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Growth and nitrogen use efficiency of irrigated maize in a semiarid region as affected by nitrogen fertilization

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Abstract

The main groundwater pollution factor in irrigated maize production areas is leaching of nitrogen below the root zone. During the years 1999-2001, experiments were carried out on irrigated maize in the semiarid region of Castilla-La Mancha to evaluate the effect of nitrogen in the growth and yield of maize. Three rates of nitrogen were tested: No (0 kg N ha^{-1}), Nop (175, 150 and 130 kg N ha^{-1} in 1999, 2000 and 2001, respectively), and Nc (300 kg N ha^{-1}). A high initial level of residual soil NO_3^- was found in the spring of 1999 as a consequence of fertilization carryover from the previous years. Although there was no plant response to N fertilization in 1999, significant responses were obtained during the following two years. Moreover, in 2000, the grain production did not show significant differences between Nop and Nc. However, in 2001, maize yield was slightly decreased due to an attempt to decrease the Nop to 130 kg N ha^{-1}, showing significant differences with regard to Nc. The differences in grain yield among nitrogen levels were mainly due to a significant variation in maximum leaf area index, leaf area duration and crop growth rate. There was a decreasing pattern in nitrogen use efficiency values with increasing fertilizer rates, indicating that crop production could be sustained with lower fertilizer applications. Fertilizer practices must be revised in order to control and prevent insofar as possible water pollution in «La-Mancha Oriental» aquifer.

Additional key words: groundwater, optimum fertilization, pollution.

Resumen

Crecimiento y eficiencia de uso del nitrógeno en maíz de regadío en una región semiárida según la fertilización nitrogenada utilizada

El principal contaminante del agua subterránea en las áreas de regadío cultivadas de maíz es la lixiviación del nitrógeno. Durante los años 1999 a 2001 se han realizado ensayos en maíz regado en la región semiárida de Castilla-La Mancha, con el objetivo de evaluar su producción y crecimiento ante tres dosis de nitrógeno: No (0 kg N ha^{-1}), Nop (175, 150 y 130 kg N ha^{-1} en 1999, 2000 y 2001, respectivamente), y Nc (300 kg N ha^{-1}). El alto nivel inicial de NO_3^- residual en el suelo durante la primavera de 1999, consecuencia de la fertilización anterior, propició la falta de respuesta a la fertilización con N. Sin embargo, se obtuvieron respuestas significativas los dos años siguientes. Además, en el año 2000, la producción de grano no registró diferencias significativas entre Nop y Nc. Sin embargo, disminuyó ligeramente la producción en el año 2001 al tratar de reducir la dosis óptima a 130 kg N ha^{-1}, presentando diferencias significativas respecto a Nc. Este hecho fue debido, principalmente, a una variación significativa en el índice de área foliar máximo, la duración del área foliar y la tasa de crecimiento del cultivo. Las dosis más elevadas de fertilizante originaron una disminución de la eficiencia de uso del nitrógeno, por lo que la producción podría obtenerse con unos aportes menores de nitrógeno. Se debe revisar la fertilización para contribuir a controlar y prevenir, en la medida de lo posible, la contaminación en el acuífero de La Mancha Oriental.

Palabras clave adicionales: agua subterránea, contaminación difusa, optimización de la fertilización nitrogenada.

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Introduction

In semiarid regions, irrigation is one of the most important inputs to increase crop productivity. Sustainable water use is particularly relevant in areas where groundwater resources are used and crops with high water requirements, such as maize, are grown, because of the pumping energy costs (Ortega *et al.*, 2004). In addition, if irrigation water is not correctly managed it can cause nitrate pollution of groundwater, which is a common problem in some of the irrigated areas of Spain (de las Heras *et al.,* 2001).

In the semiarid Castilla-La Mancha region, irrigated from La Mancha Oriental aquifer, the availability of irrigation water is very limited. The over-exploitation risk and the decrease in piezometric levels in the aquifer are very relevant, which have promoted research into irrigation in this region (Martín de Santa Olalla *et al.,* 1999). In the Albacete province, located in the south of Castilla-La Mancha, maize (*Zea mays* L.) occupies more irrigated hectares than any other crop (López Fuster, 2000).

Although many experiments have studied in depth the effect of nitrogen fertilization in maize, the variability in soil properties, weather, and cropping practices make it difficult to extrapolate the results to other environments (Muchow and Sinclair, 1995). Additionally, if nitrate enters groundwater supplies these should not be used as drinking water by humans or animals because of several health risks (Kaluli *et al.,* 1999).

López Fuster (2000) found that in most of the traditional agricultural areas of La Mancha Oriental aquifer, NO_3-N concentrations range from 5 to 11 mg l^{-1}, and even exceed 25 mg l^{-1} in some areas. Maize is usually grown with sprinkler irrigation with a N fertilization rate of up to 300 kg ha^{-1}.

The objective of this study was to evaluate the growth, yield and N use efficiency of maize as affected by different rates of N fertilization.

Material and Methods

A three-year field study was conducted at *Las Tiesas* experimental farm of the *Instituto Técnico Agronómico Provincial* (ITAP), located in Albacete, Castilla-La Mancha (Spain). The field is located at 39º14’ N, 2º5’ W, and an altitude of 695 m. This research was carried out on maize (*Zea mays* L.) grown in monoculture during the 1999, 2000, and 2001 summer growing seasons under irrigation conditions.

The climate is semi-arid, with an average annual precipitation of 372 mm and an average annual temperature of 13.7ºC, varying from 5.5ºC in January to 24.5ºC in August. The average total evapotranspiration from a standard Class «A» pan during the irrigation period (April-September) is 1,195 mm. Reference monthly evapotranspiration, obtained using Penman-Monteith’s equation (Allen *et al.,* 1998), ranges during the irrigation season from 6.5 mm d^{-1} in July to 4.0 mm d^{-1} in September.

The topography of the area is flat (slope < 0.5%). The soil was classified as Calcixerollic-Petrocalcic Xerochrept. There was no apparent constraint to root development till a depth of 0.45-0.55 m, where a cemented petrocalcic horizon was found. These soils are representative of the major agricultural soils in the centre and east of Castilla-La Mancha region. The soil was alkaline (pH 8.0) with a high content of active lime. Average values of selected physical and chemical properties are summarized in Tables 1 and 2, respectively. Before 1999, the selected field was sown with corn and vegetable crops (e.g., onion, garlic, bean) and after this was dedicated to maize monoculture. During the three experimental years, the plots were managed maintaining the same treatments in the elemental plots. Soil samples were taken from each elemental plot at the beginning and end of the crop cycle. The sample was comprised of 6 sub-samples collected at two depths in a double zigzag network. Table 2 shows the average values of the different variables measured at the beginning of the crop cycle each year.

Table 1. Average values of selected physical properties of the experimental soil

Depth (cm)	Particle size distribution			Bulk density (Mg m^{-3})	FC (wt, %)	PWP (wt, %)	TAW (mm m^{-1})
	Clay (%)	Silt (%)	Sand (%)				
0-25	6	22	72	1.34	37.4	26.3	111
25-50	10	20	70	1.42	41.4	27.7	137

TAW: total available water; difference between field capacity (FC) and permanent wilting point (PWP).

Table 2. Average values of selected chemical properties of the experimental soil (initial content at each growing season —1999, 2000 and 2001—)

Depth (cm)	Organic matter (%)	Total nitrogen (%)			C/N			Assimilable P[1] (ppm)			Assimilable K[2] (ppm)		
		1999	2000	2001	1999	2000	2001	1999	2000	2001	1999	2000	2001
0-25	1.87	0.10	0.085	0.13	11	13	8.5	10	9.36	14.58	550	284	252
25-50	1.52	0.09	0.10	0.12	10	11	7.5	2	3.64	9.34	295	178	185

[1] Olsen method. [2] Ammonium acetate N1, pH 7.

The experimental design was a randomized block with four replicates of three different N rates. Each of the 12 plots, with an area of 81.9 m^2, comprised 9 rows with a length of 13 m and spaced at 0.7 m. Maize was sown at a density of 8.9 plants m^{-2}. The characteristics of the three different treatments are summarized in Table 3.

The Nc treatment is in agreement with some recommendations (Bratos, 1990) and represents the rate applied by most farmers in the area.

The Nop treatments corresponded with the optimized fertilization according to Nemeth (1979) and Diez (1988). For the calculation of Nop doses, the soil N available for the crop was evaluated at the beginning of the crop cycle. In order to make an integral use of the soil N, the mineralized N during the crop cycle must be determined. There are some techniques for its evaluation, such as the electroultrafiltration (EUF) (Nemeth, 1979), which has been calibrated for maize under the conditions of the Jarama river plain (Madrid, Spain) (Diez, 1988; Sánchez *et al.*, 1998). Based on this experience, and considering the differences in soils, climate, etc., for the experimental field in Albacete, an optimum rate (Nop) of 175 kg N ha^{-1} was established in 1999, which was reduced to 150 kg N ha^{-1} in 2000 and to 130 kg N ha^{-1} in 2001. The results were analyzed to recalibrate the method for the new conditions.

Reference plots were established by growing maize without N fertilizer application (No). Two different fertilizers were used as N source: urea (46% N) and ammonium nitrate (34% N). This type of fertilizer was used because it is the kind most frequently applied by the local farmers. With regard to the optimized N, urea was applied since the developed methodology was intended to work with only one application. Rate and time of N application are specified in Table 3. The typical soil preparation and farming techniques from the area were used in the experiments. During each year, a sample of irrigation water was analyzed to determine the nitrate concentration and, therefore, the applied N. Water was collected from the irrigation system under normal working conditions during the peak period. Table 4 shows the water parameters analysed.

Every year, before sowing, simple superphosphate (20% P_2O_5) was applied at the rate of 35.2 kg P ha^{-1}, and all plots received 83 kg K ha^{-1} as K_2SO_4 (50% K_2O). Immediately after fertilization, the soil was tilled to incorporate the fertilizer. Weeds were controlled by pre-emergence application of atrazine at 2.24 kg a.i. ha^{-1} and

Table 3. Treatments considered in the study. Fertilizer rate and time of application

Growing seasons		Treatments				
		No	Nop	Nc		
1999	Rate (kg N ha^{-1})	0	175	80	140	80
	Time of application		11-June	11-June	05-July	13-July
	Fertilizer		Urea		Ammonium nitrate	
2000	Rate (kg N ha^{-1})	0	150	80	140	80
	Time of application		05-July	05-July	12-July	20-July
	Fertilizer		Urea		Ammonium nitrate	
2001	Rate (kg N ha^{-1})	0	130	100	100	100
	Time of application		05-July	05-July	13-July	18-July
	Fertilizer		Urea		Ammonium nitrate	

Table 4. Analysis of irrigation water in the three years of the experiment

Growing season	NO_3^- (mg l^{-1})	NH_4^+ (mg l^{-1})	Cl– (mg l^{-1})	SO_4^{2} (mg l^{-1})	CO_3H^- (mg l^{-1})	Ca^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	Na^+ (mg l^{-1})	pH	Electrical conductivity (dSm^{-1})
1999	25.31	1.20	6.00	4.50	16.05	3.95	1.80	0.03	7.68	0.85
2000	24.56	1.30	6.36	4.95	10.99	4.10	1.99	0.04	7.95	0.94
2001	22.30	1.25	6.50	5.16	11.20	4.20	1.90	0.08	7.76	1.08

metolachlor at 2.30 kg a.i. ha^{-1}. Plants were sprayed with deltametrin at 5 g a.i. ha^{-1} three times for pest control.

The commercial single-cross hybrid 'Pregia' was sown on May 5, 1999, May 19, 2000 and May 30, 2001. The experimental area was sprinkler irrigated with a permanent solid set system. Daily irrigation was scheduled with the method of the water balance according to the methodology formulated by Doorenbos and Pruitt (1984). Reference evapotranspiration was calculated on a daily basis by means of Penman-Monteith's semi-empirical formula (Allen *et al.,* 1998). Daily meteorological data was recorded with an automatic weather station installed on site. The readily available water (RAW) was calculated with the following expression:

$$RAW = TAW \times p \quad [1]$$

where p is the fraction of total available water (TAW) that can be depleted from the root zone before water stress occurs in maize. A value of 0.50 was used.

Table 5 shows the irrigation depths applied during the three experimental years, with values between 731 mm in 2001 and 792 mm in 1999.

Aboveground biomass samples were taken at the following stages: emergence (E), five leaves (V5), seven leaves (V7), nine leaves (V9), beginning of male flowering (Vt), end of flowering (R1), milk maturation of grains (R3), milk-pasty maturation of grains (R4), and physiological maturity of grains (R6) (Ritchie and Hanway, 1982). Samples consisted of 5 randomly selected consecutive plants in a row. Successive samplings took place in areas unaffected by the previous ones. Plants were cut at ground level ant then separated into green leaf blades, dry leaf blades, stalks + sheaths, tassel, husks, and ears (at harvest cob and kernels). These parts were oven dried with forced ventilation at 80ºC for 48 h and weighed for dry matter determination. Leaf area was determined with a LI-COR 3100 area meter (LI-COR Inc., Lincoln, NE, USA). When physiological maturity was achieved, the plants in a length of 6.15 m in each central row were harvested to determine grain yield and harvest index. Harvesting took place on September 30, October 8 and October 24 in 1999, 2000 and 2001, respectively. Grain yields were expressed on a 140 g kg^{-1} moisture basis.

To study the duration of the phenological periods of agronomic interest (Table 6), the following variables were determined: number of days elapsed; growing degree units accumulated, and time course moisture content of grain during the filling sub-period. Growing degree units (GDU) were calculated according to Durr *et al.* (1991) as follows:

$$GDU = [(T_{max} + T_{min})/2] - 6 \quad [2]$$

where T_{max} is daily maximum temperature, and T_{min} is the daily minimum temperature. In this calculation, when T_{max} is > 30ºC, a value of 30 is used. In the same way, when T_{min} is < 6ºC, a value of 6 is used.

The crop growth rate (CGR; g m^{-2} land area per day), net assimilation rate (NAR; g m^{-2} leaf area per day), and leaf area duration (LAD; days) were computed

Table 5. Irrigation water applied (mm) and precipitation (mm) in the three years of the experiment

Growing season	Phenological periods											
	S-V6[1]			V6-Vt[1]			Vt-R6[1]			S-R6[1]		
	IRR	P	Total	IRR	P	Total	IRR	P	Total	IRR	P	Total
1999	121	10	131	273	0	273	331	57	388	725	67	792
2000	126	16	142	231	0	231	385	2	387	742	18	760
2001	189	0.0	189	245	0	245	255	42	297	689	42	731

[1] Different growth stages (Ritchie and Hanway, 1982). IRR: volume of water from irrigation. P: volume of water from precipitation.

Table 6. Corn crop development in the three years of the experiment

Phenological periods	Growing season	Dates	Number of days elapsed	Number of days accumulated	Growing degree units (°C)	Growing degree units accumulated (°C)
Sowing (S)-emergence (E)	1999	05/05-05/11	7	7	97	97
	2000	05/19-05/27	9	9	107	107
	2001	05/30-06/05	7	7	110	110
Emergence (E)-six leaves (V6)	1999	05/12-06/14	34	41	433	530
	2000	05/28-06/29	33	42	557	664
	2001	06/06-07/05	30	37	466	676
Six leaves (V6)-end of flowering (R1)	1999	06/15-07/23	39	80	718	1,248
	2000	06/30-07/30	31	73	588	1,252
	2001	07/06-08/21	47	84	724	1,399
End of flowering (R1)-physiological maturity (R6)	1999	07/24-09/27	66	146	1,059	2,307
	2000	07/31-10/08	70	143	999	2,251
	2001	08/22-10/07	47	131	772	2,171

according to procedures described by Hunt (1982) and de Juan *et al.* (1992). In all cases, the classical growth analysis method was used because the functional method does not present variations in the different growth indices calculated. This is a limitation of the functional method, because it does not necessarily provide the best description of the phenomenon studied. In fact, it can mask the effect of some eventual environmental adversity. Nitrogen use efficiency (NUE) was calculated for aboveground biomass [NUE_1 = (kg aboveground dry matter for Nop or Nc treatments – kg aboveground dry matter for No treatment) / kg N for Nop or Nc treatments] and grain [NUE_2 = (kg grain dry matter for Nop or Nc treatments – kg grain dry matter for «No» treatment) per kg N fertilizer rate].

Analysis of variance was used for all the variables studied. The ANOVA was performed for each year data independently. Differences were declared significant at $P < 0.05$. All statistical analyses were performed using the statistical package SPSS 9.0 (SPSS, 1999).

Results

Weather conditions

There was not a relevant variation in mean air temperature and incident radiation between years. During 2001, the coldest year of the study, the GDU were only 136ºC lower than in 1999, the warmest year. Temperatures during June, July and August of 1999 were 3-4ºC above the 24-yr average. High temperatures at the beginning of the cycle had a positive influence on seedling establishment. In general, flowering took place at the end of July (Table 6) in coincidence with very high temperatures (average maximum temperature greater than 36ºC) and low relative humidity (average relative humidity lower than 45%).

Dry matter accumulation

The aboveground biomass increased when N was applied, except in 1999 (Fig. 1). This was not surprising because 179 kg N ha^{-1} was available at the beginning of the growing season and approximately 41 kg N ha^{-1} were applied with the irrigation water (Tables 4 and 5). In 2000 and 2001, significant differences were observed between N treatments at tasseling and subsequent samplings (Fig. 1). At tasseling, biomass was lower in the No treatments, indicating a N deficiency. This difference continued during the rest of the growing season. There were no significant differences between the Nop and Nc treatments in 2000. However, biomass was slightly higher in the Nc treatment in 2001. Residual soil NO_3-N levels at the beginning of the growing season were lower in 2000 (110 kg N ha^{-1}) and 2001 (91 kg N ha^{-1}).

Leaf area index

There was an increase in LAI with the advance in crop age, reaching the highest value at Vt-R1 stages of the growth cycle, varying with the experimental year and with N treatments. Later on, the LAI declined due

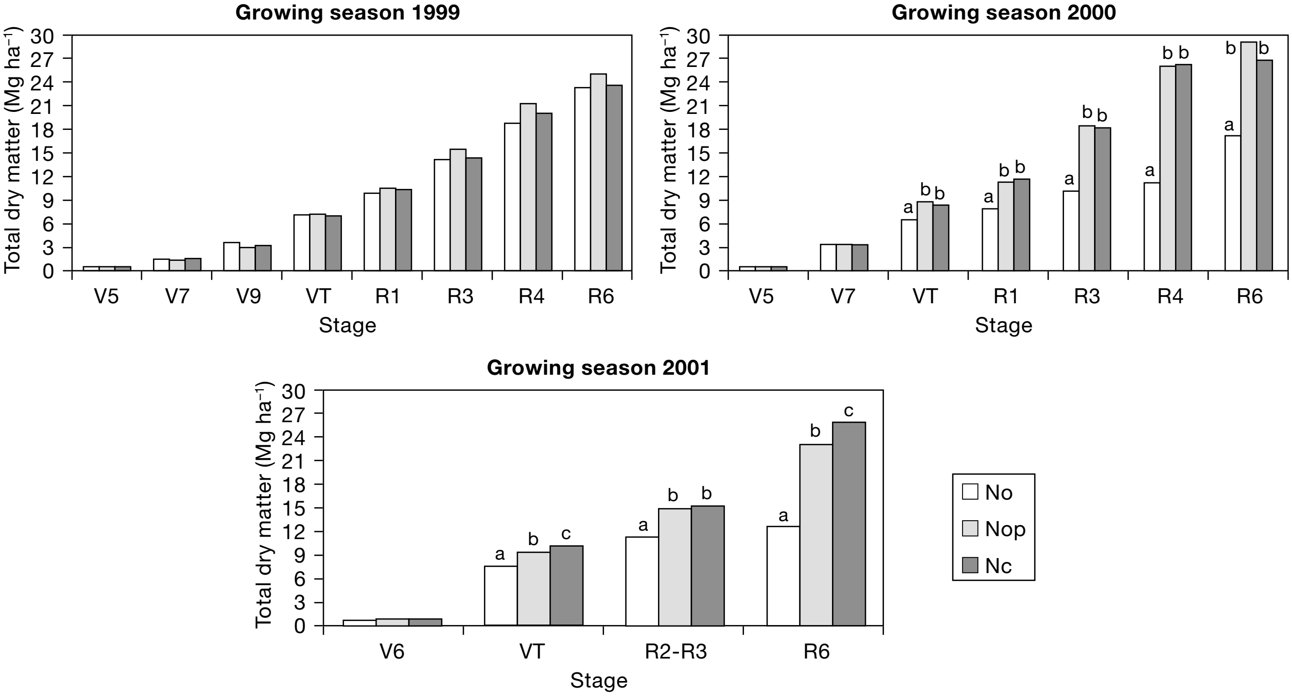

Figure 1. Cumulative total dry matter of maize for the three N fertilization treatments.

to senescence and leaf fall (Fig. 2). The highest increase in LAI was observed between the V5 and V7 stages.

Nitrogen fertilization did not increase LAI significantly in 1999, except at the end of the season, when LAI increased as the N applied increased. However, in 2000 and 2001, LAI increased with the Nop and Nc treatments from tasseling stage. These years a higher LAI was observed in the Nc treatment after the R4 stage.

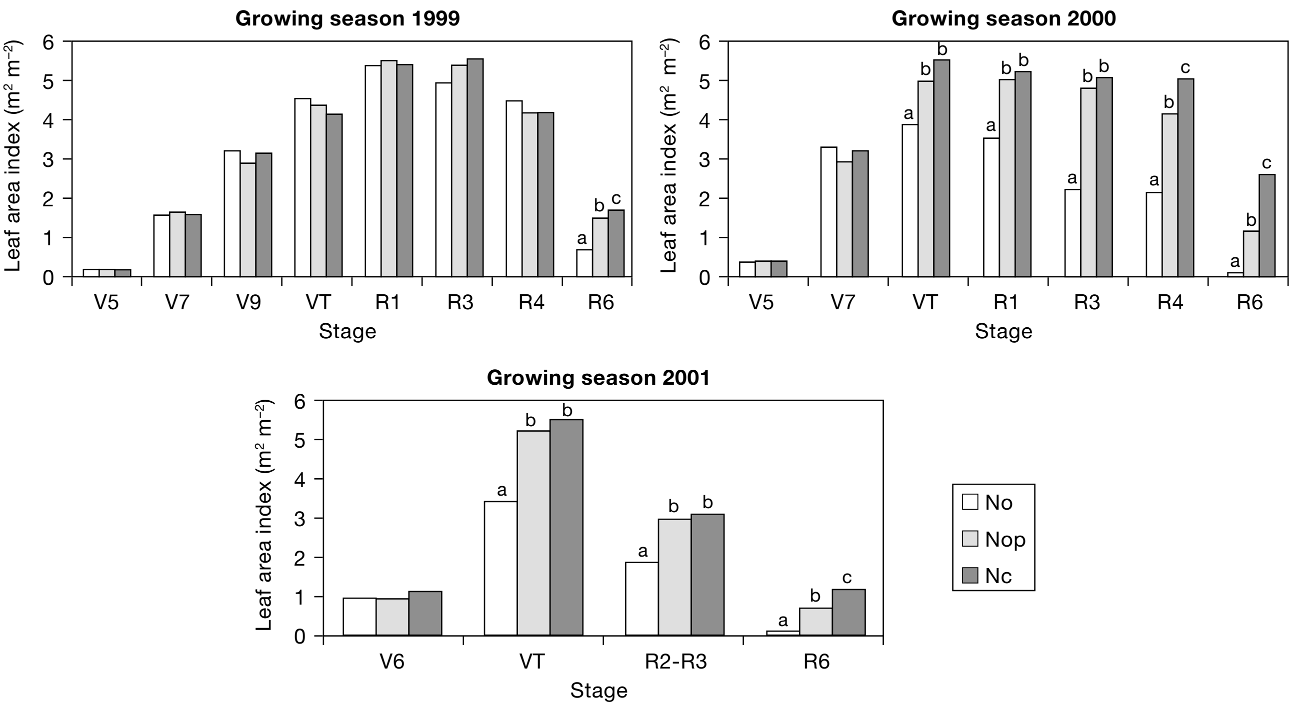

Figure 2. Leaf Area Index of maize for the three N fertilization treatments.

Crop growth rates

In general, the lowest CGR values were found during the early vegetative growth stages and increased all at once to reach a peak during the R1 stage. Then the CGR decreased steadily during the grain-filling period until harvest (Fig. 3). This period of maximum CGR in late July and early August corresponded to the late vegetative and early reproductive growth stages. In 2000, there was a second peak but only in plots fertilized with N.

Significant differences in CGR among N treatments were observed in the 2000 and 2001 seasons, except during the vegetative stages. Nitrogen fertilization increased CGR, although the differences between Nop and Nc were not statistically significant.

Net assimilation rate

The NAR was high during early vegetative growth but declined during the later stages (Fig. 4), except in the R1 stage during 1999 and 2000 and in the R4 stage in 2000, when there was a slight increase. The decrease in NAR is attributed to the shading effect of lower leaves by the upper canopy, to a general decline in photosynthetic efficiency with leaf age and also perhaps to lack of nutrients in later stages. An increase in NAR during the growing season is interpreted as a response of the photosynthetic apparatus to an increased demand for assimilates to afford rapid growth of the grain fraction.

In 1999 most of the growth stages were not significantly affected by different N fertilization levels. In 2000, the Nop and Nc treatments resulted in higher NAR than the No treatment during the late stages of crop growth. Low N levels (No treatment) restricted NAR, particularly during 2000.

Leaf area duration

In 1999, neither of the LAD indices (LADf or LADt) were significantly affected by the different N fertilization treatments (Table 7). However, in 2000 and 2001, both LAD indices were significantly lower in the No treatment. In 2000, LADf did not differ between the Nop and Nc treatments, but LADt was higher in the Nop treatment. In 2001, the LADt and LADf were higher in the Nc treatment compared with the Nop treatment.

Yield, yield components and harvest index

There were no yield differences between the different fertilization treatments in 1999. In 2000 and 2001, grain yields with N fertilization treatments were 2 (Nop treatment), 2.1 and 2.3 fold (Nc treatment) the

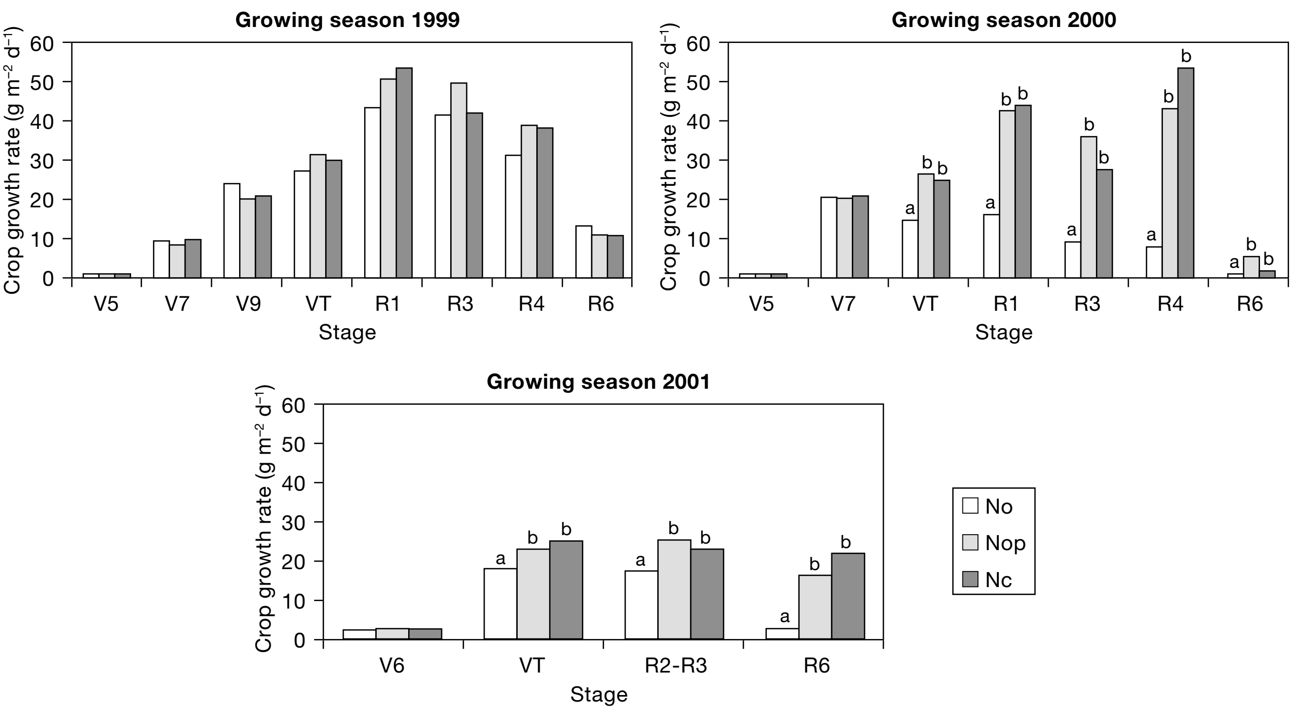

Figure 3. Crop growth rate of maize for the three N fertilization treatments.

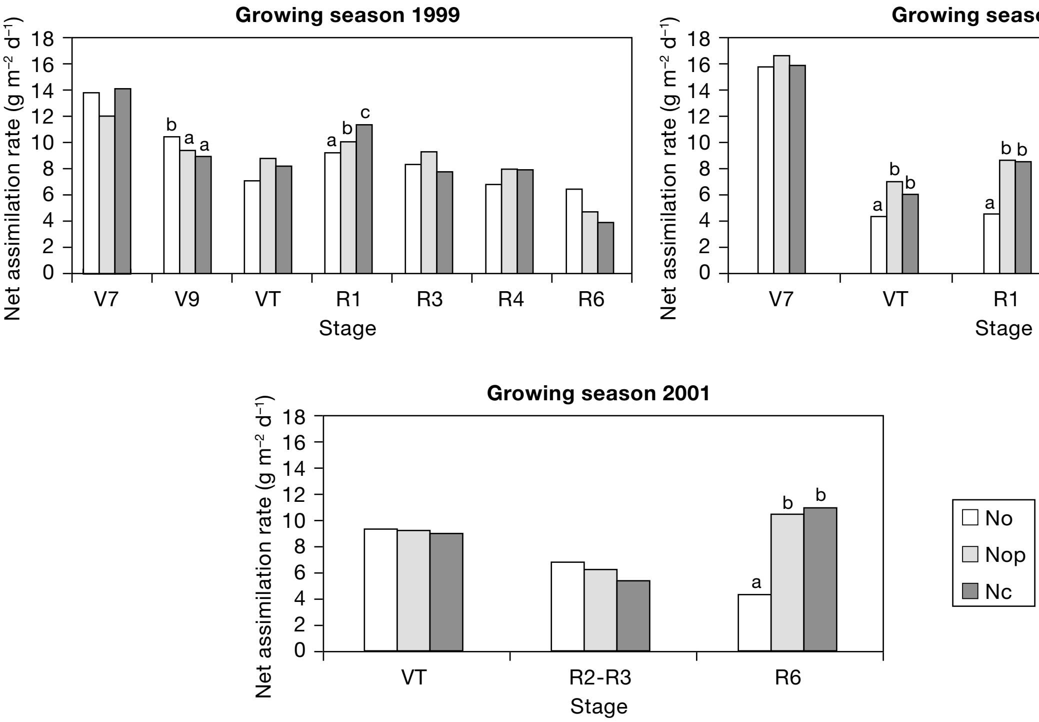

Figure 4. Net assimilation rate of maize for the three N fertilization treatments.

No treatment (Table 8). The highest yield was obtained with the highest N fertilization treatment (Nc) only in 2001, when Nop was reduced to 130 kg N ha^{-1}, which indicates an insufficient N availability with the Nop treatment this year.

There were no differences in HI among the different treatments in 1999. However, the treatments receiving N fertilisation resulted in higher HI in 2001, similarly to what occurred in 2000, but differences were statistical significant only in 2001. The higher yields were due to higher number of grains per cob and higher weight of grains (Table 8).

Fertilizer use efficiency

Nitrogen use efficiencies for TDM (NUE_1) and grain dry matter (NUE_2) were much lower in 1999 than in 2000 and 2001 (Table 9). One explanation could be the high initial level of residual NO_3 in the spring of 1999. In this growing season, a N application of 300 kg ha^{-1} reduced NUE_1 from 9.0 to 1.1 kg TDM kg^{-1} N, compared to the 175 kg ha^{-1} rate.The contrary effect was observed in NUE_2, which increased from 1.0 to 2.7 kg grain kg^{-1} N. Both NUE_1 and NUE_2 decreased with the highest N application (Nc treatment) in 2000 and 2001. In general, application of 300 kg N ha^{-1} reduced NUE_1 and NUE_2, to around 50% of NUE values of Nop treatments.

Discussion

Results from this research have implications for both the agronomic and environmental aspects of N fertilization management. Dry matter accumulation

Table 7. Leaf area duration in the three years of the experiment

N treatments	After flowering (LADf, days)			Total (LADt, days)		
	1999	2000	2001	1999	2000	2001
No	248	143 a	128 a	320	239 a	206 a
Nop	245	269 b	215 b	312	372 c	315 b
Nc	261	255 b	241 c	327	357 b	345 c

Values in each column followed by the same letter are not significantly different ($P < 0.05$, Duncan).

Table 8. Yield components, yield (Y) and harvest index (HI) of corn as affected by nitrogen fertilization

N treatments	Growing seasons														
	1999					2000					2001				
	Cob ha^{-1}	Grain cob^{-1}	WTG (g)	Yield (Mg ha^{-1})	HI (%)	Cob ha^{-1}	Grain cob^{-1}	WTG (g)	Yield (Mg ha^{-1})	HI (%)	Cob ha^{-1}	Grain cob^{-1}	WTG (g)	Yield (Mg ha^{-1})	HI (%)
No	75,290	654	309	15.21	56	75,633	423 b	253 b	8.08 b	41	74,139	440 c	221 c	7.21 c	48 b
Nop	69,350	669	333	15.46	53	72,785	705 a	323 a	16.55 a	49	75,311	572 b	348 b	14.95 b	55 a
Nc	74,824	648	334	16.21	55	77,219	632 a	350 a	17.06 a	55	76,044	554 a	397 a	16.70 a	54 a

No treatment: 0 kgNha^{-1}. Nop treatments: 175, 150, 130 kgNha^{-1} in 1999, 2000, and 2001 growing seasons, respectively. Nc treatment: 300 kgNha^{-1}. WTG is the weight of thousand grains at 14% moisture content. Yield at 14% moisture content. Means in each row followed by the same letter are not significantly different ($P < 0.05$, Duncan).

for maize under different N rates has been reported by Muchow and Davis (1988), Cox *et al.* (1993) and Uhart and Andrade (1995). However, the results reported in the literature are not always comparable, for several reasons (e.g., below-ground and dead plant parts may or may not be included in biomass measurements, genetic variation, different plant populations and sowing times, different climatic conditions).

Residual soil inorganic N levels at the beginning of the growing season were considered to be low in all the years of the study, except for 1999. The high initial level of residual NO_3-N in the spring of 1999 was a carryover from previous years of fertilization and was, at least, partially responsible for the lack of response to applied N. Similarly, Cerrato and Blackmer (1990) and Diez *et al.* (1994) also observed a lack of response caused by a carryover of residual N. Moreover, the high values of total aboveground plant dry matter and grain yield in 1999 can be compared to the maximum yields reported in the literature (Overman *et al.*, 1994). This year the CGR was around 17.1 g m^{-2} day^{-1}, exceeding the rates recorded for maize in some previous works (Overman *et al.,* 1994; Uhart and Andrade, 1995). Total dry matter and grain yield were increased by N rates up to 150 and 300 kg ha^{-1} in 2000 and 2001, respectively. However, in 2001, a delayed N application up to 130 kg ha^{-1} affected both growth parameters to a limited extent. Jokela and Randall (1989) reported an increase in yield when N rate was increased from 0 to 150 and 225 kg ha^{-1}, depending on the environment. Cerrato and Blackmer (1990) reported a linear increase in corn grain yield with N applications ranging from 0 to 100 kg ha^{-1}. However, as several models indicate, the mean economic optimum rates of fertilization ranged from 128 to 379 kg N ha^{-1}. In both years, differences in dry matter accumulation between N treatments occurred late in the growing season, at the Vt stage. The growth pattern reported here for all N treatments was consistent with those reported by Barloy (1984). Generally, differences observed in LAI corresponded to differences in TDM.

Table 9. Nitrogen use efficiency for irrigated corn grown at three N-fertilities

	Nitrogen use efficiency (kg kg^{-1})	
	Nop	Nc
Total dry matter	NUE_1^1 (kg TDM kg^{-1} N)	
1999	8.97 a	1.06 b
2000	78.92 a	32.02 b
2001	81.76 a	44.95 b
Grain yield	NUE_2^1 (kg grain kg^{-1} N)	
1999	0.96 b	2.74 a
2000	49.52 a	26.25 b
2001	52.19 a	27.74 b

[1] NUE, as presented at the end of the Material and Methods section. For each variable and year values followed by the same letter are not significantly different ($P < 0.05$, Duncan).

Cox *et al.* (1993) reported that the more sensitive period for leaf expansion to N stress was between V_{12}-V_{18}, and that LAI was not affected by an earlier N shortage. In contrast, Uhart and Andrade (1995) reported that significant differences in LAI among treatments appeared at stages V_6-V_7 of the biological cycle. In our experiments, the highest values of LAI were obtained in 2000, when N fertilization was substantially incremented from 0 to 300 kg N ha^{-1}, obtaining an increase in the maximum values from 3.9 to 5.5. Nitrogen shortage (Nop treatments) slightly reduced the maximum LAI. The increased maximum LAI due to an increase in N fertilization was associated with an enlargement in the mean leaf area because the final number of leaves was not affected by the N treatments.

Differences in crop growth rate between the three years of the experiment during the early stages of the biological cycle were attributed to leaf area development and its influence on the amount of intercepted radiation. In general, CGR was lower during the earlier stages and increased to reach a peak at the R1 stage. This late increase in CGR values is responsible for the similar total plant dry biomass at the end of the growing season and presumably contributed to Nop and Nc producing similar yields. Later, CGR declined continuously up to the physiological maturity of grains. This behaviour does not agree with the findings of Aguilar (1994), who observed two maxima in the evolution of CGR. The first maximum was just before flowering and the second one 20-30 days later. Between them, there was a minimum coinciding with the female flowering. In our experiments, the reduction in crop growth rate after the R1 stage was associated not only with a decrease in leaf area but also with a reduction in the net assimilation rate. A reduction in the photosynthetic capacity of the leaves because of leaf ageing could decrease the net assimilation values. In 2000, there was a second peak only in the plots fertilized with 150 (Nop treatment) and 300 (Nc treatment) kg N ha^{-1}, larger than the first one, because of higher LAI coupled with a slight increase in NAR in the R3 stage. Apparently, after the maximum period of stem growth, the corn plant growth and the accumulation of dry matter decrease during several days, when the aerial vegetative organs stop growing. After this period, the CGR index increases again, as the grain weight increases, and a second maximum is achieved. Finally, this decreases again at physiological maturity of the grain with a steep gradient.

The rise in CGR values with N fertilization was mainly due to a larger LAI, since CGR is a product of both LAI and NAR. A high CGR resulting from high LAI, high NAR or a combination of both, tends to lead to high yield. In general, an increase in CGR is more commonly due to an increase in LAI than to an increase in NAR. In 2000, for Nop and Nc treatments, the CGR advantage was due to higher LAI and higher NAR. In 2001, for Nop and Nc treatments, the increase in CGR was due to an increase in LAI rather than to an increase in NAR.

When comparing the Nop and Nc treatments, grain yield decreased when Nop fertilization was reduced from 150 kg ha^{-1} (2000) to 130 kg ha^{-1} (2001). However, in 2000 there were no significant differences between Nop (150 kg ha^{-1}) and Nc (300 kg ha^{-1}). Considering that the soil residual inorganic N before maize sowing was similar in 2000 and 2001, the results suggest that the Nop adjusted to the conditions of the zone should be 150 kg N ha^{-1}.

Corn monoculture has been shown to produce less grain and TDM than crop rotation, and requires more N fertilizer for maximum yield (Peterson and Varvel, 1989). In our experiment, no decline in the maximum grain yield was found (Nc treatment) (Table 8). These yields are comparable with the yield of high-producing varieties under adequate water supply and irrigated farming conditions with a high level of agricultural inputs, which is 12-14 Mg ha^{-1} in the province of Albacete (ITAP, 2002).

Differences in grain yield with N levels were mainly due to significant variations in growth parameters such as dry matter production, maximum LAI, LADt and LADf, and CGR values. These differences led to a higher TDM production and to the partitioning of a large proportion into the grain, as evidenced by an increased harvest index. The HI is used to evaluate crop efficiency and predict yields. It is also a criterion for choosing the cycle of maturity and behaviour of the crop against different types of stress. In our experiments, the average HI ranged between 41 and 56%. These values are similar to those reported by other authors, of around 50% (Grant, 1989; Aguilar, 1994; De Juan *et al.*, 1999). In both 2000 and 2001, a high N fertilization up to 150 and 130 kg ha^{-1}, respectively, resulted in higher initial partitioning of assimilates to grains and favoured the partitioning of dry matter to reproductive growth. Harvest indexes increased slightly with increasing N fertilization. Similar results have also been reported by other authors (Sinclair and Muchow, 1995).

There was a decreasing pattern in NUE values with increasing fertilizer rates, indicating that maximum crop production could be attained with lower fertilizer applications. In a study on maize performed in the Jarama river plain of Spain, the application of constant N fertilizer (300 kg ha^{-1}) and irrigation water doses according to local farming practise resulted in drainage water losses amounting to 20% of the irrigation water and N losses over 250 kg ha^{-1} (Díez *et al.,* 1994). Sánchez *et al.* (1998) evaluated nitrate lost through leaching with conventional irrigation, observing N losses of 120 kg N ha^{-1} on unfertilized plots and exceeding 240 kg N ha^{-1} on fertilized plots. Losses under optimized irrigation treatments were considerably lower than with the conventional system, ranging between 43 (unfertilized plots) and 165 (fertilized plots) kg N ha^{-1}.

Only in one year significant differences in most of the basic parameters and growth indices analysed were observed between the adjusted optimum rate and the conventional rate used in the region (300 kg N ha^{-1}). This suggests that part of the fertilizer surplus will eventually be leached to deeper horizons. Fertilizer practices (interval, timing and application technique) must be revised in order to control pollution of La Mancha Oriental aquifer. As a first recommendation, a fertilizer rate in the range of 150 to 200 kg N ha^{-1} should be adopted by the farmers. This will reduce N fertilizer cost by 33 to 55% and will reduce the risk of nitrate leaching.

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