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IMPROVING EFFICIENCIES OF IRRIGATION AND NITROGEN UPTAKE IN WHEAT

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Abstract

Three years of field studies and lysimeter experiments on irrigated wheat had the objective of finding ways of managing irrigation and N fertilization to minimize losses and reduce contamination of groundwater. Applied N had significant positive effects on crop-water consumptive use. The highest N losses occurred during early growth. Irrigation had little effect on N loss when it was practiced efficiently. Under the prevailing conditions, it is recommended that no N be applied to wheat at planting, in order to limit N losses by leaching caused by the high precipitation that usually occurs during early development when crop-N requirements are small. No more than 120 kg N ha^{-1} should be applied in total to minimize groundwater pollution and maximize N-uptake efficiency and economic returns. Also, for economic and environmental reasons, irrigation should be limited to 80% of the total requirement and to depths of 40 to 60 mm.

1. INTRODUCTION

One of the major problems facing the project area in the Doukkala region of Morocco is increasing N in groundwater as a result of excessive fertilization and poor management of irrigation. Values exceeding the limit of 50 mg N L^{-1} have been found in several wells that are sources of drinking water. The objective of the present study was to develop ways of managing irrigation and fertilization so as to minimize N losses and simultaneously decrease pollution of the environment. The optimal application of N without yield penalty, its timing with respect to irrigation and cropgrowth stage are key elements that must be better understood through research, and implemented as soon as possible through extension.

The scope of the project was to conduct field experiments and use lysimeters, with ^{15}N, to monitor patterns of N uptake and loss, and determine water balances under irrigated wheat.

2. MATERIALS AND METHODS

The study at a Moroccan Government Experiment Station (32°64'N 8°26'E, altitude 146 m), within an irrigated area of 60,000 ha where wheat and sugar beet are intensively cropped. The climate is semi-arid, with highly variable precipitation around a mean of 288 mm year^{1}, concentrated between October and March. Mean annual temperature for the past 28 years is 18.6°C, but the daily maximum can exceed 45°C during July; frosts occur, but are exceptional. The annual sunshine duration is over 3,000 h and mean relative humidity is 75 to 80%. Class-A pan evaporation is approximately 1,700 mm, with daily values varying between 2 and 8 mm, depending on the season. Winds are moderate, with speeds above 4 m s^{-1} only on a limited number of days each year.

2.1. Planting

The experimental field had been previously planted to sugar beet. It was deep plowed during summer then, prior to planting, was plowed again and fertilized with 90 kg phosphate ha^{-1} and 120 kg K ha^{-1}. Mechanical sowing of wheat, cv. Karim, took place on December 12, at the 200 kg seed ha^{-1}. This genotype is recommended for cultivation under irrigation because of its high yield potential.

2.2. Layout

The experiment consisted of a split-plot design with two factors: amount of N fertilizer (0, 120, or 180 kg N ha^{-1} as ammonium sulphate) and irrigation regime [T1: 100%, T2: 80%, or T3: 60% of maximum water requirement (ETM)] of wheat, which was determined based on daily reference

TABLE I. FORM, TIMING AND AMOUNT OF N APPLIED TO THE DIFFERENT TREATMENTS

Watering regime	N supply (kg N/ha)	Microplot	N supply stage	
			early tillering	Zadocks-30
T1	120	MP1	40^*	80
		MP2	40	80^*
	180	MP1	60^*	120
		MP2	60	120^*
T2	120	MP1	40^*	80
		MP2	40	80^*
	180	MP1	60^*	120
		MP2	60	120^*
T3	120	MP1	40^*	80
		MP2	40	80^*
	180	MP1	60^*	120
		MP2	60	120^*
T2	120	L1	40^*	80^*
	180	L2	60^*	120^*

*: treatment enriched with ^{15}N.

evapotranspiration estimated by the Penman-Monteith method multiplied by crop coefficients for wheat as determined locally.

As the soil was found to contain relatively high levels of N at planting, fertilizer applicaions were split, with one third applied at early tillering and the remainder added at Zadoks growth stage 30 (Z 30) [1], i.e. when crop requirement for N is highest.

Watering regime was applied on a main-plot basis, and N level to the sub-plots. Each of the nine plots had an area of 10 × 30 m. Within each 120 and 180 kg N ha^{-1} sub-plot, two micro-plots of 2 m^2 each were supplied with ammonium sulfate enriched in ^{15}N at 5% a.e.

In addition, two non-weighing drainage lysimeters, cropped with wheat, received 120 kg N ha^{-1} with 80% ETM (lysimeter L1) or 180 kg N ha^{-1} with 80% ETM (L2). The applied N was partitioned as described above, and was labelled with ^{15}N. The lysimeters, each 4 m^2 in area, were treated exactly as the field experiment. They served to determine the amount of percolating water and quantify amounts of leached fertilizer and soil N. Table I shows the amount of N supplied to each treatment as well as their timing and origin.

2.3. Monitoring

Water content of the soil was monitored with a neutron probe throughout the growing season. Access tubes were installed in plots of each treatment, and measurements were taken twice weekly early in the morning at soil depths 0 to 20, 20 to 40, 40 to 60 and 60 to 80 cm. Simultaneously, the neutron probe was calibrated in situ, in two plots located in the middle of the experimental site. In addition, mercury tensiometers were installed around the neutron probe access tube, at the same five depths, with two tensiometers per depth.

Reference evapotranspiration (ETo) and ETM values were estimated on a daily basis using the Penman-Monteith formula, and the data were collected locally with an automatic weather station installed within a conventional weather station adjacent to the trial site. The actual cropwater use was determined based on the in situ water balance method, taking into consideration all components except surface runoff. Drainage below the root zone was quantified using the unsaturated soil hydraulic conductivity that was also determined in situ and the soil-water content and potential that were monitored above and below the depth of 75 cm.

Soil physical and chemical characteristics were determined from composite samples for the following soil layers: 0 to 20, 20 to 40 and 40 to 60 cm. These samples were analyzed in the laboratory for initial soil-N content, determined by the distillation method following extraction with $0.005M$ $CaCl_2$ in a soil:solution of 1:10. Soil mineral-N values were determined also immediately before the first fertilizer application, at Z-30, at anthesis and at final harvest. In the micro-plots that received labelled N, soil samples were taken at 20-cm intervals through the root zone to determine total N and ^{15}N content. In addition, the soil solution was extracted using tensionics from the labelled plots of irrigation treatments T1 and T2 receiving 120 kg N ha^{-1}. The soil solution was extracted following irrigation, at depths of 20, 65 and 105 cm.

Drainage water from the lysimeters was collected and measured after each receipt of water, precipitation or irrigation, and preserved frozen pending total-N and ^{15}N-enrichment analyses.

Throughout the growing season, crop development was assessed regularly by monitoring various components, including leaf-area index using portable equipment. Chlorophyll content was followed using a SPAD meter, by taking twenty measurements in each treatment every 15 days. Plant materials were collected and analyzed for total N immediately before the first fertilizer application, at Z-30, at anthesis and at maturity. Total N was determined by the Kjeldahl method based on all aerial materials, except at maturity when grains were separated from the rest.

2.4. Final harvest

At maturity, the crop yields and components thereof were determined from plants collected from two 4-m^2 areas in each plot. Simultaneously, the two central wheat rows of each micro-plot were harvested and sub-samples taken for ^{15}N-enrichment and total-N determinations in the roots and shoots. In addition, grain and straw materials were treated separately. Total-N determinations were made on the soil, plant parts and water using the Kjeldahl method. Nitrogen-15 enrichment values were determined using dried samples that were sent to the Seibersdorf Laboratory of the International Atomic Energy Agency.

2.5. Previous trials

2.5.1. 1995–96

This experiment had the following salient features:

- Four N levels: 0, 60, 120, 180 kg N ha^{-1} with a complete randomized block design,
- Split applications of N, one third at 10 days after planting and two thirds at Z-30,
- Two lysimeters treated with 120 and 180 kg N ha^{-1}, respectively,
- A precipitation total of 485 mm, mostly between November and March with 49% in January.

2.5.2. 1996–97

This experiment had the following salient features (Table II):

- Three N levels: 0, 120; 180 kg N ha^{-1}, with a complete randomized block design,
- Split applications of N: F1 = one third the after emergence and the remainder at Z-30, F2 = one third at planting and the remainder at Z-30,
- Two lysimeters, with 120 kg N ha^{-1}, with F1 and F2, respectively,
- A precipitation total of 486 mm, 80% of which fell in December and January.

TABLE II. FORM, TIMING AND AMOUNT OF N APPLIED TO THE DIFFERENT TREATMENTS IN 1996–1997

Treatment	N supply (kg N/ha)	Microplot	N supply stage		
			Crop installation	After emergence	Zadocks-30
T1	120	MP1	0	40*	80
		MP2	0	40	80*
T2	180	MP1	0	60*	120
		MP2	0	60	120*
T3	120	MP1	40*	0	80
		MP2	40	0	80*
T4	180	MP1	60*	0	120*
		MP2	60	0	120*
T1	120	L1	0	40*	80*
T3	180	L2	40*	0	80*

*: Treatment enriched with ^{15}N.

3. RESULTS AND DISCUSSION

3.1. Soil characteristics

The soil had a sand content of approximately 50% to a depth of 1 m (Table III), and clay content increased slightly with depth. Bulk density also increased slightly with depth, whereas the organic matter content, which was relatively low, decreased with depth. The mean P content over the rooting depth, as extracted by the Olsen method, was also low by the standards of the California Fertilizer Association. The soil-exchangeable K content, however, was satisfactory by Moroccan standards. The initial N content in the surface 60 cm was around 105 kg ha^{-1}, residual from the previous crop of fertilized sugar beet. The water-holding capacity was approximately 100 mm per m of soil.

3.2. Soil moisture and hydraulic conductivity

Equations relating volumetric soil-water content (Hv in %) and the ratio between the neutron-probe count in the soil and the standard count (X), as determined by simple regression for each soil layer, were as follows:

0 to 20 cm	$Hv = 12.1 + 6.44X$	$r^2 = 0.85$
20 to 40 cm	$Hv = 5.33 + 10.5X$	$r^2 = 0.83$
40 to 60 cm	$Hv = 8.37 + 8.38X$	$r^2 = 0.72$
60 to 80 cm	$Hv = 12.9 + 8.74X$	$r^2 = 0.56$

The unsaturated hydraulic conductivity was determined in situ by the internal-drainage method. Variation of the stock of water in the soil was related to time with a relationship of the type: $S = a.t^b$. These equations allowed for the slopes dS/dt to be determined. Similarly, the variation of the total hydraulic gradient with depth was modelled for each time at which measurements were taken, which allowed for the slopes dH/dz to be determined for each depth. The unsaturated hydraulic conductivity, $K(\theta)$, was obtained for each water-content value as the ratio of these two slopes. The values of $K(\theta)$, as obtained by applying this technique to different depths, yielded a relationship of the type $K(\theta) = A.\theta^B$ with a correlation coefficient of 0.92 for all depths.

TABLE III. PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE SOIL

Layer (cm)	C.S. (%)	F.S. (%)	C.L. (%)	F.L. (%)	Clay (%)	H_{fc} (cm^3/cm^3)	H_{pwp} (cm^3/cm^3)	B.D. (g/cm^3)
0–20	22.3	28.1	6.5	8.5	34.5	32.31	19.57	1.43
20–40	21.7	27.6	6.3	8.3	38.2	29.90	19.21	1.51
40–60	22.2	26.5	6.0	8.4	38.0	28.30	18.37	1.59
60–80	21.6	26.3	6.1	8.6	38.1	29.70	19.67	1.56

Layer (cm)	pH	E.C. (mmhos/cm)	O.M. (%)	P_2O_5-P (mg/kg)	K_2O (mg/kg)	H_{FC} (%)	H_{PWP} (%)	BD (g/cm^3)
0–20	7.5	1.4	1.4	17.3	296.5	22.3	11.7	1.46
20–40	7.7	1.6	1.3	15.9	168.7	22.9	12.6	1.51
40–60	7.4	1.7	1.1	5.0	106.7	22.3	12.3	1.56
60–80						21.1	11.5	1.60

C.S.: coarse sand F.S.: fine sand F.L.: fine loam F.L.: fine loam B.D.: soil bulk density

3.3. Weather

Rainfall for the growing season was above normal for the region, with a total of 357 mm; the mean for the previous 20 years was 281 mm. The precipitation was irregular, and 92% fell from late September to early February, whereas during the period of greatest need for moisture, mid-February to late May, there were only 27 mm.

The mean air temperatures fluctuated between 24°C in September and 12°C in late January. The maximum was approximately 30°C and the minimum 6°C. Generally speaking, except for precipitation shortage causing a water deficit, the climatic conditions of the growing season were favorable for wheat.

During the growing season, the ETo values started at about 5.5 mm day^{-1} in September then decreased until reaching the lowest values of slightly above 1 mm day^{-1} in January before increasing up to 5 mm day^{-1} in May.

3.4. Water use

The water requirements of the wheat crop, as estimated using reference evapotranspiration and crop coefficients determined locally, amounted to 413 mm, in comparison with 323 mm during the previous season, due to higher temperatures. Water requirements were minimal early in the season at less than 1 mm day^{-1} and increased to a maximum of 4.3 mm day^{-1} in April.

As the year was relatively dry, especially during the period of high water requirement, irrigation was necessary to achieve reasonable yields. Treatment-T1 plots, to satisfy total water requirements, received four irrigations, whereas T2 and T3, to receive 80% and 60%, were irrigated thrice and twice, respectively.

The actual evapotranspiration (ETa) or crop-water-use values, as determined using the in situ water balance method, are given in Table IV. The control depth was 75 cm, slightly below the average rooting depth, 60 cm, of wheat in that region. The variables necessary for evaluating the actual water use by the crop, and especially soil-water content and potential, were monitored from January 14 and at harvest on May 21. During the months between planting and January 14, ETa was estimated using the method described in FAO Bulletin 33.

Applied N had a significant positive effect on crop-water consumptive use. The 180 kg N ha^{-1} treatment used the highest amount at 3,390 m^3 ha $^{-1}$ compared with 3,150 m^3 for T2 and 3,080 m^3 for T3. This result can be explained by the fact that the higher the N level the more intense was the photosynthetic activity, resulting in denser and deeper rooting. Similarly, the greater the amount of water applied through irrigation, the higher was the ETa. During the previous growing season, under water stress for all treatments, N level was found not to affect ETa, showing that N benefit was less evident under such conditions.

The daily means for actual evapotranspiration by the crop varied from less than 1 mm day^1 to a maximum of about 4.5 mm day^{-1}. The ETa values decreased during periods of no or limited precipitation and increased following each application of water, whether from irrigation or precipitation. The mean ETa over all treatments was 310 mm. Compared to the maximum water requirements of 413 mm, the crop-water use was relatively important, hence the deficit was generally low, between 18 and 37% of requirements. The mean water deficit over all treatments was just over 100 mm, i.e. around 25% of total requirement.

3.5. Yields

Yields responded positively to applied N and, to a lesser extent, to irrigation (Table IV). The highest grain yield, 5.52 Mg ha^{-1}, was obtained with 180 kg N ha^{-1} irrigated at 100% ETM, whereas the lowest, 2.32 Mg ha^{-1}, occurred with the unfertilized plants under 60% ETM. The overall mean grain yield was relatively low at 4.20 Mg ha^{-1}, because of weeds and limited crop-production technology. Statistical analysis showed no significance in the yield difference between the 100% and 80% ETM irrigation treatments. However, at 60% ETM, the yield was significantly lower because of water stress. The 80% ETM may have received more because surface irrigation was used with the application of an irrigation-efficiency coefficient to account for eventual losses associated with the system; part of the increment to account for losses may have profited the crop.

TABLE IV. YIELD AS RELATED TO WATER CONSUMPTIVE USE AND EFFICIENCY

Irrigation treatment	T1			T2			T3		
N supply (kg N/ha)	0	120	180	0	120	180	0	120	180
ETa (mm)	271	330	339	269.2	327.1	334	262	324	334
TDM (kg/ha)	9826	13780	15000	9698	13529	14700	8291	12480	13000
GY (kg/ha)	2801	5190	5520	2864	5092	5450	2322	4465	4530
TDM/ETa (kg/ha/mm)	36.26	41.74	44.4	36.02	41.36	43.9	31.64	38.52	38.8
GY/ETa (kg/ha/mm)	10.33	15.73	16.3	10.63	15.56	16.3	8.86	13.78	13.5

ETa: water consumptive use. TDM: total dry matter. GY: grain yield

Applied N had strong effects on yield. Without N fertilizer, yields were about 50% lower. The interaction effect was also significant, especially from an economic standpoint: the best treatment was 120 kg N ha^{-1} irrigated at 80% ETM.

Total dry-matter yields had the same pattern as grain yields, except for the difference between treatments with 120 and 180 kg N ha^{-1} on one hand and the unfertilized control plants on the other which were less than for grain. The mean total dry-matter yields varied between 11.3 and 12.9 Mg ha^{-1}, for the control and the maximum applied N, respectively. Most yield components were affected by the amount of applied N.

Although the maximum yield was obtained with 180 kg N ha^{-1}, there seemed to be a plateau at around the value for 120 kg N ha^{-1}, a result found for all three seasons. The relationships between yield (×100 kg ha^{-1}) and N applied (kg N ha^{-1}) were as follows:

(1) Irrigation treatment T1 (100% ETM)

– Grain $Y = -0.0008X^2 + 0.295X + 28.0$ $r^2 = 0.98$
– Straw $Y = -0.0004X^2 + 0.192X + 68.6$ $r^2 = 0.90$
– TDM $Y = -0.0012X^2 + 0.492X + 96.6$ $r^2 = 0.88$

(2) T2 (80% ETM)

– Grain $Y = -0.0007X^2 + 0.269X + 28.6$ $r^2 = 0.91$
– Straw $Y = -1\text{ E-}05X^2 + 0.135X + 68.3$ $r^2 = 0.85$
– TDM $Y = -0.0007X^2 + 0.404X + 97.0$ $r^2 = 0.87$

(3) T3 (60% ETM)

– Grain $Y = -0.0009X^2 + 0.294X + 23.0$ $r^2 = 0.89$
– Straw $Y = -0.0009X^2 + 0.276X + 59.9$ $r^2 = 0.86$
– TDM $Y = -0.0018X^2 + 0.570X + 82.9$ $r^2 = 0.91$

In comparison, the results from previous seasons gave the following similar relationships:

(1) 1996–97

– Grain $Y = -0.0006X^2 + 0.199X + 31.9$ $r^2 = 0.88$
– Straw $Y = -0.0001X^2 + 0.130X + 75.4$ $r^2 = 0.99$
– TDM $Y = -0.0007X^2 + 0.329X + 107$ $r^2 = 0.97$

(2) 1995–96

– Grain $Y = -0.0007X^2 + 0.239X + 29.7$ $r^2 = 0.99$
– Straw $Y = 2\text{E–}05X^2 + 0.124X + 67.8$ $r^2 = 0.99$
– TDM $Y = -0.0007X^2 + 0.363X + 97.4$ $r^2 = 0.99$

3.5. Chlorophyll readings

The variations in SPAD numbers between treatments confirmed the effects of applied N and, to a lesser extent, of irrigation. These numbers, which directly relate to chlorophyll content, hence to plant-N, were measured from the first N application at early tillering until 2 weeks before final harvest. Initially, there were no difference between treatments, and the SPAD numbers were low at around 30. After the first N application, differences became evident with the highest values corresponding to 180 N kg ha^{-1} followed by those of 120 kg N ha^{-1} and then by the unfertilized control. With time, the numbers increased for all treatments until they reached values of around 50 with 180 kg N ha^{-1} following the second N application. Difference between the treatments persisted throughout the monitoring period and became larger following the second application of N. Towards the end of the monitoring period, the numbers decreased and the differences among the three N treatments largely disappeared. Irrigation also affected SPAD numbers, with higher values registered in treatments T1 and T2 than in T3, throughout the monitoring period.

3.6. Water-use efficiency

Applied N had significant effects on water-use efficiency (WUE) (Table IV). The WUE values varied from 34.6 kg ha^{-1} mm^{-1}, when no N was applied, to 42.4 kg ha^{-1} mm^{-1} with 180 kg N ha^{-1}. This difference was due less to the amounts of water used than to the yield responses to N. However, irrigation affected WUE, with higher values (over 40 kg ha^{-1} mm^{-1}) obtained with treatments T1 and T2 than with T3 (36 kg ha^{-1} mm^{-1}) under water deficit. It is noteworthy that there were no difference in WUE based on grain yield or total dry matter between the 100% and 80% ETMs, due to the fact that the two treatments differed by only one irrigation. In addition, because surface irrigation was used, it was not possible to evenly apply the desired depth, hence the small differences obtained between irrigation treatments in terms of ET and most other variables.

In terms of grain yield and WUE for producing grain, the Table shows that the differences between the 120 and 180 kg N ha^{-1} treatments were modest. As a result, 120 kg N ha^{-1} may be recommended for economic and environmental reasons. This result confirms those from the two previous growing seasons. With regard to irrigation, as just discussed, treatment T2 performed in the same manner as T1, which leads to recommendation of the former for the future, for environmental and economic reasons.

3.7. Nitrogen budget

The labelling of the fertilizer with ^{15}N allowed determination of the fate of fertilizer N, sources of N in the plant: N derived from fertilizer (Ndff) and from soil (Ndfs)

3.7.1. Nitrogen from fertilizer

The N derived from the first application of fertilizer varied from 12% with 120 kg N ha^{-1} and irrigated at 60% ETM, to 51% with 180 kg N ha^{-1} at 60% ETM. The effect of the applied-N level on this variable was evident both for grain and straw, especially between 120 and 180 kg N ha^{-1}; the fraction of N derived from the first application was much higher with 180 than with 120 kg N ha^{-1}.

The N derived from the second application also varied, between 41%, with 120 kg N ha^{-1} at 60% ETM, and 67% for the same N level at 80% ETM. The difference can be explained by a greater uptake of N from the second application during rapid plant development; some 85% of total N was assimilated before anthesis.

Irrigation regime also affect Ndff, with a distinct difference between T1 and T2 on the one hand and T3 on the other. The latter registered the lowest values for Ndff, which may be attributed to water stress.

These results are similar to those from the previous growing seasons. During 1995–96, the N derived from the first application was influenced by the amount applied, with a slight increase between 120 and 180 kg N ha^{-1}. During the following season, the fertilizer-N uptake was influenced more by the time of application than by the amount applied. With one third applied after *emergence* and two thirds at Z-30, the Ndff values for the first application corresponding to 120 and 180 kg N ha^{-1} were 14% and 22%, respectively, whereas Ndff values of only 5.1% and 7.7% were obtained when one third was applied at *planting* and the rest at Z-30. With the second application, Ndff increased significantly with the fertilizer level applied.

In conclusion, it can be said that fertilizer constituted a major source of N for the crop. Uptake of N increased with the amount applied and was generally lower for the first application. The same results were obtained during the previous seasons, in particular the low contribution of the N applied early in the season, which can be explained by small N requirements during early growth in conjunction with loss by leaching.

3.7.2. Nitrogen from soil

Soil analysis prior to planting revealed the existence of 113 kg N ha^{-1} in the surface 60 cm. This relatively high quantity was the result of application of large quantities of N to the previous sugarbeet crop. Similar results had been obtained during previous seasons.

Values for Ndfs varied between 12% with 180 kg N ha^{-1} irrigated at 100% ETM, and 39% with 120 kg N ha^{-1} at 60% ETM (Table V). These were lower than those found during the previous seasons, which varied between 38% and 68% in 1996–97 with 180 kg N ha^{-1} applied as F1, and 120 kg ha^{-1} applied as F2, respectively. The difference may be due to leaching loss of most of the N applied during the early stages of the previous year. Moreover, conditions for soil-N mineralization may have been more favourable in 1996–97.

TABLE V. ORIGIN OF PLANT NITROGEN

Irrigation treatment	Nitrogen kg/ha	Ndff (%)	Ndfs (%)
T1	120	71,2	28.8
	180	87,8	12.2
T2	120	82,2	17.8
	180	-	-
T3	120	81,4	38.6
	180	74,	25.4

In the 1997–98 season, Ndfs values decreased with the increase in applied fertilizer. With treatment T1 (100% ETM) the soil's contribution decreased from 29% to 12% when the N level increased from 120 kg ha^{-1} to 180 kg ha^{-1}, respectively.

The Ndfs values decreased also with the number of irrigations. The values corresponding to treatments T1 and T2 were lower than that for T3, which can be explained by water stress with T3.

3.7.3. Nitrogen-uptake efficiency

For the first application, actual N-uptake efficiency varied from a minimum of 13% for 180 kg N ha^{-1} irrigated at 60% ETM, to a maximum of 59% with 120 kg N ha^{-1} at 80% ETM. Between 120 and 180 kg N ha^{-1} the mean decrease was 8%.

For the second application of N, N uptake was higher, with 36% for 120 kg N ha^{-1} 60% ETM, and 61% with the same N level irrigated at 80% ETM.

These results follow trends observed in previous seasons. In 1995–96, uptake of 180 kg ha^{-1} was 46% for the first application and 49% for the second. During the following season, a higher value was obtained with the first application (after emergence) than with the second at Z-30; but when applications were made at planting and at Z-30 (F2), uptake was higher from the second application.

Based on these results and given the prevailing weather conditions, especially precipitation, current technologies used for growing wheat, and the yields attained, it is concluded that 120 kg N

TABLE VI. RESIDUAL NITROGEN (Nr) FROM THE DIFFERENT TREATMENTS. 1997–1998

Irrigation treatment	Nitrogen (kg/ha)	MP	Depth (cm)	Residual N (kg N/ha)	Nr/layer (kg N/ha)	Total Nr (Kg N/ha)	Total Nr (%)
T1	120	MP1	0–20	2400	6.23	19.41	48.52
			20–40	2516	7.84		
			40–60	1729	5.34		
		MP2	0–20	2524	7.13	19.54	24.42
			20–40	2326	5.27		
			40–60	1543	7.14		
Total						**38.95**	**32.46**
T1	180	MP1	0–20	2700	9.12	21.61	36.02
			20–40	2115	5.28		
			40–60	1972	7.21		
		MP2	0–20	2456	7.50	18.18	15.15
			20–40	2329	5.45		
			40–60	2103	5.23		
Total						**39.79**	**22.10**
T2	120	MP1	0–20	2825	8.50	20.27	50.67
			20–40	2604	6.30		
			40–60	1613	5.47		
		MP2	0–20	2900	6.48	19.44	24.30
			20–40	2342	7.83		
			40–60	1920	5.13		
Total						**39.71**	**22.06**
T2	180	MP1	0–20	2600	7.85	22.08	36.08
			20–40	2412	6.78		
			40–60	2035	7.45		
		MP2	0–20	2891	5.46	18.53	15.44
			20–40	2200	7.86		
			40–60	1837	5.21		
Total						**40.61**	**22.56**
T3	120	MP1	0–20	2628	7.81	19.60	49.00
			20–40	2341	6.31		
			40–60	2165	5.48		
		MP2	0–20	2368	7.35	19.55	24.44
			20–40	1945	6.97		
			40–60	1568	5.23		
Total						**39.15**	**32.62**
T3	180	MP!	0–20	2854	9.33	22.96	38.27
			20–40	2415	8.34		
			40–60	2157	5.29		
		MP2	0–20	2947	8.23	21.03	17.52
			20–40	2547	7.51		
			40–60	2324	5.29		
Total						**43.99**	**24.44**

TABLE VII. RESIDUAL NITROGEN (Nr) FROM THE N APPLICATIONS. (SEASON 1996–97)

Treatment	MP	Depth (cm)	Residual N (kg N/ha)	Nr/layer (kg N/ha)	Total Nr (Kg N/ha)	Total Nr (%)
T1	MP1	0–20	2900	8.120	15.30	38.27
		20–40	2416	4.832		
		40–60	1570	2.355		
	MP2	0–20	3480	8.468	17.19	21.49
		20–40	2265	5.879		
		40–60	1727	2.847		
Total T1					**32.50**	**27.08**
T2	MP1	0–20	2900	5.878	16.45	27.42
		20–40	2416	7.981		
		40–60	1884	2.593		
	MP2	0–20	2900	5.210	18.40	15.34
		20–40	2416	8.680		
		40–60	1570	4.513		
Total T2					**34.85**	**19.36**
T3	MP1	0–20	2900	6.380	11.65	29.15
		20–40	2416	3.866		
		40–60	1570	1.413		
	MP2	0–20	2900	12.760	23.87	29.84
		20–40	1812	7.973		
		40–60	1570	3.140		
Total T3					**35.53**	**29.61**
T4	MP1	0–20	2465	8.535	15.29	25.50
		20–40	2114	3.809		
		40–60	1361	2.955		
	MP2	0–20	2320	12.503	24.94	20.79
		20–40	2416	8.680		
		40–60	1570	3.760		
Total T4					**40.24**	**22.36**

ha^{-1}can be recommended for implementation in the region. Moreover, where the initial soil-N content is relatively high, application of N at planting is not recommended. These practices would limit N losses to leaching caused by the high precipitation that often occurs during early growth. When N is applied later in the season, between early tillering and Z-30, yield advantages result from:

- The improvement of the capacity of the crop to absorb N because of a well developed root system,
- The N application coinciding with active development of the crop during which N requirements and uptake are high.

3.7.4. Residual N

Tables VI and VII show the N residual from the various treatments at harvest, for the 1997–98 and 1996–97 trials, respectively. With the former, 39.3 and 41.5 kg N ha^{-1} were residual from applications of 120 and 180 kg N ha^{-1}, respectively. Thus, the effect of the applied level was insignificant; the same occurred in 1996–97.

In the 1997–98 experiment, the amounts of N left in the soil from the first application were higher than those from the second. For example, with 180 kg N ha^{-1} irrigated at 80% ETM, 21.6 kg N ha^{-1} were residual from first application and 18.2 kg N ha^{-1} from the second. This result can be explained in terms of the first application being less efficiently used by the crop than the second application, for the reasons discussed above.

These results differed from those obtained in the previous two seasons during which N-uptake efficiencies were lower with the first applications (Table VII). The difference could be due to high precipitation that followed the first applications during the previous seasons that may have leached most of the N applied. During the 1997–98 season, such high precipitation did not occur and irrigations were applied at depths of around 40 mm each time, hence a larger fraction of the N applied early in the growing season remained in the soil.

3.7.5. Nitrogen losses

The amounts of water drained by the lysimeters were monitored throughout the growing season. Drainage occurred essentially after water application by irrigation or precipitation. The total depth drained amounted to 115 mm (average of the two lysimeters). This figure was below those of the previous years (220 and 238 mm) The drainage occurred mainly during the early stages of crop growth and was largely the result of precipitation, showing that most of the irrigation water was used by the crop and not lost to greater depths.

The N content of the drainage water was monitored during the entire growing season. Immediately after the first fertilizer application, the N concentration increased until it reached 30 and 45 mg L^{-1} for lysimeters L1 and L2, fertilized with 120 and 180 kg N ha^{-1}, respectively. Then it decreased before increasing again following the second application of N. In addition, the concentration in the lysimeter that received 180 kg N ha^{-1} was consistently higher than that fertilized with 120 kg N ha^{-1}. Therefore, the N losses to leaching, and hence the pollution of groundwater, were proportional to the applied amounts.

The amounts of N lost to leaching during the entire season represented 51 and 68 kg N ha^{-1} with 120 and 180 kg N ha^{-1}, respectively, lower than in previous seasons (94 kg in 1995–96).

For all three seasons, the highest N losses occurred during early growth; it is recommended that any early N application be small, in order to minimize losses and limit groundwater pollution. The N-uptake values for the early application were as low as 20%, as during the 1996–97 experiment. As it is not possible to control the amount of precipitation, the only possibility left for reducing N losses is by applying less fertilizer during early crop growth. As for irrigation, its effect on N loss was slight when it was practiced efficiently, i.e. when only small depths were applied and in accordance with the crop requirements. Therefore, irrigation may cause leaching of N only when it is not practiced judiciously; otherwise it poses no hazard for groundwater.

The use of ^{15}N allowed the determination of amounts of N derived from fertilizer that were lost by leaching. These figures were low at 2.2% for L1 and 2.8% for L2, but generally higher in previous seasons, i.e. in 1996–97, 0.2% with 120 kg N ha^{-1} applied as F1 and 4% from the same treatment applied as F2, and, in 1995–96, 13% and 15% for 120 and 180 kg N ha^{-1}, respectively. During both seasons, leaching losses increased with increased application.

3.7.6. Nitrogen in soil solution

The soil solution was extracted with tensionics when moisture content was high enough to allow sufficient water to be extracted, i.e. after water applications. The tensionics were installed in treatments T1 and T2 within the micro-plots enriched with ^{15}N in order to follow the dynamics of the applied N.

High concentrations were noted following the first application of N. As N leaching occurred, it was noted that the concentration decreased near the surface and increased downward. This phenomenon was also a result of N uptake by the crop from the surface layers of soil. Nitrogen concentration then decreased progressively before it increased again following the second N application. It was noted also that greater concentrations were found with the irrigation treatment T1 (100% ETM) compared to T2 (80%).

These results are similar to those found during the 1996–97 season when the N treatment split as F2 resulted in higher losses in depth, estimated at about 22 kg N ha^{-1}. At the same time, the F1 partitioning of N resulted in only limited losses, estimated at about 3 kg N ha^{-1}.

Enrichment in ^{15}N generally followed the same pattern as N concentration, with higher values at the soil surface immediately after the first application. Then, as the growing cycle progressed, the enrichment values decreased near the surface and increased at greater depths. Similar results were found during the previous season, especially with the F2 N split for which high enrichment values were traced at depth.

Therefore, it can be concluded that N losses to leaching were closely related to the applied amounts of both water and fertilizer. They were also affected by the timing and splitting of N applications. Losses to leaching can be reduced by limiting or avoiding the application of N at planting. Moreover, given that surface irrigation was used, it is important to control the depth of application in order to limit N losses later in the cycle.

3.7.7. Gaseous losses

By combining the ^{15}N-enrichment data from the soil and the crop, it is possible to estimate applied N lost, as well as the nature of that loss. Knowing the amount of N leached, it is possible to determine, by difference, gaseous losses that are otherwise difficult to measure directly in the field.

The budget is obtained by comparing the amount of N applied with the amount residual in the soil, the N recovered by the crop and the amount lost to leaching. The part not accounted for in represents, in principle, gaseous N resulting from denitrification and ammonia volatilization.

As evaluated using this technique, gaseous losses represented 11% and 19% for treatments with 120 and 180 kg N ha^{-1}, respectively (Table VIII). These estimates were close to those from the previous seasons, which were as follows: 16% and 22% of 120 kg N ha^{-1} for F1 and F2 in 1996–97, respectively, and only 7% of the same amount (120) in 1995–96. The differences may be explained in terms of soil temperature and water content on denitrification.

TABLE VIII. FERTILIZER NITROGEN BALANCE (kg N/ha)

	1995–1996				1996–1997*				1997–1998*			
Treatment	Nr	Gas	Le	AUE	Nr	Gas	Le	AUE	Nr	Gas	Le	AUE
120-F1					32.5	19.9	0.2	67.4	33.6	14.2	2.6	69.6
180-F1					35.5	26.7	4.8	53.0	55.8	34.6	5.0	84.6
120-F2	26.4	8.0	14.7	70.9	34.9	36	0.6	108.5				
180-F2	47.0	16.7	29.5	86.8	40.2	63	0	76.8				

Nr: residual N Le: leached N AUE: actual use efficiency

* Treatment F1 is slightly different between the seasons 1996–1997 and 1997–1998. In 1996–1997 it corresponds to the N partitioning of 1/ 3 after emergence and 2/3 at Zadocks-30, whereas in 1997–1998 it corresponds to 1/3 at tillering and 2/3 at Zadocks-30.

4. CONCLUSIONS

Synthesis and recommendations are as follows:

- Losses of water and N are intimately related to precipitation and depth of water applied through irrigation,
- Nitrogen applied at planting is likely to be lost to leaching and be a major source of groundwater pollution,
- The application of more than 120 kg N ha^{-1} results in high risk of losses and of groundwater pollution, and in low N-uptake efficiency and hence in low economic returns.

REFERENCE

[1] ZADOKS, J.C., et al., A decimal code for the growth stages of cereals, Weed Res. **14** (1974) 415–421.