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Water Dynamics and Nutrient Leaching through a Cropped Ferralsol in the Loyalty Islands (New Caledonia)

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ABSTRACT

On the South Pacific islands, the change from traditional to more intensive agricultural practices is leading to more fertilizer use, both extensively and intensively. Nutrient leaching should be minimized to avoid plant deficiencies and ground water pollution. The fate of nitrate and potassium under corn (*Zea mays* L.) and perennial grass (Rhodes grass, *Chloris gayana* Kunth.) was monitored during three wet seasons on a Ferralsol soil from Maré in the Loyalty Islands. In 1995, 130 and 41% of the applied NO_3^- and K^+, respectively, leached beyond the root zone. Split application of the fertilizers in 1996 decreased the amounts leached to 48 and 11%, respectively. This reduction occurred even though the rainfall nearly doubled from 1995 to 1996. Nitrate and potassium transport, however, can be decreased due to their retention by this Ferralsol. Nitrate can be adsorbed on the positively charged surface of aluminum and ferric oxides. Due to the rapid drainage under tropical rainfall, however, this phenomenon is not very effective. Potassium is usually tightly fixed on 2:1 clay minerals, but these are nonexistent in our soil. Potassium also is bound to humic substances and the organic matter reaches 15% in the subsoil of this Ferralsol. Leaching of K^+ was retarded compared with NO_3^-, but was still quite high compared with others studies on tropical soils.

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South Pacific islands are generally facing an increasing population as well as an evolution of the local economies. The need to maintain a certain level of food self-sufficiency and to increase the income from crops has intensified agricultural production. This evolution has resulted in a loss of traditional practices such as fallow, which could partially restore the soil fertility. Indeed, soil organic matter levels were originally quite high on most of these South Pacific islands, but more intense agricultural practices have led to their decrease (Morrison et al., 1996). Soils from the Pacific islands are usually of low fertility and deficient in available phosphorus and potassium. Nutrients applied to the surface can leach through the soil profile rapidly in tropical climates, where heavy rainfall is common (Naidu et al., 1991).

The Loyalty Islands are not troubled by excessive population growth, compared with neighboring islands where the population density can be 20 to 40 times higher (e.g., Nauru, Tuvalu, Tokelau; Morrison et al., 1996). The need for more profitable crops to earn money and feed an increasing population living in the cities, however, still leads farmers to use more fertilizers. Because of the permeable nature of the soils and underlying coral rocks coupled with high rainfall intensities, any input applied on the soil surface easily can become a contaminant of the ground water, which is the only drinking water source on these coral atolls. Further, it also means that plants could be deficient in important

Abbreviation: CEC, cation exchange capacity.

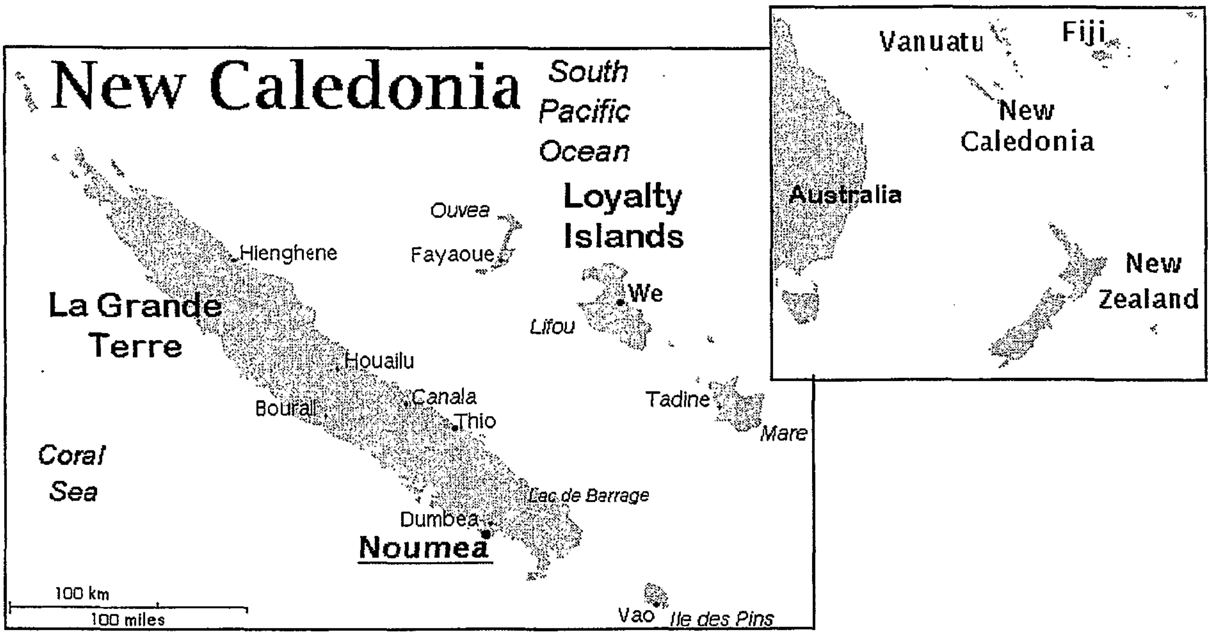

Fig. 1. Location of New Caledonia and the Loyalty Islands in the South Pacific.

nutrients if they are leached beyond the rootzone. It is thus necessary to assess the consequences of these more intensive agricultural practices on the soil and water resources. From this it should be possible to propose sustainable management practices.

In a previous paper we focused on the fate of nitrate (Duwig et al., 1998), and we presented the results of the first year of the field experiments. In this paper, we present the results of both nitrate and potassium leaching under corn and perennial grass over the 3 yr of experiments.

MATERIALS AND METHODS

Management Environment

The location of the Loyalty Islands in the South Pacific is shown on Fig. 1. The geology of the islands and the soil characteristics of the site have already been described by Tercinier (1971), Latham and Mercky (1983), and Duwig (1998). In summary, the Loyalty Islands are uplifted coral atolls where the fractured coral rock serves as a reservoir for fresh water lenses. The soils derive from volcanic ejecta and ashes. They are very shallow and primarily comprise aluminum and iron oxides with a very low level of silicates.

The main agriculture crops are traditionally yam (*Dioscorea alata* L.) and sweet potato (*Ipomoea batatas* L.). With the change in agriculture practices, vegetable and fruit cash crops are becoming more common. Nitrogen, phosphorus and potassium fertilizers are still rarely used except for a few large fruit producers, in application rates of 400 to 800 kg ha^{-1} yr^{-1}. They could however be used more extensively and intensively, as they are already on *La Grande Terre* of New Caledonia. The climate is tropical, with a wet season between December and June and a relatively dry season between October and December. The average annual rainfall is 1600 mm and the average annual temperature varies between 21 and 24°C.

Experimental Site

The field study was conducted during 1995, 1996, and 1997 on the island of Maré in New Caledonia (see the map on Fig. 1), at the experimental station in Tawaïnèdre (21°30′ S, 168°4′ E, altitude 41 m).

The soil studied here is a Geric Ferralsol (WRB, 1998) with variable charge. The average depth of the soil across the experimental site is 0.4 m. The soil profile comprises three main layers with their main chemical and physical properties shown in Table 1. Because of the presence of amorphous inorganic material, they were found to retard slightly anion transport such as nitrate and bromide (Duwig et al., 1999). But it seems that these soils have a low affinity for monovalent cations like potassium. The cation exchange capacity (CEC) of these soils is mainly due to organic matter. The CEC is dominated by Ca^{2+} and Mg^{2+} and the amount of K^+ is low. This weak sorption of K^+ in this soil can be explained in two ways. Humus shows a marked preference for divalent ions over monovalent ions, due to their high surface charge density

Table 1. Physical and chemical properties of the three soil layers of the Tawaïnèdre station.

Depth	Bulk density	Granulometry C†	Granulometry Si†	Granulometry Sa†	pH H_2O	pH KCl	Organic C	Exchangeable bases‡ Ca	Exchangeable bases‡ Mg	Exchangeable bases‡ Na	Exchangeable bases‡ K	CEC at pH 7	Total elements§ SiO_2	Total elements§ Fe_2O_3	Total elements§ Al_2O_3	Total elements§ TiO_2
cm	Kg m^{-3}	%					g kg^{-1}					cmol kg^{-1}	%			
0–15	620	42.6	39.3	4.4	6.8	6.3	76.80	15.79	10.08	0.26	0.48	26.93	nd	21.05	37.62	1.06
15–35	730	38.1	33.1	24.8	6.3	6.2	24.02	4.32	3.33	0.18	0.09	10.71	1.06	24.51	42.95	1.03
35–60	800	59.0	38.5	0.4	5.8	6.0	8.44	0.28	0.30	0.08	0.04	3.48	1.46	25.14	44.00	0.85

† Granulometry determined using a Robinson pipette, after dispersion by Na-metaphosphate [C = clay; Si = silt; Sa = sand].
‡ Tucker, 1954.
§ Digestion with perchloric acid.

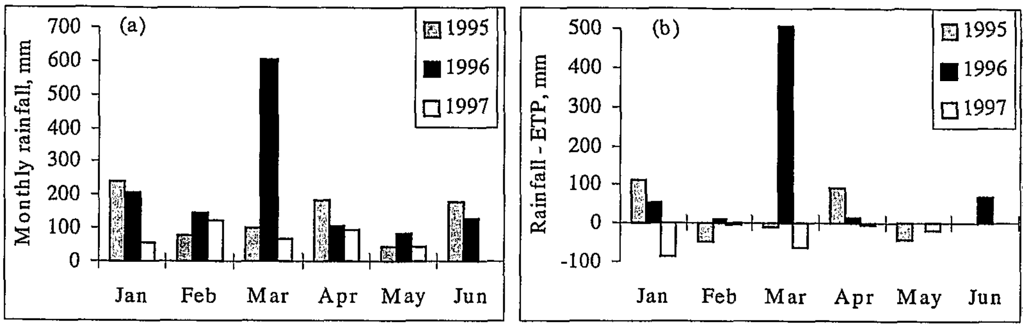

Fig. 2. Pattern of monthly rainfall (a) and balance between rainfall and potential evapotranspiration (b).

and the potential for bidentate bonds (Chung and Zasoski, 1994). Also, there is a lack of 2:1 clay minerals that exhibit a high affinity for K^+ (Haby et al., 1990).

The three seasons studied were very different in terms of their weather conditions. In 1995, the rainfall was 720 mm during the first 6 mo, whereas it was 1300 mm in 1996 and 500 mm in 1997. A cyclone occurred in March 1996, which led to 238 mm of rainfall over just 4 d with a maximum rainfall rate of 139 mm in 24 h. The monthly rainfall pattern for the three wet seasons studied is shown in Fig. 2a.

Figure 2b shows the balance between monthly rainfall and potential evapotranspiration estimated from the Penman equation. During the 1995 season, the monthly balance between rainfall and evapotranspiration was in deficit for three months out of six. In 1996, this balance was almost always in excess, whereas in 1997, it was for most of the time in deficit. This crude water balance hints at the possible risks of nutrient leaching. Through these experiments, we seek to determine the extent of these risks under different environmental conditions and management scenarios.

Treatments

The plots studied were 20 × 20 m, flat, and delineated by tractor tracks. Four different plots were monitored during the 1995, 1996, and 1997 wet seasons, between January and June. Two plots were left bare, one without any fertilizer input (A) and one with fertilizer input (B). The third was under corn (cv. Hycorn 90) (C) and the last under perennial Rhodes grass (cv. Callide) (G). The bare soil and corn plots were plowed at the beginning of the wet season, before 11 January each year. The corn was harvested at the end of April each year and replaced by a sweet potato crop for the second half of the year. The bare soil and corn plots had a similar treatment in 1994. Prior to 1994, all the plots were planted with sorghum [*Sorghum bicolor* (L.) Moench]. The perennial grass plot was plowed and sowed at the beginning of 1994. Each plot, except A, received 800 kg ha^{-1} of a 13–13–21 N P K each year, containing 104 kg ha^{-1} of nitrogen as ammonium nitrate and 139 kg ha^{-1} of potassium as potassium chloride. In 1995, all the fertilizer was applied on the day the corn was sown, 11 January. In 1996 and 1997, the fertilizer application was split in two. Half of it was applied mid-February and the other half mid-March. Corn residues remained on the plot and were incorporated into the soil before the next cropping season.

Measurements

The three plots were equipped with eight time domain reflectometry (TDR) probes to measure the water content at four different depths (10, 20, 30, and 40 cm). Because of the high rate of oxides and organic matter in the soil, TDR measurements had to be calibrated for each soil layer, using simultaneous measurements of TDR and gravimetric samples (Duwig, 1998). Ten tensiometers were used on each plot to measure the hydraulic head at five different depths (10, 20, 30, 40, and 60 cm). Measurements were made daily with the TDR and nearly every day for the tensiometers, at least when the soil moisture was sufficiently high to allow them to remain operational. Drainage below the root zone (40 cm) was estimated by using Darcy's law and water content–hydraulic conductivity relationships (Duwig et al., 1998). A battery of eight suction cups was placed at 40 cm depths in 1995 to collect samples of the soil solution. In 1996 and 1997, the number of suction cups were tripled in order to use the same cups only every 3 d. Samples were taken weekly during the rainfall event in 1995 and daily in 1996 and 1997, however samplings could only be made when the soil moisture content was high enough to permit extraction of the solution. Nitrate and ammonium contents in the samples were analyzed by colorimetry using an auto-analyzer. Potassium was analyzed by flame atomic-absorption spectrometry. Leaching of each element was calculated daily in 1996, but in 1995 and 1997, only one or two measurements were made during each rainfall event. The cumulative drainage during such an event was then multiplied by the average concentration to calculate the leaching. Rain, temperature, wind speed, and humidity were recorded on-site every hour.

RESULTS

We present here results related to measurements of water content and hydraulic head, as well as the nitrate and potassium concentrations in the soil solution and the amount of nitrate and potassium leached beyond the rootzone.

Water Dynamics

The permeable soil responds very quickly to any input of rain. This is due to its high saturated hydraulic conductivity (6.9×10^{-5} m s^{-1}) and its high porosity (70%). As an example, Fig. 3 presents the amount of the rainfall (a) for the period surrounding the cyclone of 27 Mar. 1996, as well as (b) the corresponding daily variations of hydraulic head; (c) volumetric water content; and (d) drainage at 40 cm deep for the three plots. The dynamics at the three sites are similar. Clearly the hydraulic head and water content respond to a water application on the same day. Rainfall events greater than 20 mm resulted in a rapid change in the hydraulic head, as the soil profile is shallow and the soil is very permeable (Duwig et al., 1998). Further rainfall has only a small effect. There is a limited influence of the roots because of the shallow

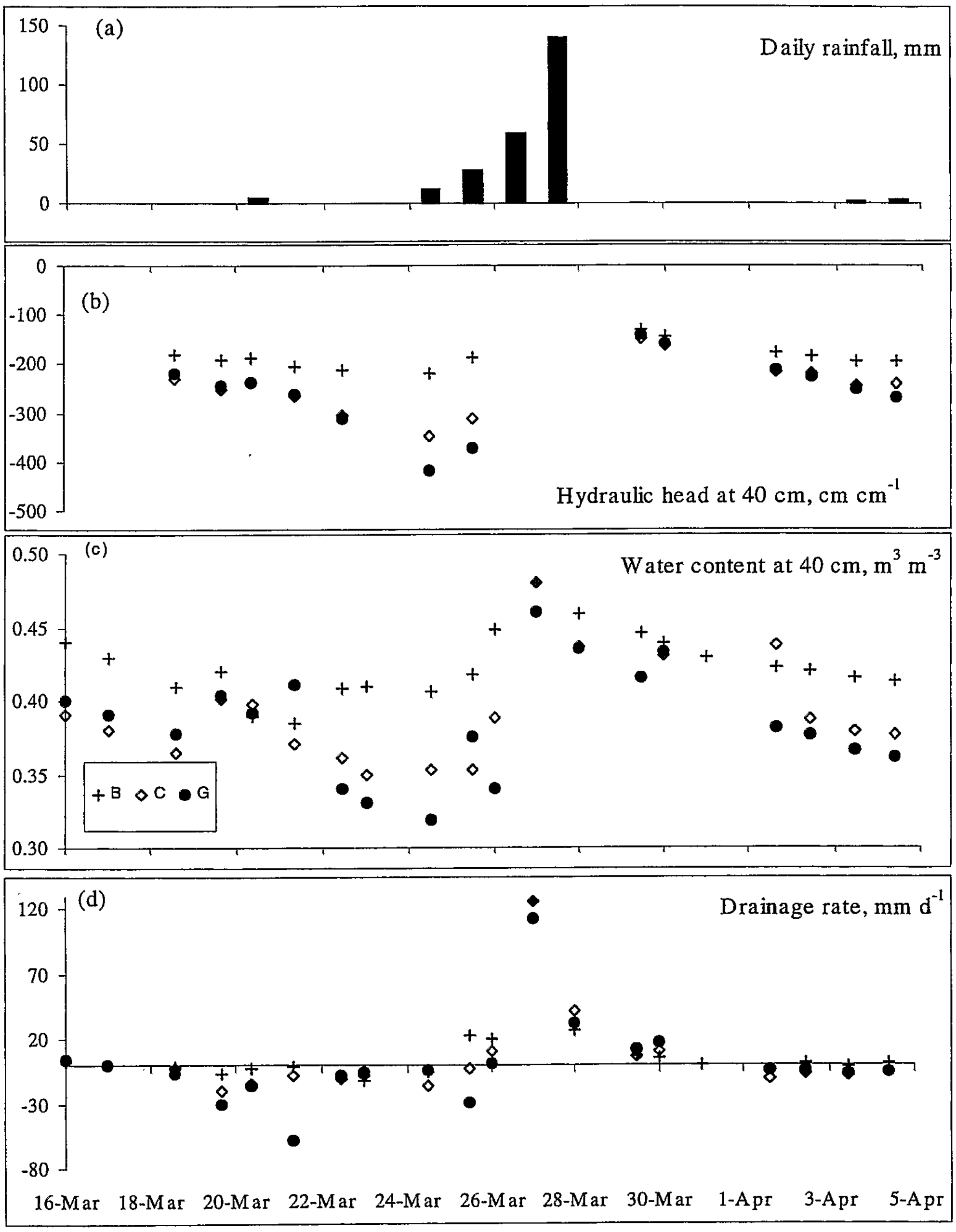

Fig. 3. Dynamics of water state variables, cumulative drainage and daily rainfall pattern, around the 24–27 Mar. 1996 cyclone, for the bare soil (B), corn (C), and grass (G) plots.

soil, with about 36 mm of available water for the plants in the 50-cm deep profile. It might be possible to notice a difference between the cropped plots and bare soil, but only after a relatively light rainfall. After a substantial amount of rainfall, the water content under the grass plot decreases more quickly than on the other plots, and this may be due to the deeper rooting pattern under grass than under young corn.

The three different treatments show a similar pattern in the daily drainage rate (Fig. 3d). The beginning of the 1995 season was characterized by 160 mm of rain falling in just 8 h. Later on in the season, other rain events did not exceed 30 mm per day. However, the hydraulic head gradient on the bare soil plot was almost always negative (not shown here), except for the first weeks of January, indicating that the soil is often subject to drainage.

In 1997, the hydraulic heads on the cultivated plots were nearly always below −700 cm and the water content at 40 cm remained relatively constant at about 0.40 cm^3 cm^{-3} throughout the season for all plots (Duwig, 1998). It was often difficult to take measurements with the tensiometers as the soil was frequently too dry. Drainage could not, in such cases, be calculated using Darcy's law. Consequently, drainage was estimated from a water balance calculation using values of evapo-

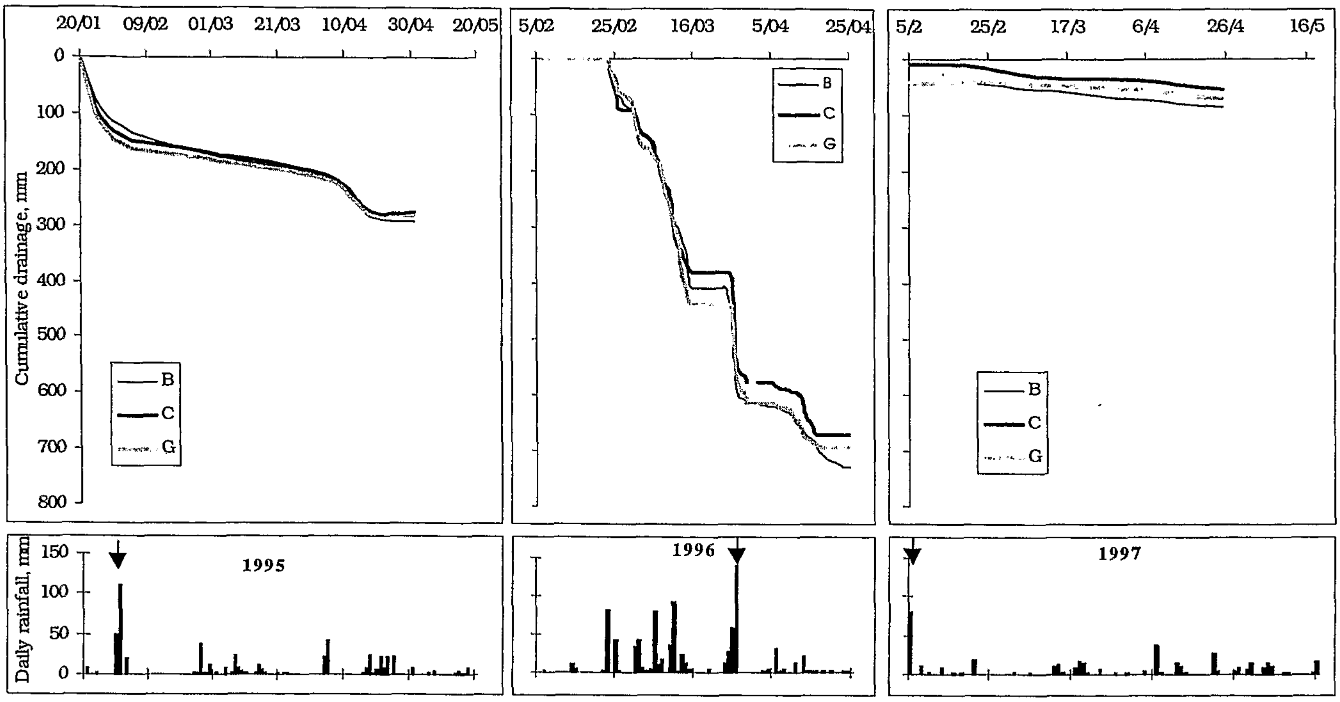

Fig. 4. Cumulative drainage under bare soil (B), corn (C), and grass (G) for the three seasons.

transpiration calculated from Penman's formula. Drainage occurred only during the four major rainfall events during the 1997 season.

Drainage

The three seasons were quite different in terms of rainfall. The amount of rainfall varied from 488 mm per 100 d in 1995 and 1099 mm per 100 d in 1996 to 352 mm per 100 d in 1997. The 1996 season presented, of course, the greatest risk in terms of nutrient losses due to the amount and intensity of rainfall. But even in 1995, where the rainfall corresponded to the average value, we recorded large amounts of drainage, even when the rainfall intensity was high for only a few hours. Such events are common in the tropics. Runoff is unlikely to happen as the plots are flat and the saturated hydraulic conductivity is very high (6.9×10^{-5} m s^{-1}), being well above the rainfall intensity. Figure 4 shows the cumulative drainage for the 3 yr and the three different treatments. The cumulative drainage expressed as a percentage of rainfall varies from 17 to 24% in 1997, 52 to 57% in 1995, and 62 to 75% in 1996, depending on the plots. An important part of this drainage results from intense rainfall events. These occurred at the end of January in 1995, the end of March in 1996 and the beginning of February in 1997 (see arrows on Fig. 4). These rainfall events represent 20 to 23% of the total rainfall during the first 5 mo of the year, but they led to 40 to 46% of the total drainage. These intense rainfall events are of course not foreseeable and it is thus difficult to predict any management to limit the drainage.

These high percentages mean that there is not much difference between the bare soil and cropped plots. Of course, the total drainage is higher under the bare soil plot than under corn or grass plots. But when intensive rainfall events occur, water uptake by plant is negligible compared with the amount of water drained. As the usable reserve of water is low, soil storage does not act as a buffer to limit the deep percolation.

Nitrate and Potassium Concentrations

We did not find important differences in the drainage below the various plots. So it is essentially the ion concentration in the soil solution at 40 cm that makes the difference in the amount of nutrients leached beyond the root zone.

Ammonium levels were always low or zero, except just after a fertilizer application. The nitrification of ammonium into nitrate must therefore be rapid. This is not surprising in this warm environment. We thus only present the results relating to N–NO_3^-.

Figure 5 shows the N–NO_3^- and K^+ concentrations during the three wet seasons and the three plots. Each point is an average between the eight samples. Standard deviations also are shown and vary between 10 and 100%. These are particularly high for potassium, but the peaks remain separated. In 1995, the total fertilizer (104 kg N ha^{-1}, 139 kg K^+ ha^{-1}) was applied on the day of corn sowing, 11 January. Both ions, K^+ and N–NO_3^-, exhibit the same behavior. After the first rainfall of the season (31 January), the concentrations are high and decrease to near zero at the end of the season. Both the K^+ and N–NO_3^- concentrations are higher under the corn than under bare soil or grass. As we previously noted, this was because the corn plants were too small at the beginning of the season to have a significant consumption of nutrients (Duwig et al., 1998). Furthermore, different previous agricultural practices had led

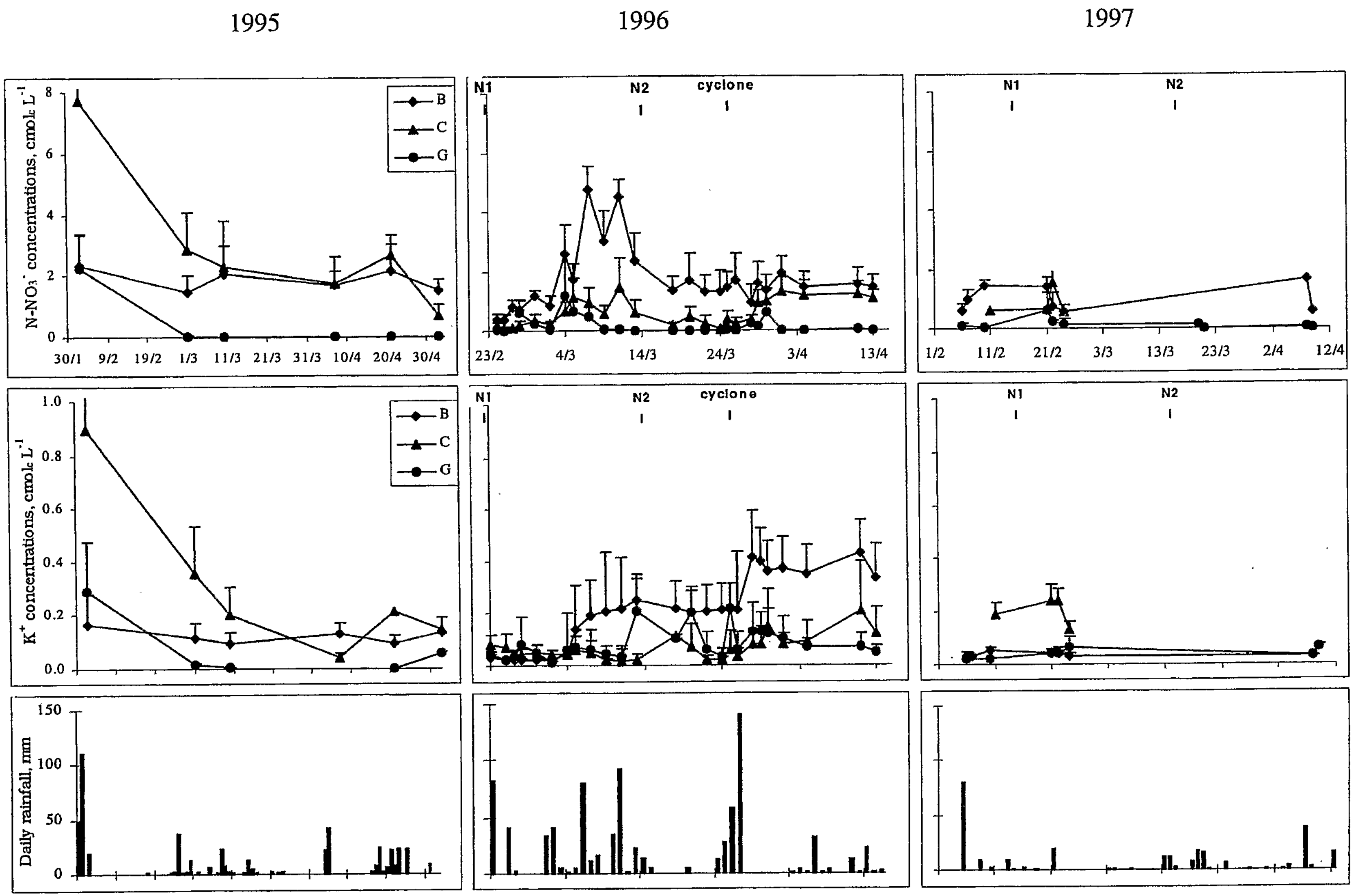

Fig. 5. Time evolution of K$^+$ and N–NO$_3^-$ concentrations measured at 40 cm depth together with daily rainfall in 1995, 1996, and 1997 for the bare soil (B), corn (C), and grass (G) plots. For clarity, only half of the error bars are shown.

to higher initial K^+ and $N–NO_3^-$ contents in the soil profile under corn than under bare soil. It also may explain why K^+ and $N–NO_3^-$ concentrations stay nearly constant throughout the season under the bare soil plot. As this plot was left bare, without fertilizer addition before 1995, the initial nitrate concentration at the beginning of the wet season is lower than under the corn plot. Furthermore, the measurements were not frequent enough to have a precise location of the peak concentration. We may have underestimated the leaching but the differences between treatments would remain similar, as the peaks occur at the same time. That is why three series of eight suction cups were installed in 1996 and 1997. It allowed us to sample the soil solution only every 3 d on the same cup, to avoid any perturbation of flux around it.

In 1996, contrary to 1995, the fertilizer was applied in two equal amounts. However, only one peak of $N–NO_3^-$ is visible on the bare soil plot. As the second fertilizer application was done 13 d before the cyclone, with no rain in between, the $N–NO_3^-$ must have been completely leached out during the 4 d of the cyclone. For K^+, the maximum of the first K^+ application seems to have been leached out after the cyclone. K^+ concentrations at 10 cm deep (not shown here) were nearly constant after the peak on 6 March, due to the first application. What has been leached down from the first application during the cyclone is thus balanced by the second fertilizer application. The K^+ leaching is obviously retarded compared the $N–NO_3^-$. However it is difficult to determine precisely the delay of the K^+ peak compared with that of the $N–NO_3^-$. We are not sure of the exact position of the maximum concentrations, due to spatial and temporal variability in our sampling. Furthermore, the K^+ peak is not as pronounced and the concentrations stay quite high until the end of the season. Under corn and grass, the peaks due to fertilizer application are much less visible. Moreover the concentrations under grass are quite low and the trend is hard to detect because of spatial variability.

In 1997, the concentrations were low for all plots. We notice a peak at the beginning of the season. However, the drainage is too low to have leached the first fertilizer input (13 February) down to 40 cm (Fig. 4). This peak must therefore be due to either fertilizer residue from 1996 or a result of mineralization. For the whole season, the amount of rainfall was so low that almost no fertilizer was leached to 40 cm deep.

Nitrate and Potassium Leaching

Figure 6 shows the cumulative leaching of K^+ and $N–NO_3^-$ at 40 cm deep for the three years and the various plots calculated from both the amount of water drained and the ion concentration. The most important result is the decrease of leaching under cropped plots from 1995 to 1996, even though the rainfall was higher in 1996. In general, the rate of K^+ leaching was lower on all plots, in relation to the rate of $N–NO_3^-$ leaching. Compared with the amount applied by fertilization, this loss varies from 0.5% to 45% for K^+ and from 1% to 167% for $N–NO_3^-$. For nitrate, these percentages are sometimes greater than 100% and show that a substantial amount of the soil store and soil nitrification also can be lost by leaching. The nitrification, cumulative nitrate leaching, and variation in the soil nitrate store are given in Table 2. The nitrification was calculated from the bare soil plots, with and without fertilizer input.

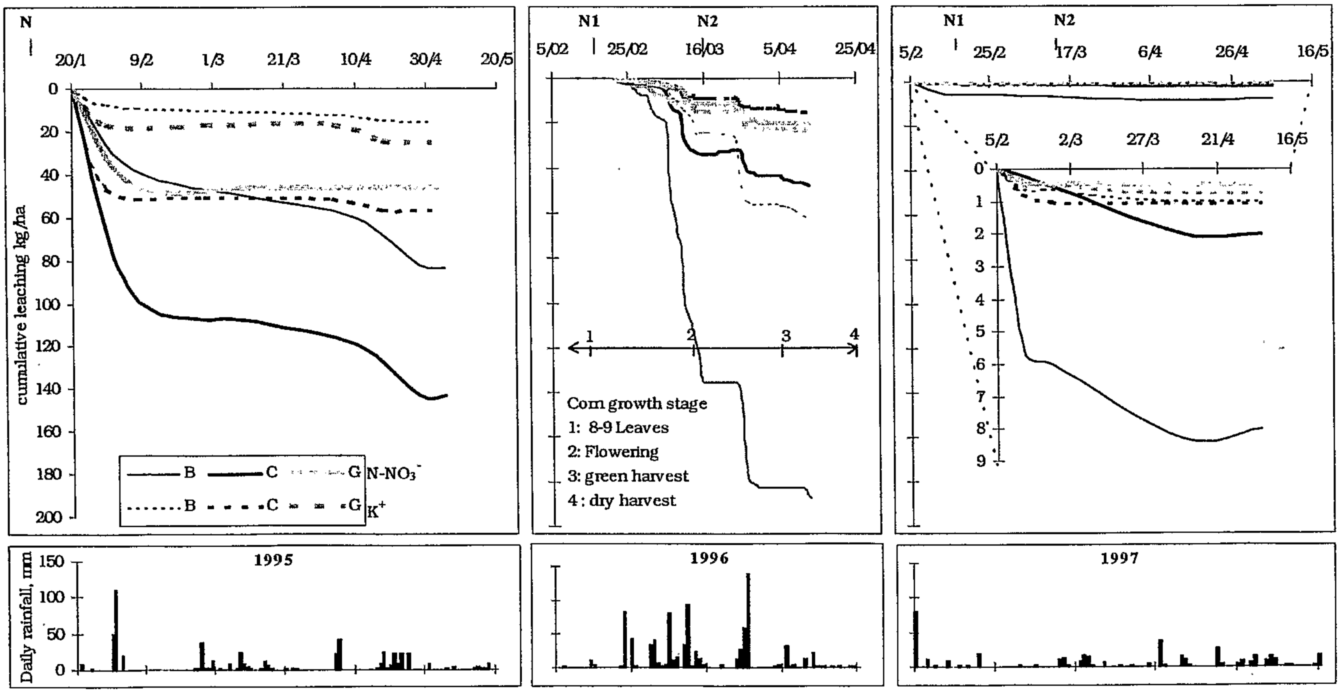

Fig. 6. Nitrate and potassium cumulative leaching at 40 cm depth for 1995, 1996, and 1997 for the three plots. In 1995, the fertilizer was applied on 11 January. In 1996 and 1997, it was split into two applications, N1 (mid-February) and N2 (mid-March).

The soil store can be very variable and it lost 100 kg N–NO_3^- ha^{-1} during the 1995 season. The nitrification also can be high, especially for the wetter season of 1996, when 60 kg N–NO_3^- ha^{-1} were produced by the soil in 80 d. Under corn, N–NO_3^- leaching decreased from 130% in 1995 to 48% in 1996, while K^+ leaching decreased from 41% in 1995 to 11% in 1996. These figures are percentages of what was applied. In 1995, the losses under corn were highest before flowering, around 15 March. Indeed, the nutrient demand by the corn plants is at a maximum at flowering (the main stages of corn growth are marked on Fig. 6). But the fertilizer was applied on the day of the sowing. The N–NO_3^- leaching is higher under corn than under bare soil in 1995. This could be due to previous agricultural practices that lead to higher initial nitrate concentration under corn than under bare soil at the beginning of the wet season. Thus, the initial nitrate was leached during the first rain of the season. Under grass, N–NO_3^- leaching also decreases from 1995 to 1996, thanks to the split application of fertilizer. The K^+ leaching stays constant from 1995 to 1996 (17%). In 1997, N–NO_3^- and K^+ leaching were very low, due to very small drainage values (Fig. 4).

DISCUSSION

Nitrate

Nitrate losses can be quite high, sometimes more than 100% of the amount applied by fertilization, especially under bare soil and heavy rainfall conditions. This is a result of the combination of highly permeable and shallow soils, intense rainfall, and a high rate of nitrification. By analyzing data from the bare soil plot, with and without fertilization (not shown here), we found for the wet season of 1996 a net nitrification rate of 0.8 to 1.0 kg N–NO_3^- ha^{-1} d^{-1}. This rate decreases to about 0.4 for a drier year, such as in 1995 or 1997. These latter rates are similar to those found in temperate climates (Kengni et al., 1994; Schepers and Meisinger, 1994). As a consequence, even without fertilizer input, the risk of nitrate leaching below the bare soil is unavoidable, especially during the wet season when the conditions for leaching also are favorable for nitrification. The initial nitrate stored in the soil also must be taken into account as it can be high depending on previous agriculture practices. However, the decrease of nitrate leaching under corn in 1996 demonstrates that this risk can be minimized with smart fertilizer management, even during a particularly wet season. We found that for the Maréan soil, nitrate has a retardation factor of between 1.1 and 1.3 in the topsoil layer (Duwig et al., 1999). That means that the adsorbed solute front is retarded from the water front by a factor of between 1.1 and 1.3. The adsorption sites are the positively charged surfaces of the Al, Fe, and Ti oxides that are present in the soil at very high levels. The adsorption can be even stronger in the subsoil layer. Although this effect should slightly reduce the amount of nitrate leached below the root zone, it is relatively ineffective since the solute transport is so rapid under tropical rainfall. Nitrate sorption also has been noticed in other highly weathered Ferralsols or in Andisols (Singh and Kanehiro, 1969; Kinjo and Pratt, 1971; Black and Waring, 1979; Katou et al., 1996).

Table 2. Terms of the nitrate balance for the bare soil, corn, and perennial grass plots for the 1995 and 1996 wet seasons. All terms are expressed in kg N–NO_3^- ha^{-1}.

Plot	Bare soil (B)		Corn (C)		Grass (G)	
Term/year	1995	1996	1995	1996	1995	1996
Fertilizer input	104	104	104	104	104	104
Nitrification	20	66	20	66	20	66
Soil store	84	−10	−100	−10	−35	0
Leaching	40	180	144	50	46	22

Potassium

The fraction of K^+ leaching was lower than that of N–NO_3^-. This could be due to sorption of potassium on exchangeable sites.

Fixation of K^+ can play a major role even in Ferralsols, even though it has been assumed that such soils cannot fix K^+ because their main clay mineral is kaolinite. Poss et al. (1991), Arkcoll et al. (1985), and Delvaux et al. (1988) found selective potassium adsorption on oxisols and other tropical soils derived form basaltic rocks. The presence of slightly interstratified 1:1 or 2:1 phyllosilicates can explain. Kirkman et al. (1994), in their review on low K^+-fixing capacities in New Zealand soils, cited Parfitt (1992), who studied an allophanic soil and found that only 6% of the potassium was leached by 280 mm of rainfall when applying 400 kg K^+ ha^{-1} into a column saturated with calcium.

Compared with these results, we found a quite high leaching rate in this Ferralsol from Maré. In this soil, mineralogical studies have not found traces of 2:1 clay minerals. Therefore, K^+ can be only electrostatically bound as an outer-sphere complex to the surfaces of humic substances. The CEC is mainly due to organic matter and this is important in the topsoil, although it decreases rapidly in the subsoil horizon, following the decline in the organic matter level. As predicted by double-layer theory, the affinity of an exchanger such as organic matter is larger for bivalent ions than for monovalent ions. Thus, potassium seems to be weakly adsorbed in Maréan soil, compared with other soils. The CEC is nearly saturated with calcium and magnesium, while the potassium content is very low (Table 1). There is little K^+ in the topsoil, about 0.48 $cmol_c$ kg^{-1}. Below 20 cm depth, it is virtually absent (0.04 to 0.09 $cmol_c$ kg^{-1}). Despite the weak adsorption, K^+ concentration peaks after the fertilizer input were retarded compared with N–NO_3^-. The selectivity of the organic matter for bivalent ions decreases markedly with increasing the concentration of monovalent ions in the solution (Stumm and Morgan, 1996). After dissolution of the fertilizer, the potassium concentration in the soil solution would be high and K^+ could be preferred to Ca^{2+} or Mg^{2+}. Therefore, the nitrate moving through the soil would mainly be accompanied by Ca^{2+} or Mg^{2+}. In the soil solution collected at 40 cm depth, the equivalent charge ratio N–NO_3^-/K^+ is close to 50 under the bare soil plot and around 20 under corn, whereas it was close to 2 in the fertilizer. Between the peaks of nitrate concentration, this ratio decreases to about 10 under these two plots. However, in 1996 under grass, the K^+ concentration varied from 0 to 0.22 $cmol_c\ L^{-1}$, while the $N–NO_3^-$ concentration was close to zero. The equivalent charge ratio is often greater than one after the first $N–NO_3^-$ peak. The counter ions with potassium leaching, when nitrate is not available, are presumably Cl^- and HCO_3^-. The Cl^- comes from rainfall and fertilizer input. A few analyses of rainfall have shown that concentrations of Cl^- range from 0.1 to 0.3 $cmol_c\ L^{-1}$. The second counter ion, HCO_3^-, derives from dissolution of carbon dioxide in water. The pH of the soil, close to 6, is favorable for the formation of HCO_3^- species. These two anions are present at relatively high levels in the ground water, respectively 0.5 and 3 $cmol_c\ L^{-1}$. Nitrate leaching can explain, in part, potassium leaching. Reduction of nitrate leaching also can serve to reduce slightly the potassium leaching. However, potassium also is leached with Cl^- and HCO_3^- as counter ions and we cannot rely on this phenomenon to limit K^+ leaching.

As we stated in the introduction, it is important to protect the ground water on the Loyalty Islands from risks of pollution. This requires smart strategies to manage agriculture practices because of permeable soils and substratum combined with high rainfall intensities. We demonstrated that split applications of fertilizer, when the plants are able to consume nutrients, can reduce considerably the amount leached beyond the rootzone. The fertilizer applications should also depend on the initial store of nutrients already in the soil and the nitrification rate, which can be high during a hot and wet season. Because of high rainfall intensities, it seems harder to manipulate the drainage. However, a more homogeneous root distribution beyond the soil surface could help to reduce water and nutrients losses, especially between corn rows. Localized fertilizer application could be another option.

CONCLUSIONS

Monitoring water transport during three cropping seasons characterized by very different climatic conditions showed that drainage can be both rapid and substantial in Maréan soil. The soil is shallow and permeable and the rain often intense. The risk of nutrient leaching toward the ground water is high.

However, we have shown that it is possible to minimize this, even during a wet season when heavy intense rainfall can occur. Split applications can considerably decrease the concentration of nutrients in the soil at a 40-cm depth.

Retention of nitrate and potassium by the soil also conspires to decrease the amount leached beyond the root zone. Nitrate is adsorbed on the Al, Fe, and Ti oxides. But this phenomenon seems weak compared with the high drainage rates. Potassium is bound to humic materials and its movement is substantially retarded compared with nitrate. However, potassium leaching beyond the root zone is still quite high, as compared with other tropical soils. This is because of the lack of 2:1 clay minerals in Maréan soil on which the fixation of potassium would be strong.

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