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Nitrogen evolution and fate in a Canary Islands (Spain) sprinkler fertigated banana plot

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Abstract

Banana and other horticultural produce cultivation, together with the population increase, has led to coastal aquifer degradation in the Canary Islands. A detailed field study to track nitrogen degradation and transport through a banana plantation soil into the aquifer is presented. The main objective of the study is to understand and quantify the hydrological behavior of the system, and quantify nitrogen leaching. The hydrogeological study of the area shows that the thin terraced soil is set on top of several layers of fractured basalt down to a massive formation where the polluted aquifer is found. When water leaves the soil profile, it is likely to quickly percolate along the preferential paths (cracks) through the basaltic layers and it is intercepted by lateral interflow in a mixing ratio of 25% irrigation drainage plus 75% interflow, before it reaches the aquifer. The soil water balance shows that most of the drainage (18% of the total irrigation + rainfall) is produced during the crop highest water demand period and during the short rainy season when no irrigation is applied. Monitoring of the soil solution showed that very high nitrate concentrations (50–120 mg/l N–NO_3) are present throughout the experimental period. The high water fluxes and nitrate concentration at the bottom of the soil profile produce a yearly loss of 48–52% of the total N applied (202–218 kg N/ha per year). Monitoring of water from springs below the experimental area shows that the nitrate lixiviates are diluted around 60% before reaching the aquifer, after mixing with the lateral flow. Smaller and more frequent applications of both N and water would help to reduce the environmental impact of the system.

Keywords: Ammonium; Bananas; Contaminant; Environment; Fertigation; Hydrology; Nitrate; Pollution; Volcanic soil; Water; Suction cups

1. Introduction

Although income from bananas is about 2% of the gross regional income in the Canary Islands (COAP, 1995), its cultivation and trade are very important for economic, cultural

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and social reasons, employing 6% of the active population. The climatic and physiographic variability of the islands impose irrigation on the crop for most of its year-around cycle to cover monthly water deficits as high as 130 mm. The introduction of fertigation and micro-irrigation techniques has allowed the expansion of the crop to areas with reduced water quantity and quality. The intensity of the banana and other horticultural crops coexisting in the same areas, demanding high inputs of water and agrochemicals, together with rural population increase, has resulted in degradation of the coastal aquifers.

The global hydrological balance in the two most populated islands (Tenerife and Gran Canaria) and the region is presented in Table 1. Evapotranspiration plus infiltration account for up to 85–98% of the total rainfall. This means surface water is a scarce resource, and the islands rely heavily on groundwater resources (95% of total water supply).

Rainfall varies significantly within each island depending on orientation and altitude. Northern areas are wetter than southern ones, and precipitation also increases with elevation. Bananas are grown on the lower, drier coastal areas, where precipitation can be as low as 100 mm per year or even less. Water consumption from both agricultural and human uses is increasing, exceeding in some instances the net groundwater recharge. This situation is forcing the introduction of expensive non-traditional water resources such as desalinization and water treatment and reuse, as proposed by the Canary Islands' Hydrological Plans (DGA-SPH, 1993; CIAGC, 1995). Water use statistics by economic activity show agriculture to be the major consumer, using 60–80% of available resources. Among crops, bananas alone consume up to 60% of the agricultural water resources (SYSCONSULT-AICASA, 1987). The scarcity of water imposes the need to conserve the resource and to use it efficiently. This concern is illustrated by the fact that the Canaries pioneered the introduction of micro-irrigation systems at both national and European levels (Sánchez Padrón, 1985).

Water management and use in the islands is threatened by pollution from human sources (agriculture and others). A recent study (DGA-SPH, 1993) shows that most of the traditional agricultural areas are already polluted. In a limited area such as an island, a polluted aquifer is a lost aquifer, thus imposing the need to resort to expensive non-traditional resources that compromise the sustainability of the system.

Table 1
Components of the hydrological cycle in the Canary Islands

Factor[a]	Gran Canaria			Tenerife			Canary Islands		
	hm^3 per year	mm per year	%	hm^3 per year	mm per year	%	hm^3 per year	mm per year	%
P	466	300	100	865	425	100	2535	507	100
ET	304	195	65	606	298	70	1665	333	66
I	87	56	19	239	117	28	590	118	23
Es	73	47	16	20	10	2	280	56	11

[a] *P*: precipitation; ET: evapotranspiration; *I*: infiltration; Es: surface run-off.

There are three major classes of groundwater pollution present in the islands: (i) volcanic activity; (ii) sea water intrusion caused by over-exploitation and (iii) drainage from agricultural lands and rural septic systems. As a result, the quality of available resources varies depending on their source. The two most common groundwater extraction systems on the islands are regular (vertical) wells and "galleries" (horizontal wells). Well water typically bears a high sodium chloride content, up to 2000 mg/l Cl and 1250 mg/l Na, with neutral pH and $EC_{25} > 5$ dS/m. Gallery water is characterized as sodium bicarbonated, with $pH > 8$, and in some cases, reaching up to 2000 mg/l HCO_3 and 500 mg/l Na. The water usually has a high silica content (50–110 mg/l SiO_2) caused by prolonged contact with the aquifer materials (fossil waters); in some areas it can also have a very high fluoride content (up to 9 mg/l).

Dumping of domestic untreated effluents and agricultural lixiviates from intensive crops are the main nitrate sources to the aquifer. In general, the affected areas correspond to those where salt water intrusion is already present. These areas in Tenerife are represented by a high density of nitrate (mg/l NO_3) concentration isolines (Fig. 1). The average nitrate concentration in the main agricultural valleys of the island ranges

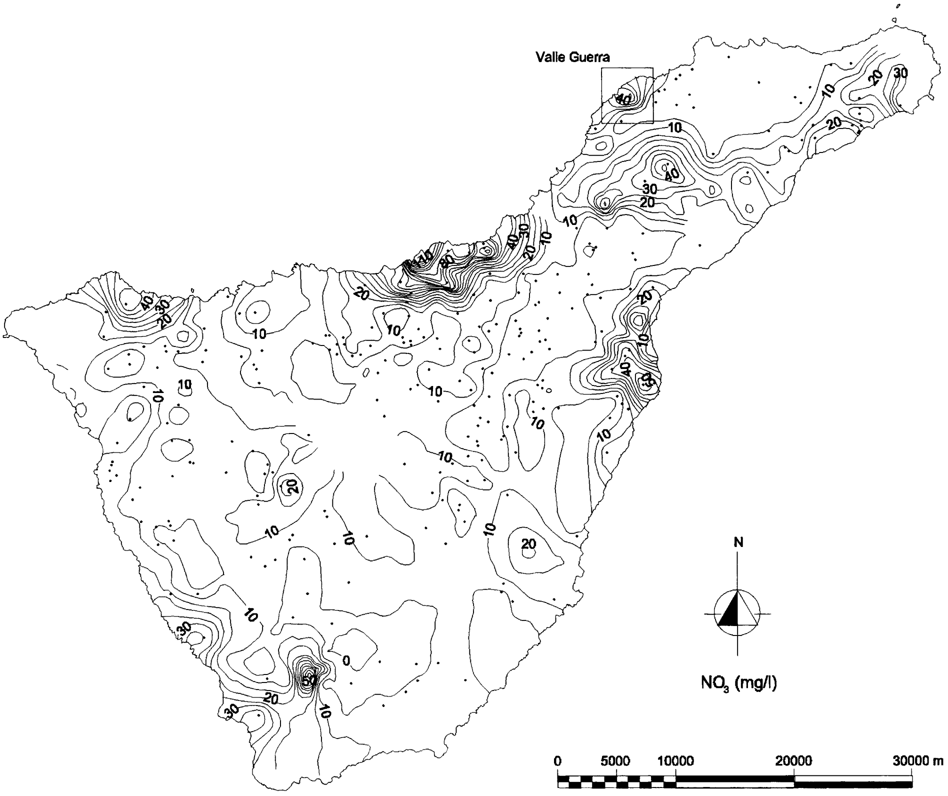

Fig. 1. Nitrate concentration isolines (NO_3 mg/l) in the island of Tenerife (DGA-SPH, 1993).

9–11 mg/l N–NO_3 (40–50 mg/l NO_3), but exceeds 25 mg/l N–NO_3 in some areas (>110 mg/l NO_3).

The Hydrological Plan of Tenerife (DGA-SPH, 1993) indicates that most of the nitrate comes from crop fertilization rather than septic systems. The study concludes that in the short- and mid-term, the groundwater resources of the island will continue to degrade as: (i) volcanism is a permanent process; (ii) there is not an abundant resource available in the short-term that will prevent aquifer over-exploitation in the coastal areas, although a significant increase in alternative sources is expected; (iii) nitrate leaching will eventually be reduced by non-point source pollution control programs but the existing levels will persist for a long time due to the slow recharge rate of the aquifer. The conclusions of the study can be extrapolated to other islands of the Archipelago, with some differences regarding salinity levels — lower in the wetter islands — but with nitrate levels still high.

The following experimental study deals with water and nutrient hydrological transport processes that take place in a fertigated banana plot, and that ultimately lead to soil and water pollution. The results will help agronomists to identify alternative management schemes that reduce environmental impact. The data obtained is also being used in field testing of a numerical model that will aid in the assessment of the proposed management schemes.

2. Methodology

2.1. Selection of experimental area

A 4800 m^2 field plot was selected within an intensive agricultural area, the valley of Valle Guerra, in the north of Tenerife (the largest island, 2057 km^2). The valley is enclosed by the Anaga Mountain range (altitude over 2000 m) on its NE side and is open to the Atlantic Ocean on its NW exposure, ending in a cliff 70 m high. The mean annual temperature for the area is 20°C (minimum of 15°C in winter), and annual precipitation and crop evapotranspiration measured at the plot are around 380 and 1000 mm, respectively.

The main crops in the valley are bananas and other horticultural and ornamental crops (under greenhouse and open air systems). The experimental plot was selected inside a 42 ha banana plantation (Las Cuevas) owned and operated by a private company. The plot was chosen to represent the average conditions of the area (fertigation and cultural practices) at the time. The plantation, located on fairly steep ground in the lower part of the valley, is terraced all the way down to the edge of the cliff, 70 m above sea level. One major spring present in the cliff face directly below the plantation (at 10 m above sea level) was also used in the experimental study.

The fertigation system used by the company for this plantation (Table 2) is of the type employed in around 13% of the total banana surface in the Canary Islands.

Banana fertilization guidelines in the area are as follows (g/plant per year): (a) applied with the irrigation system: 250–300 N, 80–100 P_2O_5, 350–400 K_2O; (b) applied to the soil in solid form: 80–150 CaO. The density of plants in the area is about 1800 plants/ha.

Table 2
Characteristics of the fertigation system

Distribution system	Emitter type	Summer application (m^3/ha)	Annual application (m^3/ha per year)	Efficiency (%)[a]	Fertigation equipment	Percent of banana area[b]
Buried PVC pipes	800 l/h placed 1 m high, precipitation: 40–80 mm/h	500 per week	14000	50	Venturi	13.24

[a] From Ingenieros Asociados de Tenerife, S.L. (1983).

[b] Data extrapolated from AGRIMAC, S.L. (1995).

In the south of the island, density goes up to 2000 plants/ha, which can be increased by a further 20–30% if micro-irrigation, new cultivars, and greenhouses are used.

2.2. Hydrogeology of the area

A detailed hydrogeological study was conducted on-site (Poncela, 1994). The area was formed as a series of fractured lava layers from the quaternary period (series III) on top of an older massive basaltic foundation (series I) closed to sea level. If enough time passed between volcanic eruptions, soil was formed so that the lava layers are alternated by these continuous impermeable layers of baked soil called "almagre" (Fig. 2).

The unsaturated zone is constituted by two types of materials: (a) thin soil layer at the surface, 0.6 m thick; and (b) fractured series III basaltic materials down to the water table, with a variable thickness of up to 70 m. There are only a few wells in production in

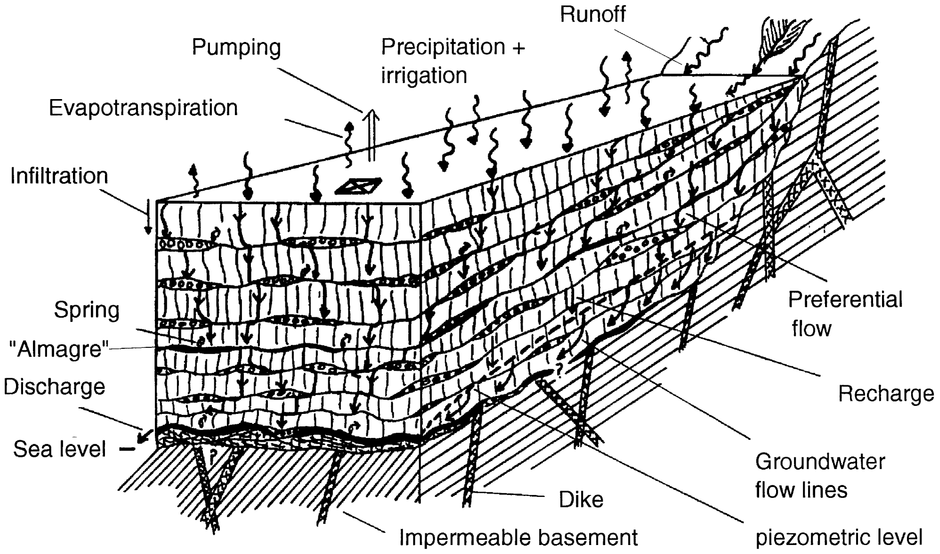

Fig. 2. Hydrogeological model at the experimental area.

the lower coastal areas due to salinization (sodium chloride) and deep water tables. Most of the irrigation water comes from galleries or a mixture of both types. The samples obtained from the network of wells around the experimental area show that nitrate pollution is present, with values above 11 mg/l $N\text{–}NO_3$ (50 mg/l NO_3) in some instances (Muñoz-Carpena et al., 1996a).

Water flow to the aquifer comes from two major sources: (a) general interflow from the adjacent mountains; (b) drainage from agricultural lands. This flow to the aquifer is intercepted by ‘‘almagres’’ and conducted laterally where it frequently appears as a spring flowing from the cliff side. The isotopic and hydrogeological study conducted using water samples (irrigation, spring and well water) from one sampling date shows that the water finally reaching the aquifer is a complex mix of about 25% drainage from agriculture and 75% general groundwater interflow.

2.3. Soil characterization

It is generally agreed that the lower limiting temperature for banana growth is 15°C. Since those conditions are only met in the lower coastal areas of the islands (preferably along the southern shores), two practical problems arise for banana (and other horticultural crops) production. First, generally speaking, the natural soil profile in the area is too thin to sustain banana cultivation due to its recent volcanic origin, and the dry and uniform climate of the lower coastal areas. Second, the fact that the landscape of the area is typically formed by steep slopes, sometimes over 10%. These conditions have resulted in the typical agricultural landscape of the islands, the ‘‘sorriba’’, terraces built across the steep slopes with rock retaining walls filled with soils imported from the high mountain areas where changes in humidity and temperature have allowed weathering of the volcanic materials and produced well developed soils. Traditionally these soils are put over a drainage layer of gross material, which lays on top of the fractured rock that constitutes the subsoil. From the soils standpoint the implications are clear: conditions at any given terrace or plot should not necessarily correspond to those found in adjacent plots, since the soil might have different characteristics depending on its origin. This imposes the need of a careful on-site soil characterization. In our case, the ‘‘sorribas’’ of the plantation (42 ha) were built by the owner during the same period (over 50 years ago) from the same soil sources, but they might not agree with soils from adjacent plantations.

In June 1994, a soil depth survey was conducted at the experimental plot by means of thin soil borer on a grid of 110 points (Fig. 3). Seven soil pits were excavated on the plot with the aim of describing (Soil Survey Staff, 1978) and sampling the soil profile to determine variability (in depth and area) of the main soil characteristics. Soil samples, both disturbed samples and undisturbed soil cores, were taken at three depths (15, 30, 60 cm) in each pit. Physical and chemical properties were determined following standard methods (Klute, 1986). The mineral content was studied with the aid of X-ray diffraction techniques.

The soil saturated hydraulic conductivity (K_S) and characteristic (moisture) curves were measured using undisturbed soil cores (Klute, 1986). The soil characteristic curves were then fitted to the van Genuchten's equation (van Genuchten, 1980). Sorption properties for ammonium were measured in the laboratory by means of batch studies

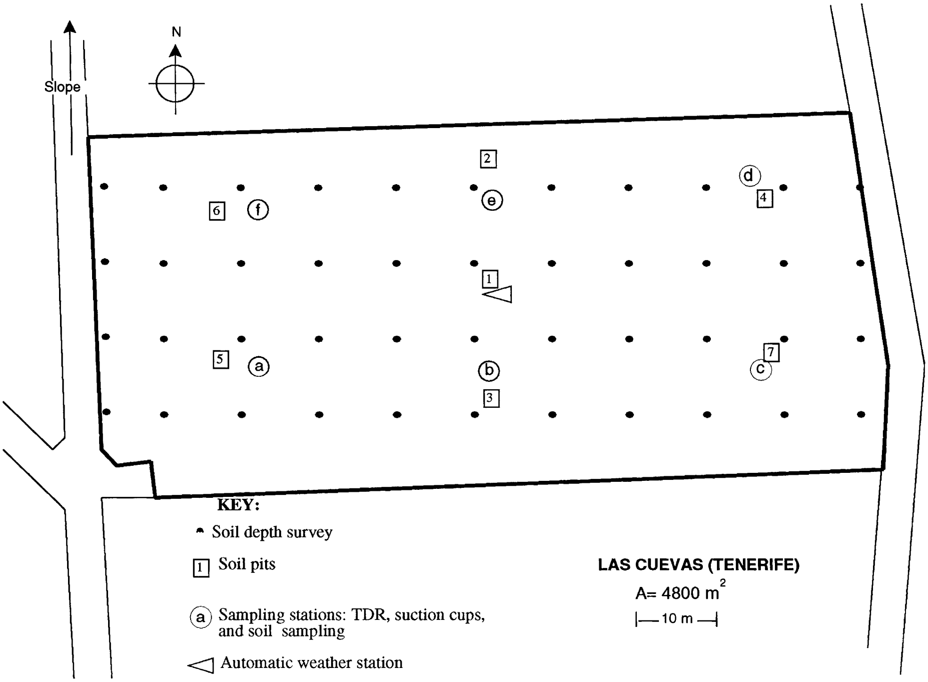

Fig. 3. Experimental field setup.

(Muñoz-Carpena et al., 1996a) and the comparison of field values of ammonium sorbed in the soil versus soil solution values. These values will help to establish the nitrogen cycle and transport at the site in concurrent modeling efforts.

2.4. Experimental design and sampling protocol

The experimental setup at the plot was designed to obtain soil and water samples from the soil section of the unsaturated zone, record the variation of the hydrologic components, and register the cultural practices and crop data at the experimental plot. Fertigation and other cultural practices were carried out by the farm following usual calendars in the area, since the intent of the experiment was to evaluate existing practices rather than to alter these experimentally.

A total of 1725 samples were collected and analyzed during the 1.5 years experimental period (August 1995–September 1996). Soil and water samples were taken at six different points in the plot to assess spatial variability (Fig. 3). Nitrogen movement was tracked by sampling the soil profile at three depths (15, 30, 60 cm). The sampling depth of 60 cm was selected to capture nitrogen content at the interface between the soil and the underlying drainage layer. Sampling took place weekly or after each irrigation event when the crop was irrigated more than once a week. Four types of samples were collected in each of the six sampling stations: (i) soil at three depths (15, 30, 60 cm); (ii) soil solution taken by ceramic suction samplers at the same three depths; (iii) effective precipitation (rainfall and irrigation) and incoming nitrogen into the soil captured by a set of ground level pluviometers, one in each of the sampling stations (Fig. 3) and (iv) water from the spring on the cliff.

The porous ceramic cups used were 60.5 mm long with an o.d. of 48.3 mm and 2 bar (200 kPa) air-entry value (SoilMoisture 653X01-B02M2, 2 bar, high flow). They were mounted on a 4.8 cm o.d. PVC tube of 15–61 cm length, closed at the top with a Santoprene stopper. Neoprene tubing was used as an access port for sample extraction and suction application. The devices were inserted vertically in clusters of three (Fig. 4), and the PVC pipes were sealed with bentonite at the surface to prevent downward water

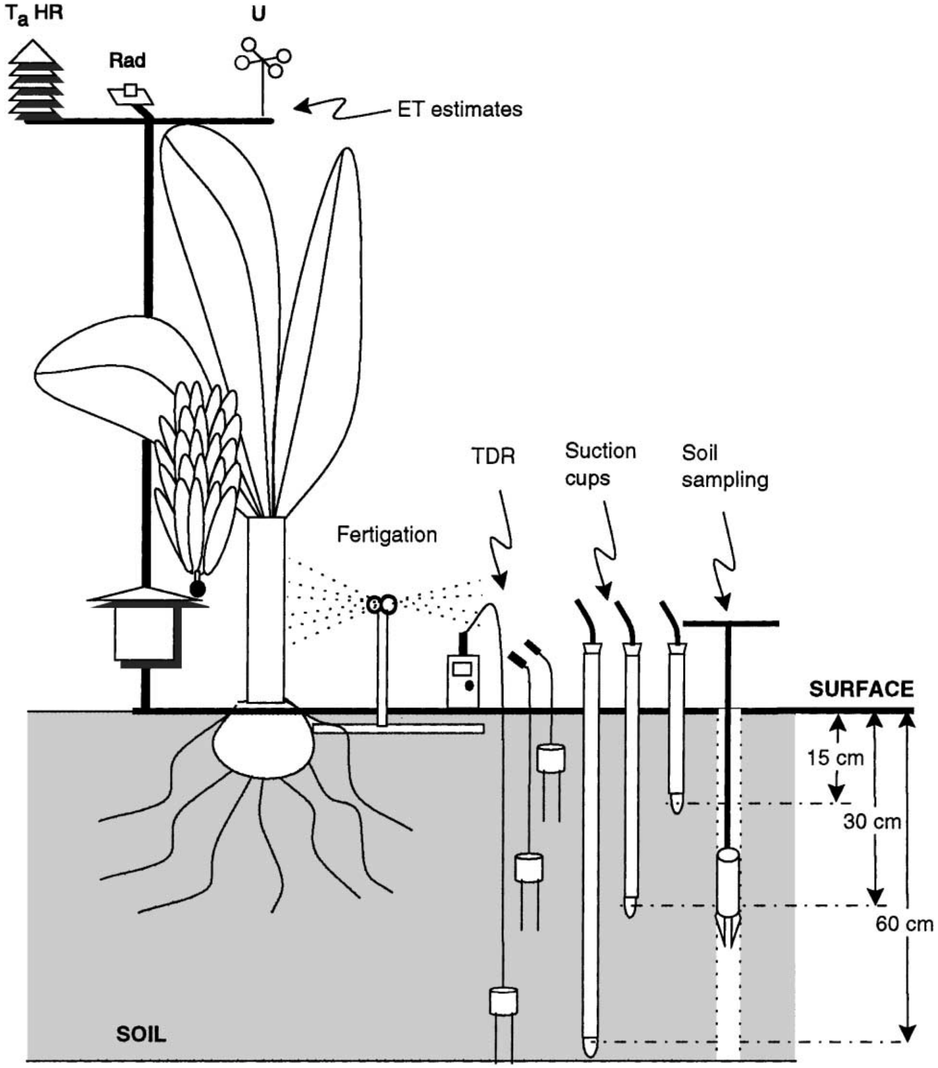

Fig. 4. Details of the sampling and monitoring equipment used in a sampling station.

movement along the external surface of the pipe. A suction of 0.60 bar (60 kPa) was applied 2 days prior to sampling. The water was collected during the period in which the suction head decreases as water enters the cup (falling head method). Suction cups are one of the early methods proposed for sampling soil water (Briggs and McCall, 1904; Wagner, 1962). The advantages of the method (nondestructive, low-cost, easiness of use) have made it one of the most widely used nowadays. The method, however, presents limitations and can yield contradictory results. Alberts et al. (1977) studied the temporal variation on the soil $N–NO_3$ content by comparing soil sample extractions with 1 M KCl with suction cup samples. Generally they found similar values between both types of samples, but in some instances large differences were attributed to the soil intrinsic variability and the limited number of repetitions. Overall, the authors concluded that this was an acceptable sampling method. Bernhard and Schenck (1986) also found an acceptable correlation ($R^2 = 0.5–0.7$) between both types of samples. Other studies show that the sample volume and concentration are not reproducible on an experimental setup, depending on the contaminant studied, material of which the suction lysimeter is made of, and the soil variability and type. Hansen and Harris (1975) in a nitrate and phosphate monitoring study observed that the variability among samplers placed close to each other was at least 30%. They explained this sample variability in terms of: (i) sorption, diffusion, washing and filtering through the cup; (ii) changes in cup permeability caused by the deposition of the fine soil particles in the small cup pores; (iii) spatial variability of the soil horizons and (iv) differences in lysimeter management such as vacuum level applied or installation. On another contaminant tracking and monitoring study of pesticides (atrazine and alachlor), using bromide as a tracer, Smith and Thomas (1990) found a coefficient of variation among nearby samples ranging from 23 to 200%. The effect of soil texture and structure on suction cup samples was studied by Shaffer et al. (1979), Barbee and Brown (1986) and Djurhuus and Jacobsen (1995). These researchers compared soil and suction cup samples obtained from soils with different textures and concluded that the method is well suited for sandy soils if the sample is taken on the same irrigation or rainfall day. For clay structured soils sample variability is high, specially when a large volume of water is applied and water moves rapidly through cracks or macropores. Djurhuus and Jacobsen (1995) concluded that in the case of structured soils, such as the one in this study, the suction cups should be preferred to soil sampling when the aim is to estimate nitrate leaching. Preferential flow though macropores in soils may affect the composition of the soil solution sampled if seepage water bypasses the suction cup (Shaffer et al., 1979; Barbee and Brown, 1986). This problem is partly a problem of spatial variability of the soils and should be addressed as such by an intensive sampling and repetition scheme. Some chemicals are adsorbed to the porous cups during the sampling process. Nagpal (1982) found very low adsorption for NO_2 and NO_3 when passing a standard solution through the cup, so that there are no limitations to its use from this point of view.

Water samples (from suction cups, pluviometers and the spring) were collected in dark glass bottles with teflon caps. Soil and water were immediately cooled down to 5°C in the field for transportation to the lab.

A typical analysis of a soil sample consisted of pH, EC_{25}, soluble $N–NO_3$ and $N–NH_4$, and total N. The $N–NO_3$ and $N–NH_4$ were analyzed using a Technicon autoanalyzer and total N by Kjeldahl's method. Water samples were analyzed in a similar manner (pH, EC_{25}, soluble N–NO_3 and N–NH_4) with the exception of the suction cups samples, where ammonium was not determined since it is known to be retained at the ceramic cup (Muñoz-Carpena et al., 1995).

An automatic weather station was installed on-site (Muñoz-Carpena et al., 1996b) to estimate reference evapotranspiration for the crop at intervals of 15 min (1 min data average) and record rainfall and soil temperature changes. Daily soil moisture content was monitored using a time domain reflectometry system (TDR). Sensors were placed at the same three depths in all six sampling stations (Fig. 4). Suction lysimeters, TDR equipment and pluviometers were protected by a mesh cage in each of the sampling stations. Soil samples were taken in a spiral fashion around the equipment cage and the sampling spot was marked with a survey flag to avoid taking a sample on disturbed soil.

2.5. Balances

A monthly water balance was established based on Penman (1950a,b) and taking the sum of daily data of precipitation, irrigation and crop evapotranspiration. Monthly average soil water content values for the whole profile were determined using the daily values of soil water content measured with TDR. Soil water content variation was calculated as the difference between consecutive monthly values. Assuming no run-off for the terraced soil, the water balance and drainage to the aquifer are given by

$$\mathrm{BAL} = (P + R) - (ET_\mathrm{c} + \Delta W) \tag{1}$$

where BAL stands for water balance, P for precipitation, R for irrigation, ET_c for crop potential evapotranspiration and ΔW for soil moisture variation.

$$D = \left\{ \begin{array}{ll} \mathrm{BAL}, & \mathrm{BAL} \geq 0 \\ 0, & \mathrm{BAL} < 0 \end{array} \right\} \tag{2}$$

where D stands for drainage.

If Eq. (1) gives negatives values, there is no drainage and actual evapotranspiration (ET_a) is set to be less than the potential evapotranspiration.

$$ET_\mathrm{a} = \left\{ \begin{array}{ll} ET_\mathrm{c}, & \mathrm{BAL} \geq 0 \\ P + R - \Delta W, & \mathrm{BAL} < 0 \end{array} \right\} \tag{3}$$

where ET_a is crop actual evapotranspiration.

A monthly nitrogen balance was also made. The N–NH_4 and N–NO_3 inputs coming from the rain and irrigation water were calculated from the analysis of field samples. Those inputs coming via fertigation were determined based on water samples taken from the sprinklers during fertigation. An estimation of the total nitrogen extraction by the crop was made combining data of banana production at the experimental plot for the period studied, foliar analyses, and considering average values found in the literature (Table 3).

A fraction of this total N extraction is assumed to return into the soil by mineralization of the crop residues left on the plot. The N–NO_3 and N–NH_4 soil concentrations were obtained from soil samples, combining them with soil water content values measured

Table 3
Annual average matter and nitrogen content of a banana plant of the Cavendish group (cv. "Grand Naine") (Soto Ballesteros, 1990)

Part of banana plant	Fresh matter (%)	Dry matter (%)	N (%)
Bunch[a]	26.85	18.2	0.87
Whole plant[b]	91.56	11.2	1.06
Shoot[c]	8.44	7.7	1.61
Whole plant + shoot	100.00	10.9	1.06

[a] Includes petiole, rib and limb.

[b] Includes bunch, pseudostem and stalk.

[c] Includes whole leaves, pseudostem, immature leave and stalk.

with TDR. The monthly variation of soil nitrogen concentration was calculated by monthly averaging the daily values (estimated by linear interpolation between weekly sample values). Taking all these factors into account, the amount of nitrogen which is lost by leaching from the soil (N_L) is given by the following balance

$$N_L = (N_P + N_R + N_F + N_{MIN}) - (N_{EX} + \Delta N_S + N_{IN}) \qquad (4)$$

where N_L is the nitrogen losses by leaching obtained with the balance method, N_P the nitrogen content in the rain, N_R the nitrogen content in irrigation water, N_F the nitrogen content of fertilizer, N_{MIN} the nitrogen content of the crop residues that are mineralized, N_{EX} the total nitrogen extracted by the crop, ΔN_S the soil nitrogen content variation and N_{IN} the nitrogen content immobilized by soil microorganisms.

Nitrogen losses by leaching will only take place in those months where drainage is observed. If the balance gives a positive value and there is no drainage, it is assumed that the nitrogen has been temporally immobilized by soil microorganisms (Gros, 1976), and the quantity is supposed to leave the soil by leaching the next month that drainage takes place.

Nitrogen losses values were compared with those independently obtained by multiplying the monthly drainage values from the water balance (Eq. (2)) by the monthly average nitrogen concentration of the soil solution in the interface of the soil and fractured rock (60 cm)

$$N_{L60} = 0.01\,D\overline{C} \qquad (5)$$

where N_{L60} is the nitrogen losses by leaching at the interface of the soil and the drainage layer (kg/ha), D the drainage (l/m^2) and $\overline{C}$ the monthly average nitrogen concentration at 60 cm (mg/l).

3. Results and discussion

The results of the soil depth survey showed that the average soil depth in the experimental plot was 60 cm, with a range of 50–80 cm, below which a net contact with the fractured basaltic rock was found.

Table 4
Physical properties of the soil at the experimental site[a]

Depth (cm)	Hydraulic conductivity, K_S (cm/h)	Bulk density, ρ_b (g/cm^3)	Specific density, ρ_S (g/cm^3)	Porosity, P (cm^3/cm^3)	van Genuchtens parameters			Texture (USDA)[b]
					α	n	θ_r	
15	13.0 ± 13.77	1.09 ± 0.06	2.51 ± 0.19	0.55 ± 0.02	0.28 ± 0.04	1.38 ± 0.05	0.15 ± 0.03	C
30	8.38 ± 2.08	1.18 ± 0.06	2.49 ± 0.06	0.52 ± 0.03	0.22 ± 0.04	1.41 ± 0.05	0.15 ± 0.03	C
60	7.65 ± 2.18	1.09 ± 0.10	2.34 ± 0.20	0.49 ± 0.03	0.19 ± 0.04	1.29 ± 0.05	0.11 ± 0.03	C-L

[a] Values shown are $\overline{X} \pm S_x$, number of samples = 7.

[b] C: clay; L: loam.

Average values and their standard deviations of the soil physical and chemical properties are summarized in Tables 4 and 5. The mineral content shows presence of volcanic amorphous materials, ferric minerals (hematites and goethite) and 1:1 clays with pH dependent charge (halloysite) and 1:2 (nontronite). The soil displays andic properties (Soil Survey Staff, 1978).

The particle analysis shows that the soil has a clay percentage above 40% (USDA texture from clay to clay–loam). The K_S literature values for these soil textures are 0.06–0.2 cm/h (Rawls and Brakensiek, 1983) or 1.07–3.63 cm/h (McCuen et al., 1981). Our soils give values around five times higher than those reported in the literature ($K_S = 7.65$–13.0 cm/s). This may be explained in terms of the high Fe-oxyhydroxides content in volcanic soils that leads to strong particle aggregation. This is consistent with a dual-porosity soil model revealing a slow flow-diffusive transport region inside the aggregates and a fast flow-convective transport region in between aggregates, as proposed for this soil by Regalado et al. (2001). This preferential flow process is widespread and leads to high effective K_S values, well above standard levels for their texture, and also to the soil fast response to inputs in the system (water and solutes).

The higher clay content in the surficial layers results in an increased moisture retention capacity as shown in Fig. 5. Values for pH and EC_{25} remain constant with depth, but organic matter (OM) is high on the surface layer due to the large amount of leaves that bananas produce, which are typically left on-site after harvest.

Table 5
Average chemical properties of the soil at the experimental site at two different times[a]

Depth (cm)	Organic matter (%) December 1995	EC_{25} (dS/m)		pH		CEC (meq/100 g)	Sorption $KdNH_4$
		December 1995	October 1996	December 1995	December 1996		
15	2.32 ± 0.79	1.85 ± 0.16	1.08 ± 0.04	6.92 ± 0.16	7.07 ± 0.21	37.1 ± 3.40	10.1 ± 2.8
30	1.70 ± 0.63	1.88 ± 0.13	1.02 ± 0.05	6.98 ± 0.11	7.17 ± 0.09	33.7 ± 2.24	13.3 ± 3.6
60	1.03 ± 0.24	1.65 ± 0.13	1.23 ± 0.09	7.25 ± 0.08	7.35 ± 0.11	32.0 ± 2.75	18.9 ± 4.1

[a] Values shown are $\overline{X} \pm S_x$, number of samples = 7.

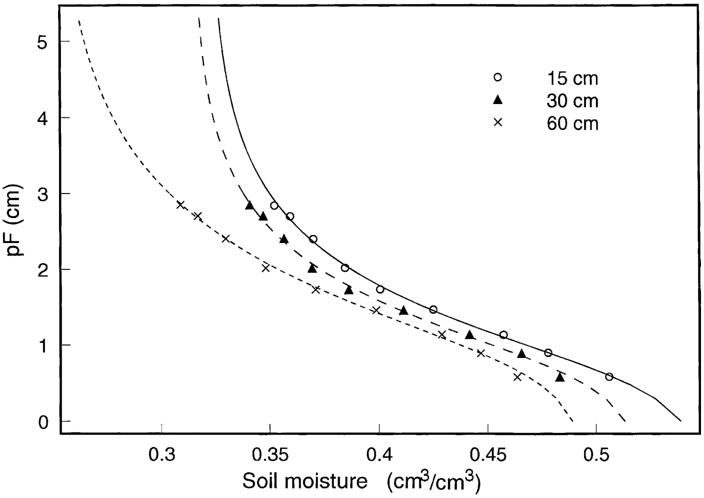

Fig. 5. Average suction curves at the experimental site (lines: van Genuchten's equation; symbols: data).

The evolution of the soil water content for the period studied (1 August 1995 to 30 September 1996) is shown in Fig. 6. It represents the average daily moisture variation at each soil depth in response to water exchanges from the soil (R, P, ET_a, D). The average coefficients of variation among sampling stations for each soil depth TDR readings were 21.2, 16.6, 18.3% for 15, 30 and 60 cm, respectively. The rainy period at the end of 1995 and beginning of 1996 results in a noticeable increase in average soil moisture content in the soil profile. Average moisture content begins to drop after that date, specially between March and June (when irrigation decreases). At 60 cm there is less depletion in soil water content. The increase of the irrigation volume in the following months reestablishes the water content of the superficial layers to the average levels.

Fig. 7 shows the components of the monthly water balance for the period studied. Potential and actual crop evapotranspiration for the period studied was 1177 and 1059 mm, respectively. The total drainage reaches 237 mm per year, which corresponds to 18% of the rain and irrigation applied in the plot during a year (439 and 873 mm, respectively). This amount is not uniformly distributed, but it takes place after long periods of precipitation or frequent irrigation. Between November and March, there is less evapotranspiration and therefore the input of water by irrigation and rain results in the largest amounts of drainage. Irrigation excess produces also some drainage in April, May and July of 1996.

Fig. 8 shows the nitrogen content in the soil solution during the year. The average coefficients of variation of $N–NO_3$ among sampling stations for each soil depth were 37.6, 34.2 and 25.0% for 15, 30 and 60 cm, respectively. Likewise, 49.9, 41.2 and 47.2% are the average coefficients of variation of $N–NH_4$ at those depths. While fertilization increases nitrogen in the whole profile, there is a marked reduction in the surficial horizon (15 cm) due mostly to plant extraction (roots found at 1–40 cm depth) and to leaching downwards.

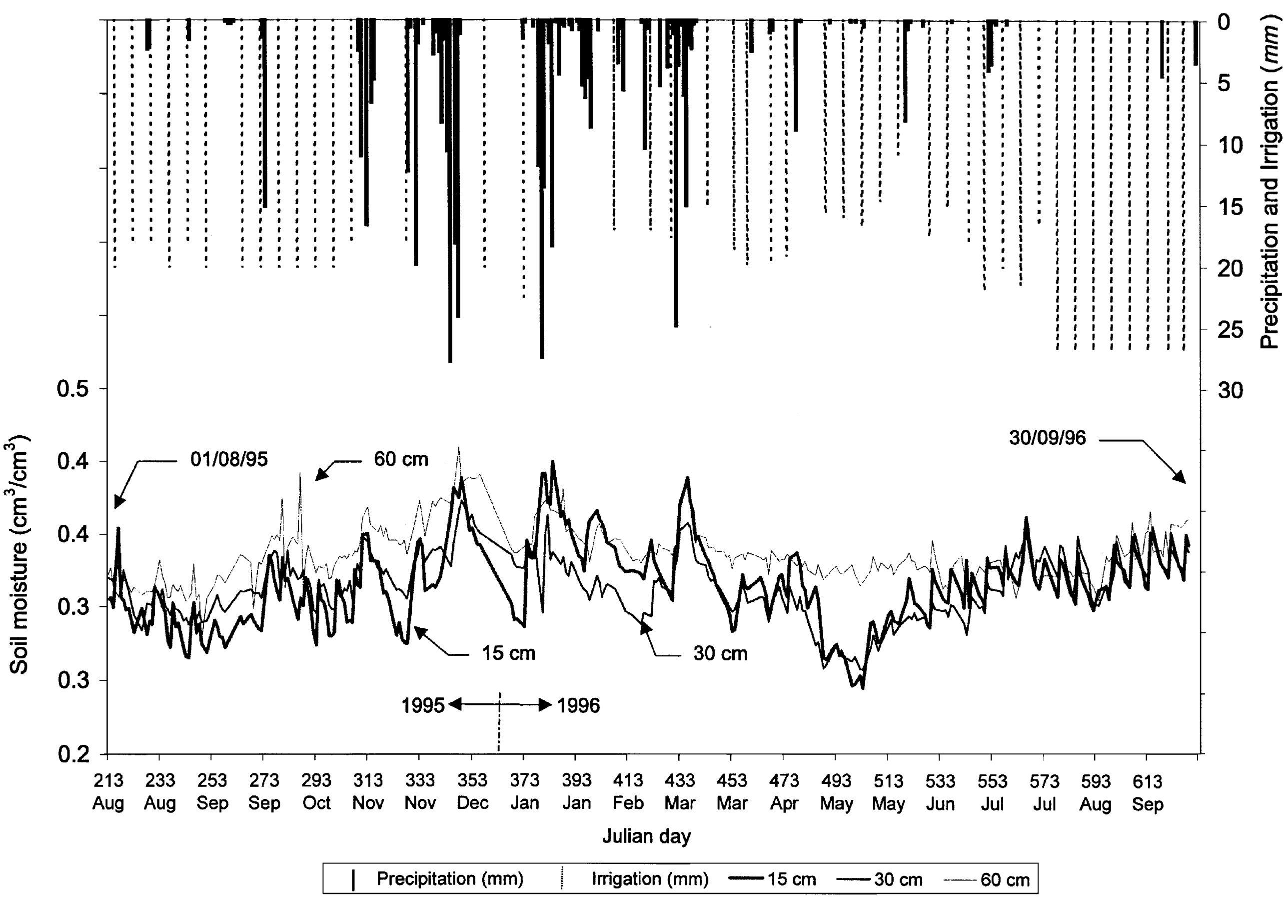

Fig. 6. Soil moisture variation at the experimental plot.

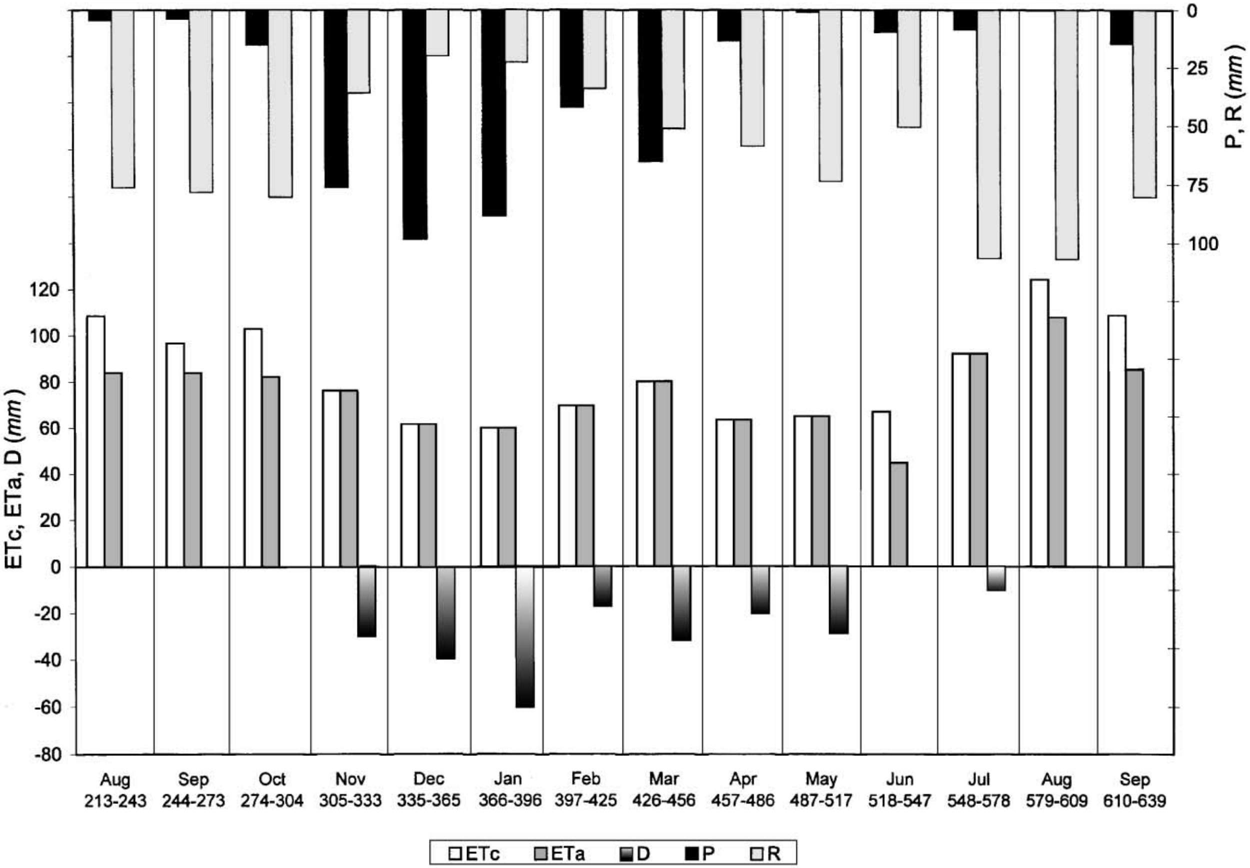

Fig. 7. Water balance at the experimental plot.

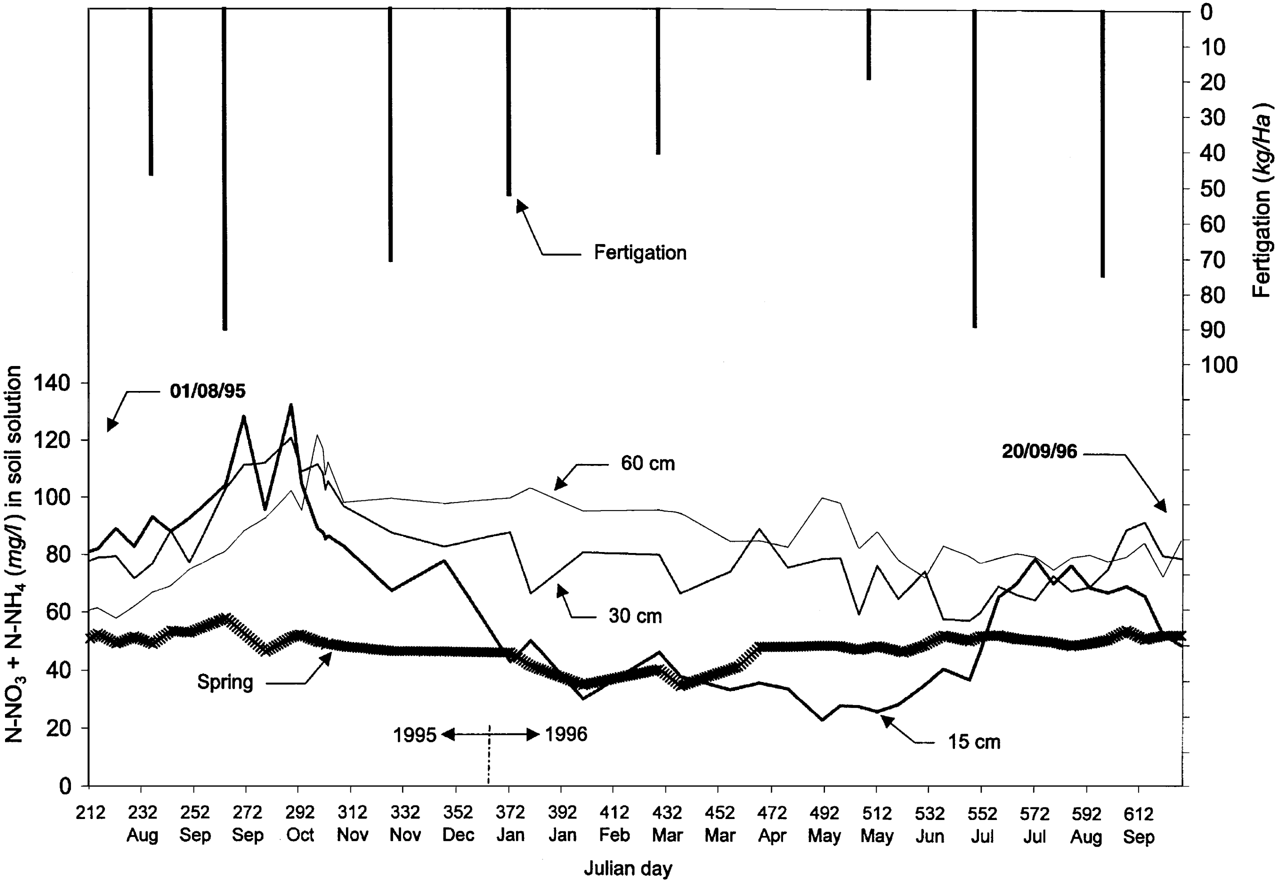

Fig. 8. Nitrogen content variation measured at the experimental plot and in the spring water samples.

Table 6
Fresh and dry matter and N-uptake of the crop for the experimental period studied (46.7 Tm/ha yield)

Part of banana plant	Fresh matter (kg/ha)	Dry matter (kg/ha)	N (kg/ha)
Bunch[a]	46679.38	8495.65	73.91
Whole plant[b]	159176.47	17827.76	188.97
Shoot[c]	14676.49	1130.09	18.19
Whole plant + shoot	173852.96	18949.97	199.14

[a] Includes petiole, rib and limb.

[b] Includes bunch, pseudostem and stalk.

[c] Includes whole leaves, pseudostem, immature leave and stalk.

Table 6 presents annual nitrogen content and fresh and dry matter distribution among the different parts of the banana plant at the end of the year based on Table 3 and a yield 46.7 Tm/ha per year. Fig. 9 presents the net nitrogen extraction curve by the crop, i.e. discounting the fraction which returns into the soil by mineralization of the crop residues left on the plot. In January and August, maximal extraction is observed, while in May and November, the nitrogen uptake is the smallest.

Fig. 10 summarizes the monthly nitrogen balance for the period. Nitrogen losses by leaching reach 202 kg/ha per year, which represents 48% of total nitrogen applied as fertilizer. Comparison of Figs. 7 and 10 shows that these losses are caused by excessive fertigation at times when leaching was produced by rainy periods or intensive irrigation. In October 1995, August and September 1996, nitrogen inputs are high but there is no drainage so that the excess stays immobilized in the soil profile. There are two possible explanations to the origin of the excessive N-applied. One explanation could lay on poor knowledge (or unrealistic expectations) of the N requirement by the crop, so that excess N is being applied even when no extra yield will be obtained. Alternatively, it could be the case where increased nitrogen levels do produce higher yields and so a reduction for environmental reasons would have economic implications. Although experience shows that in general unrealistic yield expectations (limited by micro-meteorological conditions, plant material and cultural practices) might be the key to the problem, further agronomic studies beyond the scope of this work (i.e. plant responses to different N-fertilization levels, timing and application technique), might be needed to establish the probable cause.

An alternative to reduce nitrogen leaching could be to decrease soil drainage. There are practical limitations to this option based on salt leaching requirements (LR). LR are expressed as the additional percentage of water to irrigate, above that needed to satisfy crop water needs, in order to maintain salinity in the root environment at acceptable levels. For a sprinkler irrigation system, LR can be calculated following Ayers and Westcot (1976) as $\mathrm{LR} = \mathrm{EC_W}/(5\mathrm{EC_e} - \mathrm{EC_W})$, where $\mathrm{EC_W}$ is the electrical conductivity of the irrigation water used and $\mathrm{EC_e}$ is the maximum soil extract electrical conductivity for different potential crop yields (Y). Based on weekly analyses, irrigation water used in the plot during the experimental period had an $\mathrm{EC_W}$ range of 0.7–1.4 dS/m with an average of 0.93 dS/m. Following work by Israeli et al. (1986) with bananas of the same variety, $\mathrm{EC_e}$ values for $Y = 100$ and 90% are 1.8 and 2.5 dS/m, respectively. This translates in average leaching requirements in excess of 12% for maximum potential

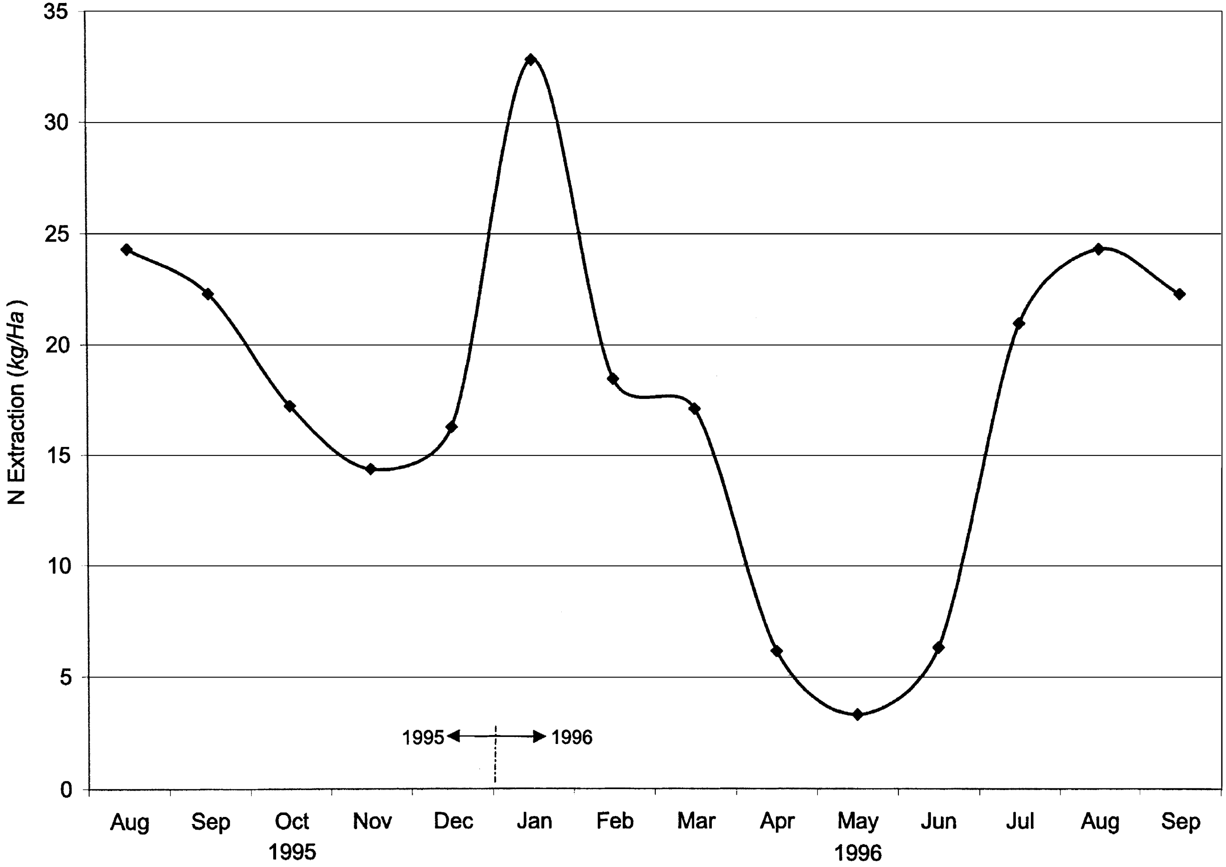

Fig. 9. Nitrogen extraction from the soil by the crop.

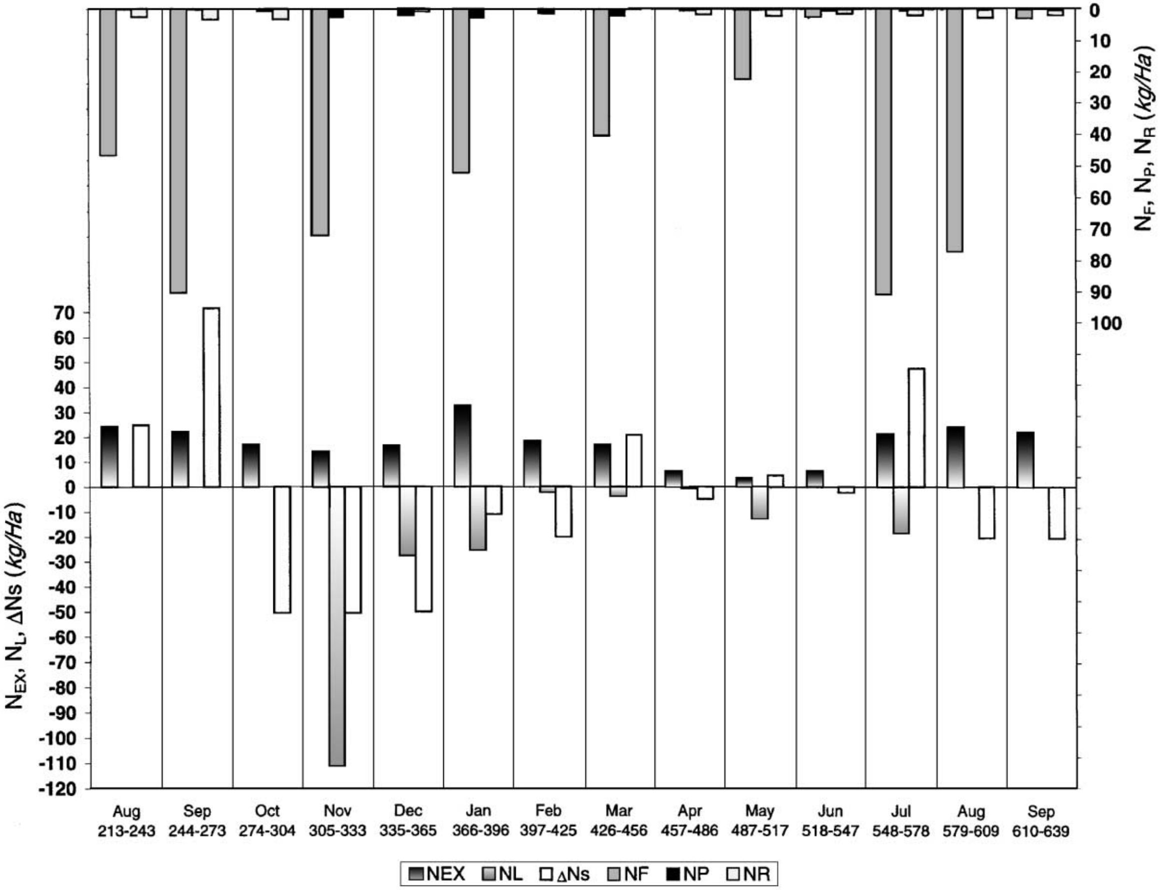

Fig. 10. Nitrogen balance in the soil.

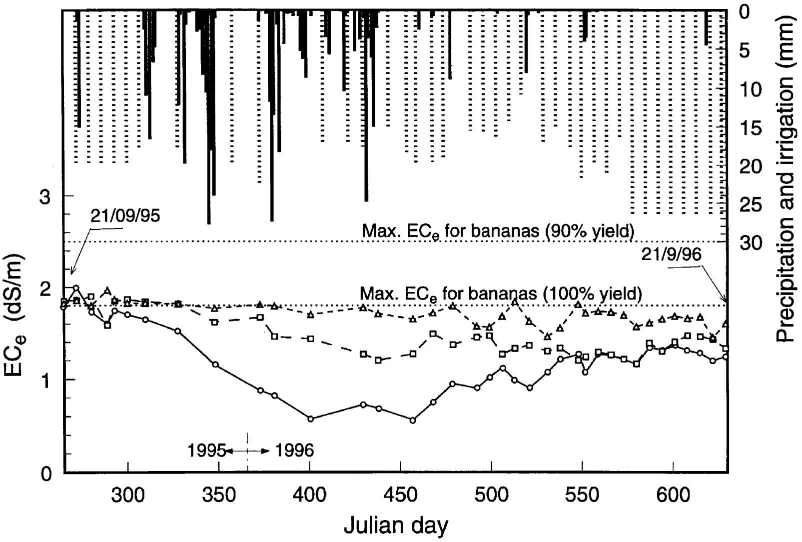

Fig. 11. Salinity (soil extract EC_e, dS/m) variation in the soil profile for the experimental period.

yield and of 8% at 90% potential yield. Results from our water balance show the actual annual LR = 18%. The effect of this LR on salinity levels at the plot is shown in Fig. 11. Weekly values for EC_e were calculated from soil solution (suction cups) electrical conductivity values (EC_{SW}) using the relationship proposed by Ayers and Westcot (1976) where $EC_e = 0.5EC_{SW}$. The figure shows that EC values in the root zone (15 and 30 cm) are always maintained below those for maximum potential yield and are only over that in a few instances for the deeper soil layer (but always below the 90% yield level). Since actual EC values at the root zone will depend on irrigation (and rainfall) applied, crop water requirements and drainage, it is always advisable to leave a margin so that salinity levels do not become a limiting factor at any given point in the crop cycle. Ayers and Westcot (1976) suggest LR values in the range 15–20%. This suggests that to avoid salinity problems, reduction in nitrate leaching should be achieved through improved fertilization practices.

As a comparison, nitrogen losses were also calculated combining drainage volumes with nitrogen soil concentration at 60 cm (Eq. (5)). Both methods yielded similar annual results. The amount determined by the drainage method results in 218 kg/ha per year, which is 16 kg/ha per year higher than the amount calculated with the balance method. However, monthly values estimated by the two methods are different (Fig. 12). This discrepancy has been reported by other authors (Djurhuus and Jacobsen, 1995; Parker and van Genuchten, 1984), in terms of the dependency of soil water quantity sampled by each method. The soil balance method deals with the resident or volume-averaged concentration, whereas the drainage method considers the flux concentration, i.e. mass of solute passing through a given cross section at an elementary time interval. Parker and van Genuchten (1984) showed that the concentrations obtained by each method are different, and thus the nitrate leaching estimates.

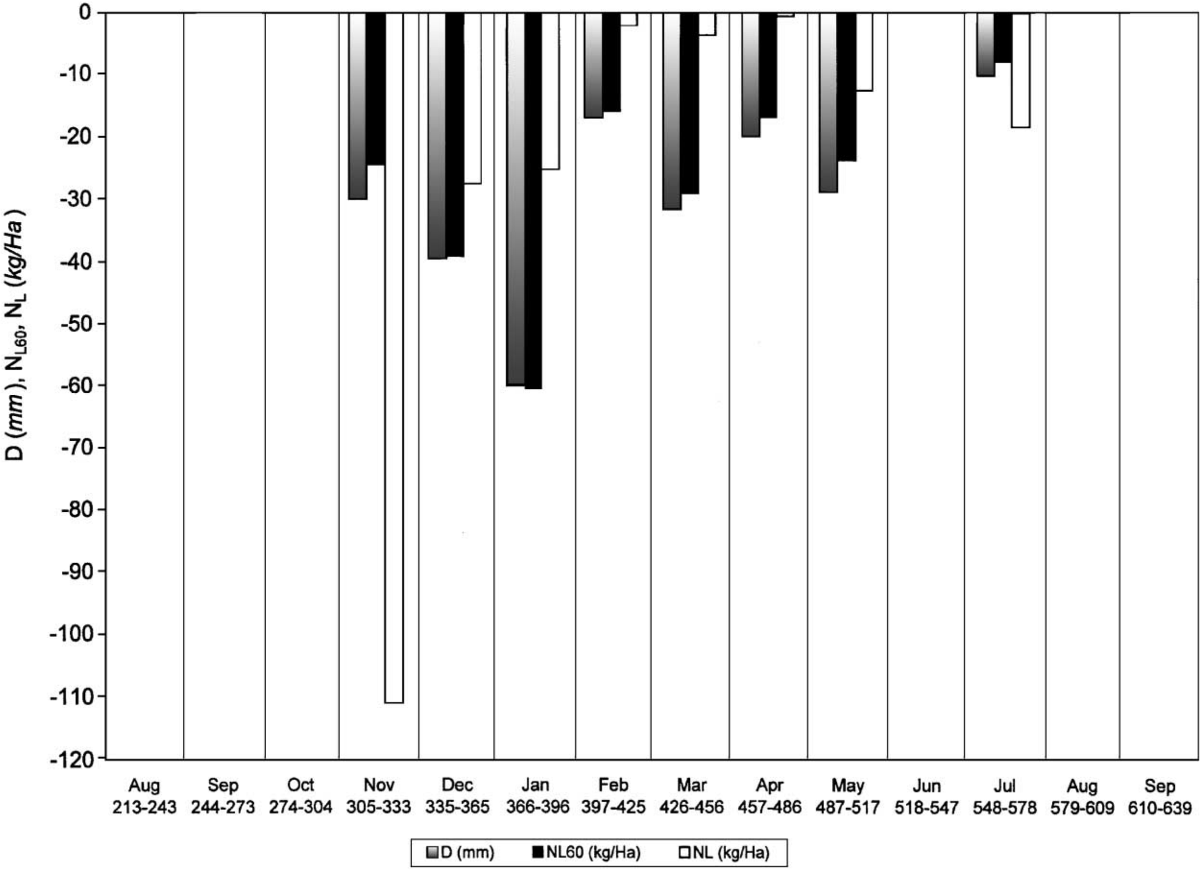

Fig. 12. Nitrogen losses according to two methods: monthly balance and soil drainage at 60 cm.

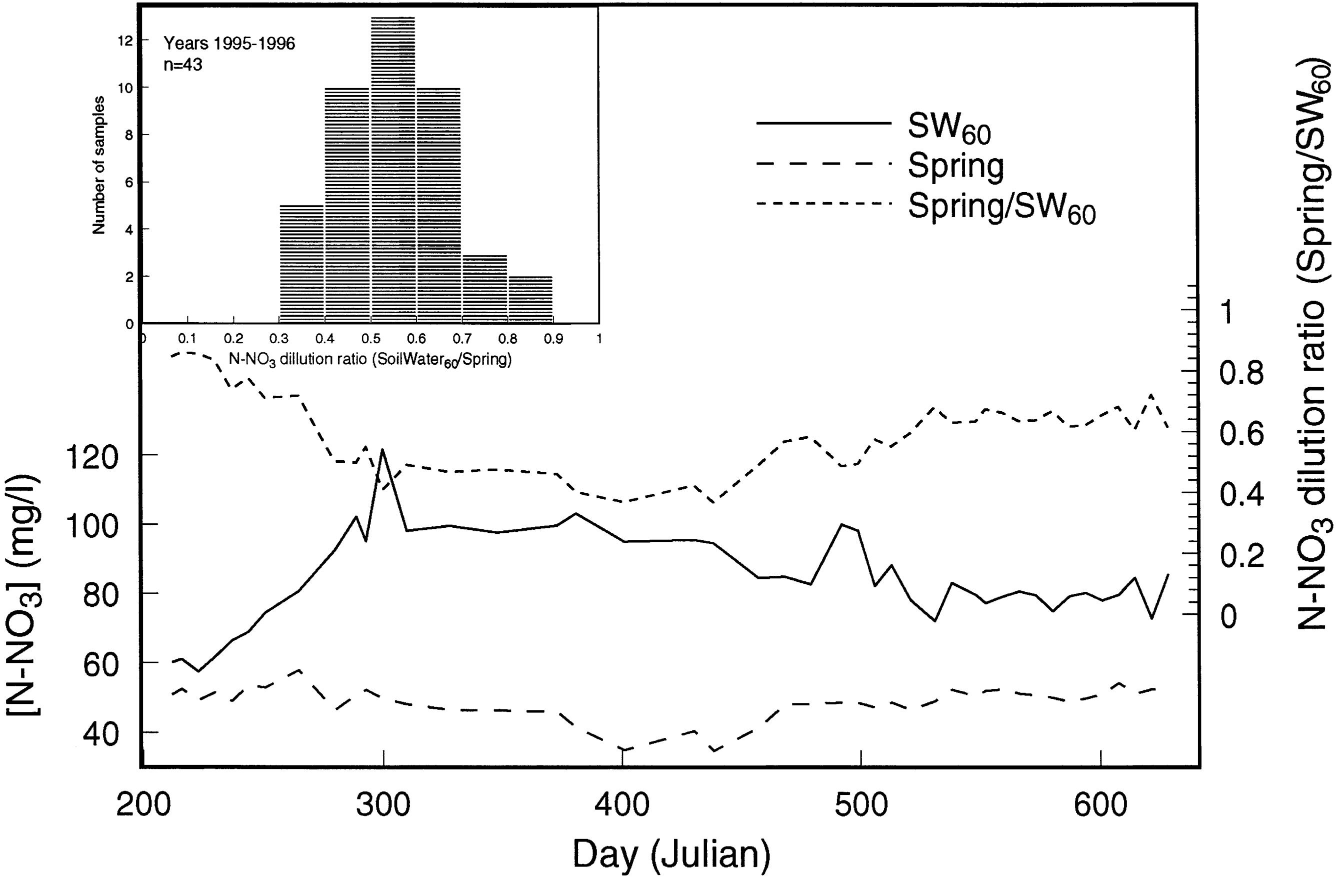

Fig. 13. Dilution effect after leaching from the soil down to the lower springs in the sea side cliff.

The hydrogeological study (Section 2.2) helps to understand N–NO_3 concentration data collected at the springs (Fig. 13) and how the aquifer might be actually receiving the pollutants from the agricultural soil. Comparison of the nitrate concentrations found at the bottom of the soil profile (60 cm) with those found in the spring shows a dilution effect (from yearly mean concentration of 85 mg/l N–NO_3 to 49 mg/l) as the water moves through rock fractures in the non-soil section of the unsaturated zone. A nitrate dilution ratio of 0.60 can be calculated as concentration of the spring water samples over the concentration of the soil drainage (taken as the soil water concentration at the lower soil interface, 60 cm) (Fig. 13). This is not in agreement with the 0.25 ratio established in the isotopic study using water samples (irrigation, spring and well water) from one sampling date. This partial isotopic result, though interesting, does not take into account: (i) temporal variability; (ii) the regional scale effect implicit in the spring water sample collected, and (iii) the time of travel from the bottom of the soil profile down to the spring through the unsaturated fractured volcanic material. There is no immediate extrapolation of this result to the simple nitrate dilution ratio calculated above. The concentration at the spring is an aggregation of the leaching contributions from the different farms and crops in the surrounding area, affected by the delay caused by the travel time of the contaminant in its way to the outlet, and partial mixing with groundwater interflow. To illustrate this point a screening for agrochemicals was performed on the spring water samples collected (Muñoz-Carpena et al., 1996a). The study revealed a herbicide used in other horticultural crops in the area (metribuzine) which had never been applied in the 42 ha banana plantation.

4. Conclusions

Bananas in the Canary Islands must be grown with the aid of irrigation to cover monthly water deficits in excess of 130 mm. Among the diverse crops produced in the Canaries, banana is the major consumer of water. Since water is a very scarce resource, not only in terms of quantity but also in quality, pollution from agricultural lands threatens the sustainability not only of that crop but of others in the islands.

The study conducted herein shows that over 48–52% of the total nitrogen applied (202–218 kg/ha N) is not used by the plant but rather lost into the aquifer from a banana crop with sprinkler fertigation system. Such losses are concentrated in periods when fertigation or rainfall is intensive. Since due to salt-leaching requirements total water drainage should not be significantly reduced, fertilizer practices (amount, timing and application technique) must be revised in order to control aquifer pollution.

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