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Controlling nitrate pollution of aquifers by using different nitrogenous controlled release fertilizers in maize crop

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Abstract

The effects of applying different commercial, controlled release fertilizers (CRF) as a means of controlling NO_3^- pollution of groundwater in an irrigated maize crop were tested. The polluting effects of two sources of irrigation water with different NO_3^- content were also evaluated.

The results showed that conventional agricultural practices are one of the main causes of NO_3-aquifer pollution. Excess nitrogenous fertilization occurs because of the lack of soil monitoring to rationalize the fertilizer dosages and because the flood irrigation system, used with the frequency and rates applied, accelerates NO_3^- leaching. The results also show the inefficient use made of water.

An analysis of the results, using the evolution of the NO_3- leaching rate, proved to be a more reliable source of information for assessing pollution than the concentrations detected in the soil water solution, below the root zone when the water flow was downwards.

The use of two different sources of irrigation water (well, 43 mg NO_3^- l^{-1} and stream, 3 mg NO_3^- l^{-1}) showed no significant differences on the NO_3^- leached during the maize growing period owing to the high levels detected in the soil and the high dosages of N applied.

In the stream irrigation water experiment, a greater polluting effect was observed with conventional fertilizer application (urea) than with CRF.

The results obtained with Floranid 32 showed the effects of control over NO_3^- leaching both in the case of stream and well-water irrigation sources. With Multicote this is only observed with the use of NO_3^- free water.

1. Introduction

Nitrogen application rates above crop requirements and irrigation rates unmatched to potential evapotranspiration (ET), are the main causes of aquifer pollution by nitrates in agricultural areas (Prat, 1984; Ramos et al., 1989). In the mid-basin of the Jarama river (Central Spain), widespread cultivation of irrigated maize and urban and industrial impact on the aquifer's recharge area (Pelaez et al., 1971) have led to NO_3^--N concentrations near the EC tolerance limit for human consumption (European Economic Community, 1980).

Under conventional cultural practices, maize cultivation may include a single top-dressing N rate of up to 300 kg ha^{-1} (Bratos, 1990; Tejedor, 1991) and extensive use of surface irrigation with

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variable application rates. Matching irrigation management to potential water consumption has been addressed by a water-balance study (R. Roman, R. Caballero, A. Bustos, J.A. Diez, M.C. Cartagena and A. Vallejo, unpublished data, 1983).

Partitioning N application has been recommended as a means of reducing pollution risk and improving N-use efficiency (Keeney, 1986; Olson and Kurtz, 1989; Ramos et al., 1989). However, the maize canopy makes this technique impractical in commercial farming conditions. The only way of fertilizing the crop in advanced growth stages is via water irrigation using sprinklers.

The use of controlled release nitrogenous fertilizers (CRF) in intensive crops could be an alternative to reduce these effects but there is little information on its application. This is largely because such fertilizers are somewhat more expensive than conventional ones even though they may involve considerable advantages, such as higher N-use efficiency and pollution control which could more than offset the price difference (Jiménez et al., 1988).

Some of these fertilizers are being marketed whilst others are at the experimental stage (Cartagena et al., 1991). Their greatest advantages lies in the fact that N is gradually released matching the plant's rate of absorption.

The purpose of this paper is to test the effects of two CRF on the control of ground-water nitrate pollution against conventional fertilizers such as urea, in an irrigated area of central Spain under maize cropping. At the same time, the polluting effects of two sources of irrigation water are evaluated. One water source is a low nitrate content stream and the other a well with higher nitrate levels located on the experimental farm. Both fertilizer and irrigation dosages applied conform to local agricultural practices.

2. Material and methods

A 4000 m^2 experimental field was established in La Poveda Field Station (CSIC) located in the district of Arganda del Rey (Madrid) on the Jarama river plain, traditionally used for irrigated crop growing. Twenty four (11m×9m) single plots, spaced 3 m apart, were marked out within the experimental field. Half these plots were irrigated with well water and the other half with stream water. The analytical data of water sources are given in Table 1.

Nitrogen application was carried out with three different fertilizers as follows: (1) urea; (2) Floranid 32 whose nitrogenous component is isobuthylidendiurea (a low solubility compound); (3) Multicote 4 (a urea-base coated fertilizer). Dosage and method of application are specified in Table 2.

Textural variations within the experimental field were assessed by taking six undisturbed samples of the soil profile down to the gravel layer. Individual soil samples were also taken on each single plot. There is no defined structure in the first 50 cm, in which the texture is fairly homogeneous (Table 3). The gravel layer depth within single plots varied between 1.3 m and 2.2 m.

Soil samples were taken from all the single plots before starting the experiment to assess the nutrient dynamics using the electro-ultrafiltration technique (Nemeth, 1979; Table 4). On the basis of this information, a study of the actual fertilization requirements of the crop was made via a laboratory analysis, paying special attention to the evaluation of available N in the soil (Wickliky et al., 1981).

The experiment was laid out in a randomized complete block design with four replications, using 12 single plots with each source of water. Maize cultivar 'Prisma 800XL 72AA' was planted on 24 April and harvested as grain crop on 7 November, 1991. For seedbed preparation 800 kg ha^{-1} of a compound 8:15:15 ($N:P_2O_5:K_2O$) were applied.

Moisture was monitored by a neutron probe and the water flow path through the soil profile by a set of ten tensiometers per single plot (Roman et al., unpublished data, 1993). The soil-water solution was sampled using a ceramic candel extraction system with tips at depths of 50

Table 1
Analysis of irrigation water at the beginning of the experiment

Source of water	NO_3^-	NO_2^-	NH_4^-	Cl^-	$SO_4^=$	CO_3H^-	Ca^{++}	Mg^{++}	Na^+	K^+	pH	Conductivity (μmhos)
Well	43.0	–	–	64	521	465	215	68	121	14	7.3	1980
Stream	3.7	1.1	6.3	43	149	201	81	19	60	8	7.6	870

All values are mg l^{-1}.

Table 2
Characteristics of the fertilizers and method of application[1]

Fertilizer treatments	Characteristics	Activity time (months)	N contained (%)	Top-dressing N rate	
				Urea (kg ha^{-1})	CRF (kg ha^{-1})
Urea	Soluble	2	46	294	–
Floranid 32	Low solubility (ISODUR)	4	32	94	200
Multicote 4	Coated	4	29	94	200

[1]All treatments received additionally 64 kg N ha^{-1} as 8:15:15 compound with seedbed preparation.

Table 3
Average figures and coefficient of variation (cv) of the grain size within the experimental field at different soil depths

	Soil-depth					
	50 cm		90 cm		140 cm	
	Mean	cv	Mean	cv	Mean	cv
Sand	37.7	14.8	51.9	22.9	71.9	17.5
Loam	45.5	9.5	36.1	25	21.2	48.6
Clay	16.9	11.5	13.1	39.7	6.4	59.3

Table 4
Average figures for K, P and N evaluated by EUF in the 24 plots (mg·100 g^{-1} of soil)

EUF.K		EUF.P		EUF.N	EUF - NO_3^-	AvailableN
20°C	80°C	20°C	80°C	20°C+80°C	20°C+80°C	kg N·ha^{-1}
12.25	8.95	1.48	1.6	8.37	1.85	320

cm, 90 cm and 140 cm. Only data from 140 cm were used as soil water reaching this depth leached to the groundwater table.

One sprinkler irrigation at the rate of 60 l m^{-2} plus eight surface irrigations at even rates of 43 l m^{-2} were applied over the maize growing season. Rainfall during the same period was 109 l m^{-2}.

The soil's water reserve and hydraulic charge profile were periodically monitored. Sixteen operations of this type were performed throughout the growing period. Using these data, the drainage volumes were determined periodically. Integrating these data enabled the drainage relating to each of the soil solution samplings to be calculated (Roman et al., unpublished data, 1993). Sampling was carried out when water flow was downwards so that samples from the deeper layers are directly linked to groundwater pollution. A total of seven soil solution samplings were made from April 24 at the following intervals: 82, 95, 111, 129, 146, 153 and 250 days. In the first sampling no water was found at a depth of 140 cm.

The estimate of leached nitrate was calculated from the product of the NO_3^- concentration in the soil solution, below the root area, and the volume of drainage water, calculated by integration for each period.

Total N in the EUF extracts (EUF-N) was determined by digestion with UV radiation and subsequent oxidation with potassium persulphate in an alkaline medium (Díez, 1988), in order to transform all the nitrogenous compounds into NO_3^-. The analytical NO_3^- determinations both of the soil-water solution from the porous ceramic cups, and of the EUF extracts, were performed colorimetrically using a Technicon AAII (Technicon, USA) autoanalyser with N 1 naphthylethylenediamine. P was determined using an ammonium molybdate reagent and K by flame emission photometry.

N extraction by crop was estimated at 390 kg ha^{-1} for a maize production of 13 t ha^{-1}. On the basis of the EUF soil analyses and according to criteria as established by Wiklicky and Nemeth, (1981), the available soil-N was assessed at 320 kg N ha^{-1} (Table 4). These calculations would have led us to apply a moderate dosage of approximately 100 kg N ha^{-1}.

However, as our purpose was to test the polluting effects of excessive nitrogenous fertilizer, we chose to follow the traditional practice of the farmers, estimating the top-dressing dosage to be applied as 294 kg N ha^{-1}. This dosage represents the average in the area and is in agreement with some recommendations (Bratos, 1990).

Another nitrogen input not always taken into account is that from irrigation water. In view of the fact that we used two sources of water, with different characteristics in the experiment, an additional contribution of 32 kg N ha^{-1} with well water and 2.3 kg N ha^{-1} with stream water is estimated for that supplied throughout the maize growing cycle.

3. Results

Nitrate concentrations in the soil solution, detected at different depths, showed an important variability in space and time whose coefficients

Table 5
NO_3^- concentrations (mg l^{-1}) in the soil solution at a depth of 140 cm at varying water irrigation sources and fertilizer types ($x \pm sd$)

Treatments	Samplings					
	2	3	4	5	6	7
Stream						
Multicote[1]	391±124	276±67	270±88	281±112	305±141	315±67
Floranid[1]	180±10	315±65	315±94	325±31	335±37	325±41
Urea[2]	506	794	685	637	668	257
Well						
Multicote	442±8	565±72	560±80	542±119	450±40	450±36
Floranid	390±131	325±75	170±87	163±37	253±92	270±44
Urea	533±267	613±286	505±180	275±117	253±110	271±113

[1]Slow release N fertilizers.
[2]Only one complete piece of data useable in the whole series ($n=4$).

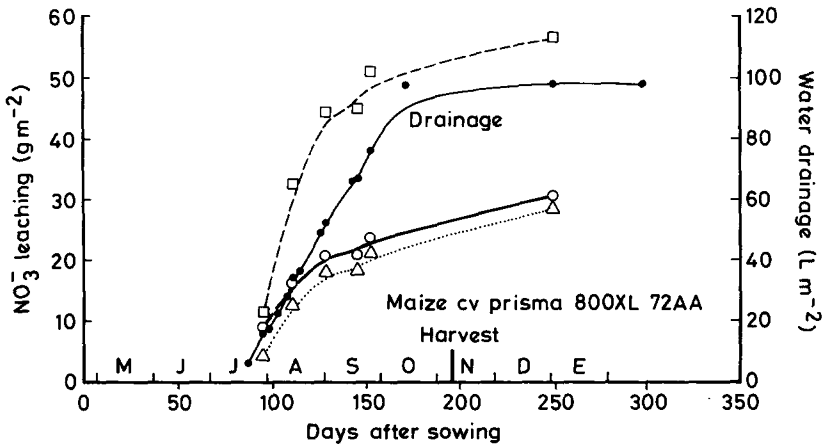

Fig. 1. Accumulative nitrate leaching and drainage in maize crops. Stream irrigation water. •—•, drainage; o—o, Multicote; △······△, Floranid 32; □- - -□, urea.

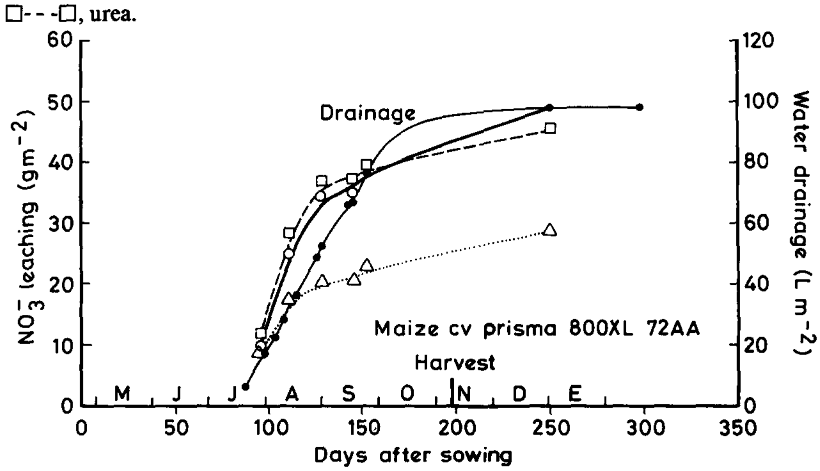

Fig. 2. Accumulative nitrate leaching and drainage in maize crop. Well irrigation water. •—•, drainage; o—o, Multicote; △······△, Floranid 32; □- - -□, urea.

of variation were generally high. Average figures for NO_3^- concentrations at a depth of 140 cm, together with the standard deviation are given in Table 5. This table shows that NO_3^- concentrations in the first samples are relatively high, indicating that before the experiment commenced, there was an appreciable accumulation of NO_3^- from previous practices. We can also see that standard deviations are relatively high in some cases (well, urea; stream, Multicote). Similar results have been reported by other researchers in studies of this nature (Biggar, 1978). To the difficulties arising from the spatial and temporal variability are added others deriving from the periodic obstruction of the ceramic cups, despite detecting sufficient moisture content through the neutron probes.

Letey et al. (1977) have studied the correlation between the NO_3^- of irrigated soils in California and nitrogenous fertilization and volume of drainage. The N leached correlated significantly with the volume of drainage and with the dosages of fertilizer added however, it had no relation with NO_3- concentrations in the soil solution. Consequently, NO_3^- leached was evaluated (concentration of $NO_3^- \times$volume of drainage) periodically for each of the treatments throughout the experiment. The results are presented as cumulative curves, with the cumulative volume of water leaching in Figs. 1 and 2.

It can be seen from the figures that drainage increases rapidly throughout July and the beginning of August, i.e. coinciding with irrigation time and providing that the water supplied exceeds actual evapotranspiration. Quantification of this process during the growing period gives approximately 97.6 l m^{-2}, which proves that both the flood irrigation system used and the frequency and dosages applied accelerate leaching of salts and, particularly, of nitrates. At the same time a 20% water loss through drainage is confirmed. In addition, an uneven distribution of water in single plots is detected. It accumulates in the ground's typical depressions which originates a certain variability affecting the uneven distribution of water to cover the crop's requirements and, consequently, the information obtained in the experiment.

4. Discussion

Before starting the experiment an objective evaluation of the actual nitrogenous fertilizer requirements was made as a function of the N available in the soil, in order to assess the agreement between the dosage necessary (100 kg N ha^{-1}) and the dosage applied (294 Kg N ha^{-1}): the latter was the final choice.

This substantial difference obviously proves that, in many cases, nitrogenous fertilizers are applied in excess because, on the one hand, farmers rarely using soil analyses to evaluate their fertilizer requirements and, on the other, because there is insufficient awareness of the risks of pollution which results from the use of excess nitrogenous fertilizer.

Fig. 1 shows that the rate of NO_3-N release is more intense in the first stages coinciding with the greater intensity of drainage. A turning point is observed after 125 days in CRF and, after 140 days in urea. In general, the most intense NO_3^- leaching is detected in the first phase because of the greater intensity of drainage but also because in the CRF treatments a proportion of N was supplied as urea in order to ensure nitrogenous nutrition of the crop in the early growth stages (see Table 2).

The urea treatment showed a NO_3^- leaching rate clearly higher than that obtained by CRF. This behaviour could mean that the high solubility of urea has a short period of activity giving rise to high concentrations of NO_3^- in the soil water solution. This is finally turned into high leached N figures as can be seen in Fig. 1.

In contrast, the CRF showed moderate leaching rates which give rise to lower leached N figures. Fig. 1 shows that almost twice as much N leached from the urea treatment than the CRF treatment with stream-water irrigation. The two CRF treatments showed similar amounts of leached N. The leaching of NO_3^- from the urea treatment followed the accumulative drainage curve closely.

In the experiment using well water as an irrigation source, the NO_3^- leaching curves (Fig. 2) showed similarities with those obtained using stream water; thus a higher NO_3^- leaching rate again occurred in the first stages with a turning point similar to that found with the stream water.

Owing to its high solubility, urea again exhibited an accelerated rate of N release at the beginning, which determines a low use of N by the plant, finally causing a marked NO_3^- leaching process.

However, Floranid partially controlled N release with lower NO_3 concentrations in the soil solution which finally turns into moderate NO_3^- losses through leaching.

N-leaching in Multicote well-water treatment runs at a higher level than that observed with stream water irrigation, displaying figures similar to that of urea. No reasons justifying this behaviour were found.

The NO_3^- concentrations in the soil detected at the beginning of the experiment demonstrate an appreciable NO_3^- pollution of the soil at origin, which makes it difficult to clearly separate the effect of applying different types of fertilizer. Under these circumstance, it is difficult to appreciate the effect of two different types of irrigation water which, whilst different in their NO_3^- content, nevertheless represent relatively small contributions compared with the content of the soil.

The amount of NO_3^- lost through leaching depends on the amount of water moving through the soil and the concentration of NO_3^- present when the water is draining through the rooting zone. According to Pratt (1984), once the crop has been selected, management, irrigation and nitrogenous fertilizers must ensure that the crop has a competitive advantage over other factors affecting N.

5. Conclusions

In farming conditions, excess amounts of N fertilizer are used owing to a lack of soil monitoring to determine dosages. This is one of the main causes of NO_3^- soil pollution. The high space and time variability observed in NO_3^- concentrations detected below the root zone only enabled us to observe trends between fertilizer treatments as standard deviations were relatively high in some cases.

Nevertheless, Floranid showed promising results in controlling N-leaching in comparison with urea. A favorable effect with Multicote was observed only in treatment with stream water.

Analysing results as cumulative fluxes of NO_3^- leached, proved to be more reliable than NO_3^- concentrations from ceramic cups for evaluating the polluting effect from the different fertilizer treatments.

Irrigation in accordance with farmers' usual practices gave rise to drainage losses in the order of 20% of water which contributes to accelerating the aquifer NO_3^- pollution process. These results prove that there is a need to optimize irrigation systems both in dosages and in frequency.

These results, which in some cases require more extensive experimentation, suggest that it should be possible to control the nitrate pollution of soils by rationalisation of the fertilizer dosages via soil analyses, improving control of the irrigation water dosages and using CRF suited to each crop.

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