7. Water balance and nitrate leaching in an irrigated maize crop in SW Spain

F. MORENO, J.A. CAYUELA, J.E. FERNÁNDEZ, E. FERNÁNDEZ-BOY, J.M. MURILLO AND F. CABRERA
Instituto de Recursos Naturales y Agrobiologia de Sevilla, P.O. Box 1052, 41080 Sevilla, Spain

Abstract

During three consecutive years (1991-93), a field experiment was conducted in an intensively irrigated agricultural soil in SW Spain. The main objective of this study was to determine the water flow and nitrate leaching below the root zone, under an irrigated maize crop and after the growing season (bare soil and rainy period). The experiment was carried out on a furrow irrigated maize crop using one of the highest nitrogen fertilization rates traditionally used by farmers in the region [about 500 kg $N \cdot (ha \cdot yr)^{-1}$] and another that represents one third of the former [170 kg $N \cdot (ha \cdot yr)^{-1}$] to provide data that can be used to propose modifications of nitrogen fertilization to maintain crop yield and to prevent the degradation of the environment. The terms of water balance (crop evapotranspiration, drainage and soil water storage), and the nitrate leaching were determined by intensive field monitoring of the soil water content, soil water potential and extracting the soil solution through use of a neutron probe, tensiometers and ceramic suction cups. Nitrogen uptake by the plant and NO_3-N produced by mineralization were also determined. The results showed that, in terms of water balance, crop evapotranspiration was similar with both N-fertilization rates used. During the irrigation period drainage below the root zone was limited. Only in 1992 the occurrence of rainfalls during the early growing period, when the soil was wet from previous irrigation, caused a considerable drainage. Nitrate leaching during the entire experimental period amounted to 150 and 43 $kg \cdot ha^{-1}$ in the treatments with high and low N-fertilization, respectively. This leaching occurred mainly during the bare soil and rainy periods, except in 1992 when considerable nitrate leaching was observed during the crop season owing to high drainage. Nitrate leaching was not so high during the bare soil period as could be expected because of the drought during the experimental period. A reduction of N-fertilization strongly decreased nitrate leaching without decreasing yield.

7.1   Introduction

Increases in the nitrate concentration in both groundwater and surface water are related to agricultural practices. The use of nitrogen fertilizers at rates higher than the rate of uptake by the plant increases the potential for increased nitrate leaching, as has been shown for nitrogen-fertilized corn (Roth & Fox, 1990). Addiscott et al. (1991) showed that

95

the increase of nitrate concentrations in both groundwater and surface water in England, during the last 30 years, is related to the increased use of nitrogen fertilizer.

In Mediterranean areas, farmers often use amounts of N-fertilizers that exceed the N requirements of crops (Cayuela et al., 1994; Danalatos, 1992) and thereby increase the amounts of potentially leachable nitrate in the soil. Under irrigated agriculture, drainage below the root zone is required to maintain salt balance. The water flow below the root zone can produce nitrate losses. Water flow and nitrate leaching depend on the soil characteristics, amount of water applied by irrigation or natural precipitation, and the amount, timing and species of nitrogen applied. Shepherd (1992) posed the question, "Are the effects of irrigation on nitrate leaching loss good or bad?", and goes on to point out "both opinions have recently been expressed". Some papers (e.g. Cayuela et al., 1994; Ramos & Varela, 1990) have shown the relationship between the use of high N-fertilization and nitrate leaching in Spain. This leaching generally occurred during the rainy period when the soil was bare.

The objective of this study was to determine the water flow and nitrate leaching below the root zone under an irrigated maize crop and after the growing season (bare soil and rainy period) in SW Spain during three consecutive years. Results presented in this paper correspond to the irrigation and fertilization practices normally used in this region, and the use of a reduced nitrogen fertilization rate. The study was conducted following a multidisciplinary approach to obtain data necessary for a better understanding of the problem, and to propose modifications of the rate of N-fertilization while maintaining crop yields and preventing the degradation of the environment.

7.2   Materials and methods

7.2.1   Experimental site

The experiments were conducted at the experimental farm of the Instituto de Recursos Naturales y Agrobiologia de Sevilla (IRNAS, CSIC) located at Coria del Rio close to Seville city in SW Spain (37°17'N, 6°3'W). The climate is typically Mediterranean with mild rainy winters and very hot, dry summers. The average annual rainfall (1971-1992) is 550 mm and falls between October and May.

An experimental plot (0.1 ha) was used (Fig. 7.1). The soil is a sandy loam (Xerocrept), developed on lime sandstone of the Aljarafe Miocene, with a depth of more than 3 m. The spatial variability of some soil

properties was studied after taking samples at 45 grid nodes of a 5 x 5 m cell mesh, at two depths, 0-0.5 m and 0.5-1 m. Mean textural values are, at 0 -0.5 m and 0.5-1 m, respectively: coarse sand 60.7±4.9% and 57.3±4.6%; fine sand 16.8±2.8% and 17.8±3.0%; silt 9.0±1.8% and 8.3±2.1%; clay 13.1±2.2% and 16.4±1.9%. Organic matter contents are 0.88±0.15% and 0.55±0.09% at depths of 0-0.5 m and 0.5-1 m, respectively.
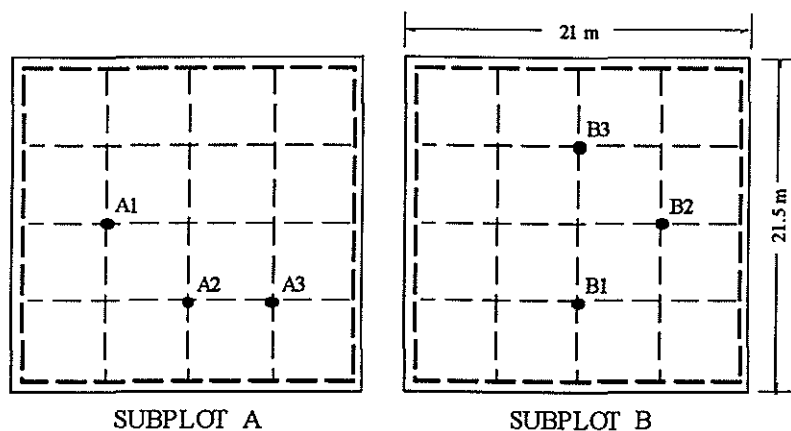

Figure 7.1 Experimental layout at the field site

7.2.2   Crop management and treatments

The experimental plot was divided into two subplots, A and B (Fig. 7.1), each of 450 m^2, with the aim of establishing two nitrogen fertilization treatments. Both subplots were cropped with maize (cv. Prisma) during three consecutive years from 1991 to 1993. Planting was carried out on the 5th of April 1991, 24th of March 1992, and 24th of March 1993. The rows were 0.8 m apart with a plant density of 75,000 plants ha^{-1}. Subplot A had 510 kg N·(ha·yr)$^{-1}$, a rate widely used in the area. Subplot B at 170 kg N·(ha·yr)$^{-1}$ received one-third of the normal rate. Fertilization was applied at three times: one deep fertilization of 1000 kg·ha^{-1} (15-15-15 complex fertilizer) some 10 d before planting, and two top dressings at about 45 and 75 d after planting. Each top dressing consisted of urea at 400 kg·ha^{-1} (46% N) in subplot A and one third of this amount in subplot B. Standard management practices typical for the Guadalquivir river valley, the main area for irrigated maize in the region, were used. The crop was irrigated by furrow in both subplots, but some sprinkler irrigations were applied between planting and the establishment of the furrows. Dates and quantity of irrigation are given in Fig. 7.2.

Irrigation stopped at about the end of July, or the beginning of August, some 20 d before harvest. The crop was kept healthy and free of weeds. With the land surrounding the experimental plot cropped every year with furrow or sprinkler irrigated crops (maize or cotton) advection was minimized. Rainfall during the experimental period is given in Fig. 7.2. The soil of the plot was kept bare during the period between the harvest and the beginning of the next crop season.
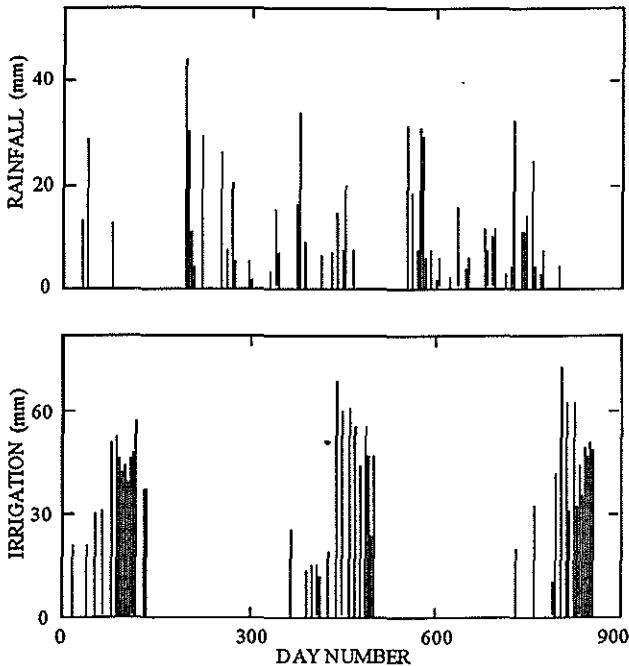

Figure 7.2 Rainfall and irrigation during experimental period. Day 0 is 20 March 1991

7.2.3 Measurements

Several measurement sites were installed in every subplot (three in subplot A and three in subplot B), each one equipped with the following equipment: (a) one access tube for the neutron probe to measure soil water content every 0.1 m to a depth of 2.3 m (b) five mercury tensiometers at depths of 0.3, 0.5, 0.7, 0.9 and 1.1 m (c) three ceramic suction cups at 0.3, 0.6 and 0.9 m to extract the soil solution (d) soil water content was monitored every 5-7 d during the crop period; during the bare soil period these measurements were carried out every 2 weeks, and always after a rainfall; tensiometer readings were recorded daily during the crop season, and 1-2 times per week during the bare soil period (e) rainfall and micrometeorological data were obtained from a

meteorological station 200 m away from the plot situated in the experimental farm (f) some crop development parameters (crop height, leaf area index and root density), nitrogen uptake by the crop and yield were determined and (g) the soil solution was extracted with suction cups at least once per week when the soil water content allowed this extraction. The soil solution was analyzed for nitrate content by ionic chromatography using a solution of 0.0013 M borate and 0.0013 M gluconate in acetonitrile (12% v/v) at pH 8.5.

In 1992 one 2 x 2 m plot (C) was also established on bare soil without fertilization. This plot was irrigated with the same amount of water and on the same dates as subplots A and B. The objective was to measure the water flow and the NO_3-N concentration in the soil solution in order to calculate the NO_3-N produced by the mineralization of the soil organic matter.

7.2.4   Determination of water balance and nitrate leaching

The water balance was calculated from the mass conservation equation

$$\Delta S = R + I - D - AET \tag{7.1}$$

where ΔS is the change in water storage (mm) in the soil profile exploited by the roots, R the rainfall (mm), I the depth of irrigation applied (mm), D the drainage (mm) at a depth (z_r) below the root zone, AET the actual evapotranspiration (mm). Water runoff was neglected because it was practically nil on this field site.

The drainage component D was estimated using Darcy's law:

$$D = q\Delta t = -[K(\theta) \text{ grad } H] \Delta t \tag{7.2}$$

where q is the mean volumetric flux density (mm·d^{-1}) during Δt, Δt the measuring interval (d), $K(\theta)$ the hydraulic conductivity (mm·d^{-1}) corresponding to the water content θ at a depth z_r and grad H the total hydraulic head gradient at the same depth. For the application of this method $K(\theta)$ must be known. The $K(\theta)$ relationship was determined by the internal drainage method (Hillel et al., 1972) at a selected site of the plot, and by the application of the "zero flux plane" method (Vachaud et al., 1978) at every measurement site. A typical result is given in Fig. 7.3.

The amount of NO_3-N leached LN below the root zone at a depth of 0.9 m was obtained from the relation

$$L_N = DC_{0.9} \tag{7.3}$$

where D is the water drainage calculated at a depth of 0.9 m from (7.2) and $C_{0.9}$ the NO_3-N concentration in the soil solution at the same depth. The depth of 0.9 m was established for the calculation of drainage and nitrate leaching because results of the root length density obtained in this study showed that the root system was situated above this depth.
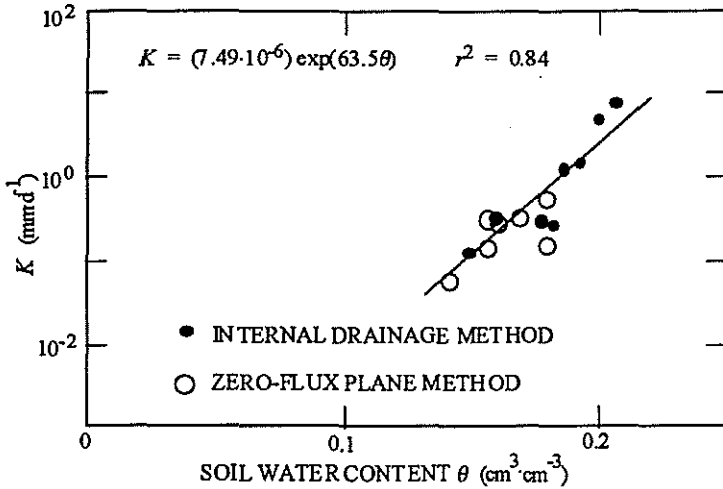

Figure 7.3 Relation between the hydraulic conductivity K and the soil water content θ obtained *in situ*

The amount of NO_3-N in a soil layer at a given time was calculated by multiplying the NO_3-N concentration of the soil solution by the water stored in this layer. For this purpose we assumed that the soil solution extracted at a depth of 0.3 m was representative of the 0-0.4 m soil layer, that at 0.6 m of the 0.4-0.7 m soil layer, and that at 0.9 m of the 0.7-1 m soil layer. Summing the three values obtained in this way gave the total amount of NO_3-N in the soil profile at a given date. At harvest time it was not possible to extract the soil solution and soil samples at 0-0.3, 0.3-0.6 and 0.6-0.9 m were thus taken to determine the NO_3-N content in the soil.

The years of the experimental period (1991-93) were characterized by total rainfalls which were lower than the annual average of the period 1971-1992 (Table 7.1). It is noticeable that during the autumns of 1991, 1992 and 1993, respectively, rainfall was 20, 35 and 41% less than the average (Table 7.1). Distribution of rainfall was also different from that normally observed in the region.

Table 7.1 Comparison of rainfall during the experimental period with the 20-y average in the region

Period (Sep-Sep)	Rainfall (mm)	Average rainfall Sep 1971-Sep 1992 (mm)	Period Sep-Dec	Rainfall (mm)	Average rainfall Sep-Dec, 1971-92 (mm)
1990-91	458		1991	201	
1991-92	446	550	1992	160	247
1992-93	353		1993	147	

7.3   Results and discussion

7.3.1   Water balance

Fig. 7.4 shows the cumulative values of the actual evapotranspiration *AET* and drainage during the cropping seasons of 1992 and 1993 for both subplots. Results of water balance for the crop season of 1991 are not presented in this way because measurements in the experimental plots started at the beginning of June when the crop was about 0.6 to 0.7 m high.

The total water input (rainfall and irrigation) in both subplots during the cropping seasons (March-August) of 1992 and 1993 were 731 and 666 mm, respectively. The *AET* in subplot A during the cropping season of 1992, amounted to 640 mm and the drainage was 142 mm. In contrast, in subplot B the *AET* was 578 mm, and the drainage below the root zone was 241 mm. During the crop season of 1993 the *AET* amounted to 646 and 637 mm in subplots A and B, respectively. Water losses by drainage during this crop season were 57 and 85 mm in subplots A and B, respectively.

The fact that greater drainage was observed during the cropping season in 1992 than in 1993 may be due to the rainfall distribution. In 1992 about 90 mm of rain fell during the early growth period, concentrated mainly in a few days, when the soil was wet from previous irrigations, and while water consumption by the crop was still low. After this rainfall the water uptake by the crop in subplot A was higher than in subplot B. This can be explained because the leaf area index *LAI* at this time was higher in subplot A than in subplot B. The higher crop evapotranspiration in subplot A than in subplot B is in part responsible for a lower drainage in subplot A. In the 1993 cropping season no heavy rain occurred early in the growth period, so the crop evapotranspiration was similar in both subplots.
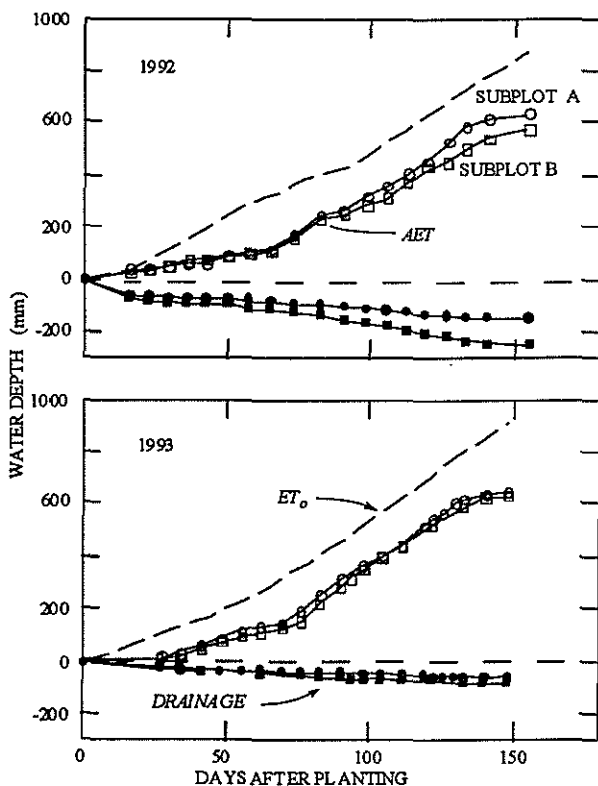
Figure 7.4 Cumulative drainage and evapotranspiration during the crop seasons of 1992 and 1993 in subplots A and B

7.3.2   Nitrate-N in the soil profile

The maximum amount of NO_3-N stored in the soil profile (0-1 m) in plot C (bare soil not fertilized) during 1992 reached about 84 kg NO_3-N·ha^{-1}. This maximum was observed in April and also in the autumn after the first rainfalls. Results obtained in the laboratory from experiments of mineralization on soil samples, taken at a depth of 0-0.3 m showed that the amount of NO_3-N produced in 8 weeks for this soil layer was 53 kg·ha^{-1}. This clearly shows that NO_3-N production from the mineralization of the soil organic matter is very important even though the organic matter content of the soil is low.

In subplots A and B, the NO_3-N contents in the profile (0-0.9 m) at harvest time in 1991-93 are shown in Table 7.2. Most of this NO_3-N was found in the soil layers 0-0.3 m and 0.3-0.6 m. These amounts were very high in subplot A, but different from one year to other. In 1992 the NO_3-

N content in the profile was 265 kg·ha^{-1} (Table 7.2), lower than in 1991 and 1993 years in which drainage during the crop season was low. These results show that the nitrate potentially leachable during the rainy period is high when a N-fertilization rate such as that in subplot A is used. The NO_3-N contents in the profile for subplot B were much lower than in subplot A in accordance with the lower N-fertilization. The highest NO_3-N contents in the profile in 1993 for both subplots must be related to the lowest drainage observed during the cropping season and to a lower crop performance than in 1991 and 1992.

Table 7.2 NO_3-N content in the soil profile (0 - 0.9m) at harvest

Year	NO_3-N (kg·ha^{-1})	
	Subplot A	Subplot B
1991	293.4±109.4	61.2±36.9
1992	265.5±101.3	49.2±11.1
1993	375.2± 89.7	125.4±25.1

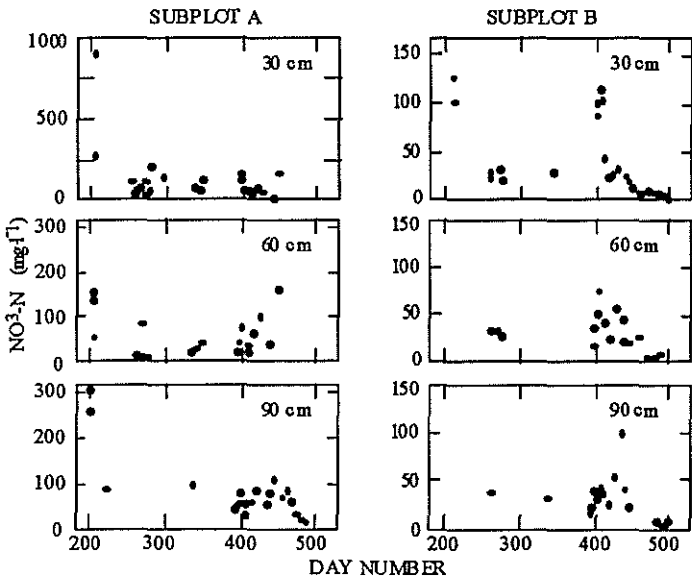*Figure 7.5* NO_3-N concentration in the soil solution at different depths in subplots A and B. Day 0 is 20 March, 1991

7.3.3   Nitrate leaching

An example of changes in the NO_3-N concentration in the soil solution, extracted at three depths in both subplots is shown in Fig. 7.5. These

results correspond to the period between the 10th of October 1991 (day number 209 from the beginning of the experiment) and the 25th of August 1992 (day number 524). Clearly, the NO_3-N concentrations at all depths were higher in subplot A than in subplot B.

With the data obtained by systematic monitoring of the concentration of NO_3-N in the soil solution at a depth of 0.9 m, and the use of Darcy's law, the amount of NO_3-N leached below the root zone was estimated. Fig. 7.6 shows the cumulative water drainage and the cumulative NO_3-N losses for the entire experimental period. The total drainage observed in subplot B was higher than in subplot A. As mentioned in the section on water balance this greater drainage is related to a lower water uptake by the crop in subplot B than in subplot A, particularly during the cropping season of 1992. Total drainage values represent 13.4 and 21.4% of the water applied by irrigation and rainfall in subplots A and B, respectively.

NO_3-N leaching generally occurred during fall and winter (rainy period) when the soil was bare. These nitrate losses were probably smaller than expected owing to a lower rainfall than the average for this period (Table 7.3). In contrast, considerable nitrate leaching was observed during the early growth period in the second cropping season (1992), owing to rainfall (90 mm) when the soil was wet from the previous irrigation and the water consumption by the crop was still low.

Table 7.3 Mean values of drainage and NO_3-N leaching below 0.9-m soildepth

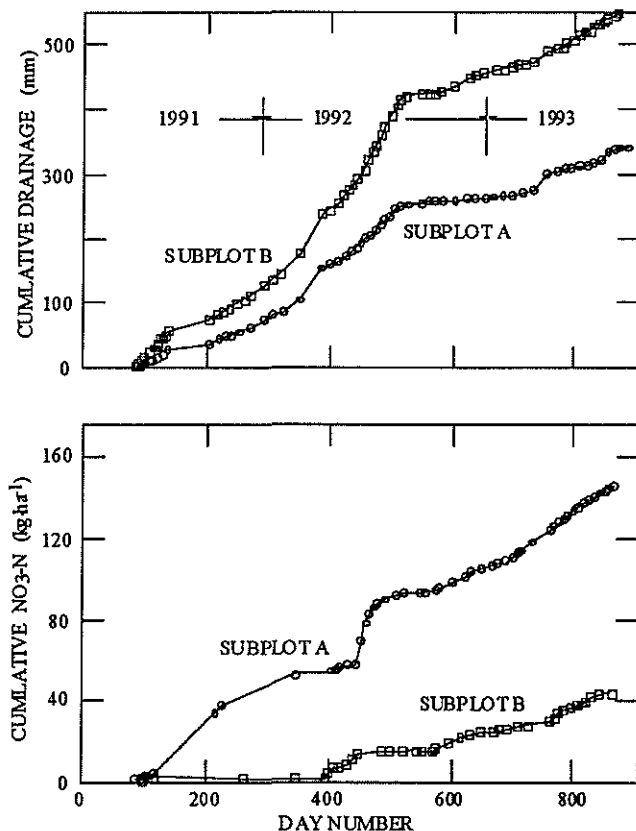| Period	Subplot A		Subplot B	
	Drainage (mm)	NO_3-N $(kg \cdot ha^{-1})$	Drainage (mm)	NO_3-N $(kg \cdot ha^{-1})$
6 Jun 1991 -25 Aug 1991 (cropping season)	25.0± 6.8	3.2± 1.0	47.8±13.5	0.3± 0.4
25 Aug 1991 -24 Mar 1992 (bare soil)	79.7±14.0	49.7±10.6	127.1±21.1	1.3± 1.5
24 Mar 1992 -25 Aug 1992 (cropping season)	149.2±19.2	40.4±13.8	243.0±24.6	12.7±16.4
25 Aug 1992 -24 Mar 1993 (bare soil)	36.6±11.7	25.3± 6.5	53.6± 9.6	12.9± 4.1
24 Mar 1993 -25 Aug 1993 (cropping season)	57.0±13.6	28.4± 8.7	85.0±13.2	16.4± 6.5

Figure 7.6 Cumlative drainage and NO_3-N leached below the depth of 0.9 m in subplots A and B during the experimental period. Day 0 is 20 March, 1991

Nitrate leaching was always higher in subplot A, where a high N-fertilization rate was applied, than in subplot B, even though the drainage was higher in subplot B. Total NO_3-N leached was 147.5 and 44.0 $kg \cdot ha^{-1}$ in subplots A and B, respectively. These amounts are not as high as could be expected under our conditions possibly because of the drought during the experimental period. This is particularly true in subplot A if we take into account the high NO_3-N contents in the soil profile at harvest time. Nitrate leaching was strongly reduced by decreasing the N-fertilization rate by one-third.

7.3.4   Crop response

Table 7.4 shows some parameters of the crop development and yield in both subplots. Plant heights measured when the crop was fully developed were not significantly different between subplots. In contrast, the leaf

area index *LAI*, also measured when the crop was fully developed, was higher in subplot A than in subplot B, although mean values were not significantly different. Bennett et al. (1989) showed that in an optimally irrigated maize crop with a plant density similar to that used in our study the *LAI* in the low N treatment was lower than in the treatment with high N-fertilization. The only significant difference for crop yields was the 1000-kernel weight in 1991 (Table 7.4).

Table 7.4 Mean values of plant height, leaf area index *LAI*, 1000 kernel weight and yield

Year	Treatment	Plant height[1] (m)	*LAI* [1]	1000 kernel weight (g)	Exported N (kg·ha^{-1})	Yield (Mg.ha^{-1})
1991	Subplot A	2.91a[2]		314b	261	13.0a
	Subplot B	2.94a		334a	241	13.2a
1992	Subplot A	2.24a	4.11a	329a	270	12.5a
	Subplot B	2.30a	3.47a	320a	220	12.5a
1993	Subplot A	1.80a	3.38a	322a	221	9.7a
	Subplot B	1.83a	2.78a	328a	216	9.6a

[1]Plant height and *LAI* were measured when the crop was fully developed.
[2]Values followed by the same letter in the same column per year do not differ significantly at the level $P < 0.05$.

Nitrogen exported by the crop (determined in the above ground part of the plant at harvest) was higher in subplot A than in subplot B in 1991 and 1992, but was nearly the same in 1993. Nitrogen exported by the crop in subplot B (between 216 and 241 kg·ha^{-1}) was higher than that applied by fertilization [170 kg N·(ha·yr)$^{-1}$] indicating that the crop used NO_3-N from mineralization of soil organic matter and irrigation water.

In both subplots the yield decreased from 1991 to 1993, probably owing to the continuous cropping with maize and/or the unusual climatological conditions prior to flowering in 1992 and 1993. With the reduction of the N-fertilization rate we have not observed differences in the crop yield. In our conditions, the N-fertilization rate of about 500 kg N·(ha·yr)$^{-1}$ is too high, but in contrast 170 kg N·(ha·yr)$^{-1}$is probably too low for a continuous maize crop in order to maintain an adequate fertility level in the soil.

7.4   Conclusion

From results obtained in our experiment it seems that the use of the method based on measurements of soil water content by neutron probe

and soil water potential by tensiometers to determine the water balance is appropriate if we use the hydraulic conductivity versus water content relationships determined *in situ*. From the drainage calculated at a depth below the root zone and the NO_3-N concentration in the soil solution it was possible to calculate the NO_3-N leaching below the root zone.

The use of a high N-fertilization rate (500 kg·ha^{-1}), traditionally used by farmers in our region, for an irrigated maize crop is excessive and causes a high NO_3-N content in the profile at harvest time that is potentially leachable during the rainy period in autumn and winter when the soil is bare. During the experimental years rainfalls below the average and with an altered distribution did not produce leaching as could be expected. In contrast, during the cropping season the occurrence of heavy rainfalls when the soil profile was wet from previous irrigations caused a considerable NO_3-N leaching. With a N-fertilization rate that represents one-third of that normally used by farmers and with the same irrigation the NO_3-N content in the soil profile at harvest was much lower and consequently leaching was significantly reduced. The reduction of N-fertilization did not affect the yield. A lower leaf area was observed in the crop with the low N-fertilization than in the crop with the high N-fertilization. Even though our soil has a low organic matter content the NO_3-N produced by mineralization together with the NO_3-N of the irrigation water was enough to recover partial nitrogen needs of the crop with low fertilization, at least for three years. In our conditions 175 kg N·ha^{-1} of fertilization for a continuous maize crop is probably too low in order to maintain an adequate fertility level of the soil.

ACKNOWLEDGEMENT

REFERENCES

Addiscott TM, Whitmore AP & Powlson DS (1991) Farming, fertilizers and the nitrate problem. CBA International, Wallingford, UK (pp. 170)

Bennett JM, Mutti LSM, Rao PSC & Jones JW (1989) Interactive effects of nitrogen and water stresses on biomass accumulation, nitrogen uptake, and seed yield of maize. Field Crop Res. 19: 297-311

Cayuela JA, Fernandez JE, Moreno F, Murillo JM & Cabrera F (1994) Estimación de las pérdidas de nitrato en un suelo con cultivo de maiz y riego. Riegos y Drenajes XM, 75: 30-34

Danalatos NG (1992) Quantified analysis of selected land use systems in the Larissa region, Greece. Doctoral thesis, Agric. University, Wageningen, The Netherlands (pp. 370)

Hillel D, Krentos VD & Stilianou Y (1972) Procedure and test of an internal drainage method for measuring soil hydraulic characteristics in-situ. Soil Sci. 114: 395-400

Ramos C & Varela M (1990) Nitrate leaching in two irrigated fields in the region of Valencia, Spain (pp. 335-345). In: Calvet R (Ed), Nitrate-Agriculture-Eau. Proc. International Symposium, Paris

Roth LV & Fox RH (1990) Soil nitrate accumulations following nitrogen-fertilized corn in Pennsylvania. J. Environ. Qual. 19: 243-248

Shepherd MA (1992) Effect of irrigation on nitrate leaching from sandy soils. Water and Irrigation Review 12: 19-22

Vachaud G, Dancette C, Sonko M & Thony JL (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. Agronomiques 29: 1-36