (1988) method was assessed in Chopart and Vauclin (1990) and they also found a good agreement between the two estimations of ETR.

On all plots, the soil water content at 40 cm was maintained within a narrow band, being between 0.25 and 0.35 cm^3 cm^{-3}. This was much less than variations of water content near the surface. This small variation made easier the Darcy calculation of drainage, as $K(\theta)$ was known in this range. Rains were relatively heavy and regular during the study. The temporal evolution of the water content within the profile became different for each plot during the second part of the cycle studied. Here the rainfall was less intense, albeit still regular, and the plants' consumption was more significant.

During the first part of the cycle of the corn's growth (for the first 70 days after sowing), the hydraulic head gradients (Fig. 3) under the young corn and for the bare soil were basically similar. The water consumption by the young corn was not significant at this stage. Under grassland, the active roots of the well-developed grass took up the water from the top soil, and thereby decreased its water content. The remoistening of this upper horizon by water drawn from below created a highly positive, upward hydraulic head gradient. During the second part of this study, the consumption of water by the growing corn became greater and the gradient also became strongly positive by the end of the study. On the other hand, the bare soil and the grassland maintained a similar pattern because the mature grass had reached the end of its growth cycle and was probably becoming senescent. In summary then, the variation of the hydraulic head gradient was found to be rapid yet critical in establishing the direction and rate of water flow. Compared to the sandy and permeable soil studied by Vachaud et al. (1978) in Senegal, where the gradient reached the value of 3 after the dry season of 7 months, this ferrallitic soil of Maré under a tropical climate displays similar behaviour, but with an even quicker temporal response. However, for the soil studied by Kengni et al. (1994) under temperate conditions, a glacial terrace soil near Grenoble, France, the variation in the hydraulic head gradient was far less important.

Finally, during drainage periods, cumulative amounts of drainage calculated for each plot are very similar, probably because in this humid climate, the amount of water consumed by plants is small compared to the drainage. Drainage was found to be about 50% of the rainfall. For the first event, a tropical storm, 55% of the total drainage was lost within 2 days, 80% in 3 days and drainage became negligible within 7 days of the rain. Overall the total drainage was about 64% of this 170 mm rainfall event. This indicates that on Maré water is rapidly lost in significant amounts. In this case, the soil is not able to retain the water and the plant can derive little benefit from such heavy and intense rains. Given this dominance of precipitation, the behaviour of the bare soil and the cropped site were not that different. However, this would not be the case when a heavy rain occurred after a long dry period, for the cropped site would now be drier than the bare soil because of root water extraction. In such a case, the drainage could be less on the cropped site.

4.2. Nitrogen leaching

At the beginning of the study, the high nitrogen levels found under the corn probably reflected the low level of uptake by the young corn plants. Under grassland, the applied nitrogen had all disappeared within the first month, presumably because of rapid uptake or immobilization. However, for the initial period of the first 70 days after sowing, the amount of nitrogen leached under corn was high compared to that from bare soil. Indeed, the two plots had been ploughed at the same time and the young corn was not yet effective at uptake. Another corn plot was also studied, and although detailed results are not presented here. We found the amount of nitrogen leached during this first period was less high, being 4.2 g m^{-2}. This difference between the two plots, some 5.9 g m^{-2}, may be due to spatial variability, and more likely to the error in estimating drainage or measuring the nitrogen content. Indeed, the standard deviations in nitrogen concentration (Table 2) are high. Furthermore, measurements were made every week during the rainfall period, as recommended by some authors (Poss, 1991; Kengni, 1993). In Maré where fluxes are rapid in this permeable soil, more frequent measurements may be required. Furthermore, high variability in results might also result from variability of the soil, the heterogeneity of fertilizer supply, and the local variability in the location of roots in this case of corn sown in rows.

Furthermore, the leaching losses can be higher than the nitrogen fertilizer input. So, the mineralization of organic matter can even contribute to the leaching. In the case of corn, for the whole growing period, 133 kg N ha^{-1} was lost by drainage and we found that approximately 50 to 100 kg N ha^{-1} was consumed by plants. Compared to the amount of nitrogen supplied (104 kg N ha^{-1}), the mineralization on this cultivated plot is relatively weak, between 0.6 and 1% of the native organic nitrogen contained in the 0–0.3 m layer of this plot (Table 1). A higher mineralization rate, up to 1.5%, could have been expected in this aerated and fine-textured soil (Schepers and Meisinger, 1994). Boudot et al. (1988) found that gross mineralization rate for N was inversely related to contents of amorphous Al and allophanic constituents. Indeed, the amorphous Al in this soil is high, and that could explain the accumulation of organic matter in the 0–0.3 m layer.

5. Conclusions

The tensiometer-TDR method of hydraulic characterization, coupled with the infiltrometer, provided us with a good measure of the hydraulic properties of this permeable tropical oxisol. These characteristics suggest that this thin, very permeable soil, and a tropical climate with high rainfall intensities, conspire to create an agricultural ecosystem that has the potential to pollute underlying groundwater due to significant leaching. We found high rates of nitrogen loss, especially on bare soil, and on plots where the plant cover was not yet active, or where native nitrate levels were high. The nitrogen contents recorded in the soil solution were between 0 and 72 g m^{-3} of NO_3–N, being almost always higher that the maximum level suggested by WHO for drinking water (12 g m^{-3} of NO_3–N). The exception was under grassland one month after the fertilizer application. So fertilizer supply needs to be carefully tailored to match the plants' ability to extract it. In our case, the ammonium content was found to be negligible. Hence, there appears to be a rapid nitrification of ammonium into nitrate in this warm and moist tropical soil.

This experiment has already led to changes in the fertilizer programme, with an emphasis now on more frequent applications of small amounts. In the future, the frequency of experimental measurements will be likewise increased in order to find out exactly what happens after a tropical rainfall and to determine more precisely the water balance. Some additional analyses, such as the amount of nitrate taken up by the plants, and the amount of mineralization, will lead to even better estimates of the nitrogen balance of this fragile tropical agro-ecosystem.

Acknowledgements

This research was supported by the ''Contrat de Développement entre la Province des Iles et l'ORSTOM pour l'étude des risques de dégradation de la fertilité des sols et de pollution des lentilles d'eau douce'' and by the French Ministry of University Education and Research for the Operation no. 6DEF. The authors thank the analysis laboratory staff from ORSTOM–Nouméa for the chemical analyses and CIRAD for their collaboration in the field.

References

Angé, A.L., 1992. Environmental risks of fertiliser use. Overuse or misuse. FADINAP regional seminar fertilization and environment, 7–11 september 1992, Chiang Mai, Thailand, 57 pp.

Ankeny, M.D., Ahmed, M., Kaspar, T., Horton, R., 1991. Simple field method for determining unsaturated hydraulic conductivity. Soil Sci. Soc. Am. J. 55, 467–470.

Boudot, J.P., Brahim, A.B.H., Chone, T., 1988. Dependence of carbon and nitrogen mineralization rates upon amorphous metallic constituents and allophanes in Highland soils. Geoderma 42, 245–260.

Brookfield, H.C., 1989. The human context of sustainable smallholder development in the Pacific. In: IBSRAM Proc., Bangkok, 8, 189–204.

Brunel, J.P., 1994. L'évaporation sous différents climats du Sud-Ouest Pacifique. Etudes énergétique et isotopique. Thèse Doct., Univ. Paris-Sud, ORSTOM Ed., 426 pp.

Chopart, J.L., Siband, P., 1988. PROBE: programme de bilan de l'eau. Mém. Trav. IRAT 17, 76 pp.

Chopart, J.L., Vauclin, M., 1990. Water balance estimation model: field test and sensitivity analysis. Soil Sci. Soc. Am. J. 54, 1377–1384.

Clothier, B.E., White, I., 1981. Measurement of sorptivity and soil water diffusivity in the field. Soil Sci. Soc. Am. J. 45, 241–245.

Kengni, L., 1993. Mesure in-situ des pertes d'eau et d'azote sous culture de maïs irriguée. Application à la plaine de la Bièvre (Isère). Thèse Doct., Univ. Joseph Fourier (UJF), Grenoble 1, 200 pp.

Kengni, L., Vachaud, G., Thony, J.L., Laty, R., Garino, B., Casabianca, H., Jame, P., Viscogliosi, R., 1994. Field measurements of water and nitrogen losses under irrigated maize. J. Hydrol. 162, 23–46.

Latham, M., Mercky, P., 1983. Etudes des sols des îles Loyauté. Carte pédologique et carte d'aptitude culturale et forestière à 1:200 000. ORSTOM, Notice Explic. 99.

Naidu, R., Haynes, R.J., Gawandar, J.S., Morrison, R.J., Fitzpatrick, R.W., 1991. Chemical and mineralogical properties and soil solution composition of acid soils from the South Pacific Islands. In: Wright, R.J. et al. (Eds.), Plant–Soil Interactions at Low pH. Kluwer Academic Publishers, pp. 4–53.

Poss, R., 1991. Transferts de l'eau et des mineraux dans les terres de Barre du Togo. Conséquences agronomiques. Thèse Doct., Univ. Paris VI, 291 pp.

Poss, R., Saragoni, H., 1992. Leaching of nitrate, calcium and magnesium under maize cultivation on an oxisol in Togo. Fert. Res. 33, 123–133.

Schepers, J.P., Meisinger, J.J., 1994. Field indicator of nitrogen mineralization. In: Soil Testing: Prospects for improving Nutrient Recommendations. Soil Sci. Soc. Am. Spec. Publ. 40, 31–47.

Sumner, M.E., McLaughin, M.J., 1996. Adverse impacts of agriculture on soil, water and food quality. In: Naidu, R., Oliver, D.P., Rogers, S., McLaughin, J.M. (Eds.), Contaminants and the Soil Environment in the Australasia–Pacific Region, Adelaide, Australia, 18–23 February 1996. Kluwer Academic Publishers, pp. 125–181.

Tucker, B.M., 1954. The determination of exchangeable calcium and magnesium in carbonate soils. Aust. J. Agric. Res. 5, 706–715.

USDA, 1975. Soil Taxonomy, a basic system of soil classification for making and interpreting soil survey. U.S. Dep. Agric. A and B, 436 pp.

Vachaud, G., Dancette, C., Sonko, S., Thony, J.L., 1978. Méthodes de caractérisation hydrodynamique in situ d'un sol non saturé. Application à deux types de sol du Sénégal en vue de la détermination des termes du bilan hydrique. Ann. Agron. 29, 1–36.

Vachaud, G., Vauclin, M., Colombani, J., 1981. Bilan hydrique dans le sud tunisien. 1. Caractérisation expérimentale des transferts dans la zone non saturée. J. Hydrol. 49, 31–52.

WRI (World Resource Institute), 1990. 1990–91 World Resources. A Guide to the Global Environment. Oxford Univ. Press, New York.

Note to Contributors

A detailed Guide for Authors is available upon request. Please pay special attention to the following notes:

Language
Manuscripts should be written in English. Authors whose native language is not English are recommended to seek the advice of a colleague who has English as his mother-tongue before submitting their manuscript.
Authors in Japan please note: Upon request, Elsevier Science Japan will provide authors with a list of people who can check and improve the English of their paper (*before submission*). Please contact our Tokyo office: Elsevier Science Japan, 1-9-15 Higashi-Azabu, Minato-ku, Tokyo 106; Tel. +81 3 5561 5032; Fax +81 3 5561 5045.

Preparation of the text
(a) The manuscript should preferably be prepared on a word processor and printed with double spacing and wide margins and include an abstract of not more than 500 words. (b) Authors should use IUGS terminology. The use of S.I. units is also recommended. (c) The title page should include the name(s) of the author(s), their affiliations, fax and e-mail numbers. In case of more than one author, please indicate to whom the correspondence should be addressed.

Keywords
Except for the journals *Coastal Engineering* and *Hydrometallurgy*, authors should provide 4 to 6 keywords. These must be taken from the most recent American Geological Institute GeoRef Thesaurus and should be placed beneath the abstract. Hydrometallurgy authors will be provided with a list of keywords by the editor upon submission of manuscripts.

References
References in the text consist of the surname of the author(s), followed by the year of publication in parentheses. All references cited in the text should be given in the reference list and vice versa.

Tables
Tables should be compiled on separate sheets and should be numbered according to their sequence in the text. Tables can also be sent as glossy prints to avoid errors in typesetting.

Illustrations
(a) All illustrations should be numbered consecutively and referred to in the text. (b) Colour figures can be accepted providing the reproduction costs are met by the author. Please consult the publisher for further information.

Page proofs
One set of page proofs will be sent to the corresponding author, to be checked for typesetting/editing. The author is not expected to make changes or corrections that constitute departures from the article in its accepted form. Proofs should be returned within 3 days.

Reprints
Fifty reprints of each article are supplied free of charge. Additional reprints can be ordered on a reprint order form which will be sent to the corresponding author upon receipt of the accepted article by the publisher.

Submission of manuscripts
Three copies should be submitted to: Editorial Office Geoderma, P.O. Box 1930, 1000 BX Amsterdam, The Netherlands. Illustrations: Please note that upon submission of a manuscript THREE SETS of all photographic material printed SHARPLY on GLOSSY PAPER or as HIGH-DEFINITION LASER PRINTS must be provided to enable meaningful review. Photocopies and other low-quality prints will not be accepted for review. The indication of a fax and e-mail number on submission of the manuscript could assist in speeding communications. The fax number for the Amsterdam office is +31-20-4852696. Submission of an article is understood to imply that the article is original and unpublished and is not being considered for publication elsewhere. Authors are requested to submit, with their manuscripts, the names and addresses of four potential referees.

Submission of electronic text
Authors are requested to submit the final text on a 3.5" or 5.25" diskette. It is essential that the name and version of the word processing program, the type of computer on which the text was prepared, and the format of the text files are clearly indicated. Authors are requested to ensure that the contents of the diskette correspond exactly to the contents of the hard copy manuscript. If available, electronic files of the figures should also be included on a separate floppy disk.

∞ The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992, (Permanence of Paper).

PRINTED IN THE NETHERLANDS

Volcanic Ash Soils

Genesis, Properties and Utilization

by **S. Shoji, M. Nanzyo** *and* **R.A. Dahlgren**

Developments in Soil Science Volume 21

Volcanic eruptions are generally viewed as agents of destruction, yet they provide the parent materials from which some of the most productive soils in the world are formed. The high productivity results from a combination of unique physical, chemical and mineralogical properties. The importance and uniqueness of volcanic ash soils are exemplified by the recent establishment of the Andisol soil order in Soil Taxonomy. This book provides the first comprehensive synthesis of all aspects of volcanic ash soils in a single volume. It contains in-depth coverage of important topics including terminology, morphology, genesis, classification, mineralogy, chemistry, physical properties, productivity and utilization. A wealth of data (37 tables, 81 figures, and Appendix) mainly from the Tohoku University Andisol Data Base is used to illustrate major concepts. Twelve color plates provide a valuable visual-aid and complement the text description of the world-wide distribution for volcanic ash soils. This volume will serve as a valuable reference for soil scientists, plant scientists, ecologists and geochemists interested in biogeochemical processes occurring in soils derived form volcanic ejecta.

Short Contents:
1. Terminology, Concepts and Geographic Distribution of Volcanic Ash Soils.
2. Morphology of Volcanic Ash Soils.
3. Genesis of Volcanic Ash Soils.
4. Classification of Volcanic Ash Soils.
5. Mineralogical Characteristics of Volcanic Ash Soils.
6. Chemical Characteristics of Volcanic Ash Soils.
7. Physical Characteristics of Volcanic Ash Soils.
8. Productivity and Utilization of Volcanic Ash Soils. Appendices. References Index. Subject Index.

1993 312 pages
Dfl. 290.00
(US $ 165.75)
ISBN 0-444-89799-2

Elsevier Science B.V.
P.O. Box 1930
1000 BX Amsterdam
The Netherlands

P.O. Box 945
Madison Square Station
New York
NY 10160-0757

The Dutch Guilder (Dfl.) prices quoted apply worldwide. US $ prices quoted may be subject to exchange rate fluctuations. Customers in the European Community should add the appropriate VAT rate applicable in their country to the price.

ELSEVIER
SCIENCE B.V.