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Nitrate contamination and its relationship with flood irrigation management

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SUMMARY

Nitrate contamination is a significant unresolved environmental issue for agriculture in the 21st century, with longstanding challenges in its control and allocation to a specified territory. In order to address these challenges, real-world meticulous irrigation area studies are required. The objective of this investigation is to analyze the evolution of nitrate contamination in relation to agronomic and management changes within a traditionally irrigated land. Specifically, the impact of changes in irrigation allowance assignment, changes in irrigation method from rotation to on-demand flood irrigation, and creation of water consumption accounts were analyzed.

To this end, nitrogen monitoring and annual balances were carried out in a small irrigated hydrological basin (95 ha) located in Northeastern Spain throughout the years of 2001 and 2005–2008. The evolution of the nitrate contamination index was also analyzed, which relates the mass of nitrates exported to the fertilization necessities of a specific irrigated area.

The results demonstrated that although changes in crop pattern caused a 33% reduction in the nitrogen required through fertilization, the fertilization rates applied are still double the necessities. Changes in irrigation management decreased the mass of nitrates exported by half and the nitrate contamination index by 24%, but the nitrate levels present are still approximately double of those registered in modern irrigation areas.

The changes implemented by the Irrigation District in the irrigation management were effective. However, this study confirms that a greater effort is still required to achieve adequate nitrogen fertilization matching the crop necessities.

1. Introduction

The elevated use of water and fertilizers in relation to the actual crop necessities causes excessive leaching of nitrate in the soil, which ultimately reaches aquifers and rivers and pollutes their waters (WHO, 2004). For this reason, water quality problems are mostly associated with changes implemented in agriculture, with nitrates derived from nitrogen fertilization being a very important contributor.

Until the middle of the XIX century, nitrogen contributions to plants were made thru organic fertilizers and nitrogen present in the soil transformed by bacterial action. However, the pressing need to produce greater quantities of food propelled the introduction of mineral fertilizers to achieve higher yields (Betrán, 2006).

Since then, the use of inorganic fertilizers became indispensable to increasing and maintaining agrarian production (Fuentes, 1999). Nevertheless, the increase in fertilization also has led to an increase in the nitrogen available in the soil, which, combined with inadequate irrigation treatment or intense rain events, results in contamination in aquifers and rivers (Quílez et al., 2006). Nitrate concentrations of up to 1200 mg/l (Ju et al., 2006) were found in the waters of agrarian areas of China – more than 20 times the upper limit of 50 mg/l established for water destined to human use (WHO, 2004).

The focus on nitrate versus other chemical elements is due to its fast effect on human health when found in high concentrations in drinking water. Chemical elements are generally noxious to health after prolonged exposure. Consumption of water with high concentrations of nitrate causes an increase in the rate of formation of methemoglobin in the blood, decreasing its oxygen-carrying capacity and leading to tissue hypoxia (WHO, 2004).

Abbreviations: D-XIX-6, nitrogen in the ditch; D, drainage of the hydrological basin; Dep, nitrogen in atmospheric deposition; Des, nitrogen from desnitrification; E, nitrogen extractions from the crops; Fix, nitrogen from symbiotic fixation; I, nitrogen in irrigation; IE, irrigation efficiency; LSC, nitrogen in lateral subterranean contributions; $N{-}NO_3^-$, nitrates exported by the studied irrigation area; NA, nitrogen applied; NAI, nitrogen application index; NCI, nitrate contamination index; NF, nitrogen fertilization necessities; NI, nitrogen inputs; NO, nitrogen outputs; NS, nitrogen storage; P, nitrogen in precipitation; Sa, storage of nitrogen in the aquifer; VC, variation coefficient; Vol, nitrogen in volatilization; WHC, water holding capacity.

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The occurrence of high concentrations of nitrate in rivers and oceans also has a negative environmental impact on aquatic plants and animals, with the development of anoxic zones and eutrophication of aquatic environments (Diaz, 2001). These phenomenons have been evident on the coasts of the United States (Scavia and Bricker, 2006) and China (Wang, 2006).

The pressure for having established quality standards for water resources has been increasing since the 1990s, with organizations such as the World Health Organization (WHO, 2004) the Food and Agriculture Organization of the United Nations (FAO; Ayers and Westcot, 1994), and governmental agencies (US Environmental Protection Agency, European Environment Agency) developing regulations and action guidelines for the use of water in the consumption sector (EU, 1998, 2000; EPA, 2000).

Within the European performance guidelines, the Directive on the protection of waters against agricultural nitrate contamination is especially important (EU, 1991) along with the EU Water Framework Directive (EU, 2000) and the Directive on the protection of subterranean waters against contamination (EU, 2006), all developed to organize the management of water masses and to identify, reduce, and minimize its deterioration.

In Spain, EU Directive (1991) originated the Royal Decree 261/1996 on the protection of waters against contamination produced by nitrates of agrarian sources, leading to the implementation of vulnerable zones to nitrate contamination, agrarian codes of good practice, actions programs, and strict measures to minimize the impact of nitrate fertilization (BOE, 1996; BOA, 1997, 2001).

A serious issue in the control and allocation of contamination to a specific territory lies in the extreme difficulty of tracking the specific origin of nitrate contamination in the agrarian environment as its contamination pattern is diffuse.

Traditionally, studies based on lysimeters or monitoring of small experimental plots have been performed to verify the influence of physical and agronomical factors on the use of resources and the contamination induced by irrigation return flows (Roman et al., 1999; Caballero et al., 2001; Spalding et al., 2001; Isla and González, 2006; Feng et al., 2005; García-Garizábal and Causapé, 2010; Gehl et al., 2005; Bustos et al., 2006; Li et al., 2007).

Although studies with lysimeters or controlled plots are a good experimental tool, it is necessary to broaden the scale and analyze the most influential factors for nitrate contamination in "real" irrigated areas.

Of special interest are studies based on the monitoring of irrigated hydrological basins that explored the variation of contamination generated as a function of the physical and agronomical characteristics of the irrigated area (Basso et al., 1990; Tedeschi et al., 2001; Lasanta et al., 2002; Cavero et al., 2003; Causapé et al., 2004a,b; Isidoro et al., 2004, 2006; Ribbe et al., 2008).

Unfortunately, the short duration of these aforementioned studies (one or two year investigation projects) has prevented the elaboration of temporal series analyses. This highlights an interest in collecting pluriannual information from which to study the effects of changes in irrigation management on the nitrate contamination generated.

The objective of this investigation is to analyze nitrate contamination and its relationship to flood irrigation management through the development of annual nitrogen balances in an irrigated basin during 2001 and 2005–2008.

2. Description of study area

The study zone includes the hydrological basin of drainage ditch D-XIX-6 (95 ha) of Bardenas Canal Irrigation District n° V, located in North-eastern Spain. 96% of this basin's surface are soils subjected to flood irrigation with good quality waters coming from the Yesa reservoir.

The climate of the study zone is classified as Mediterranean warm weather (ITGE, 1985) with rain concentrated during autumn/spring months and a greater evapotranspirative demand in summer. The study period (2001 and 2005–2008) encompassed the climatic variability of the zone, comprehending one hydrological rainy year (2001: 526 mm), one dry year (2005: 211 mm), and three years with intermediate registries (2006: 450 mm; 2007: 372 mm; 2008: 305 mm) that are closer to the historical average (460 mm/year; GA, 2009a).

Geologically (ITGE, 1995), 75% of the basin is located on a glacis of gravel with loamy matrix (maximum thickness 5.5 m), constituting a free aquifer with saturated thicknesses of up to 4 m that introduces lateral subterranean contributions into the basin from the Northwest – as detected by the hydrological gradient obtained from the piezometer network of the zone (Fig. 1). The lateral subterranean contributions join the water introduced into the basin by irrigation and rain and is evacuated by the ditch that circulates

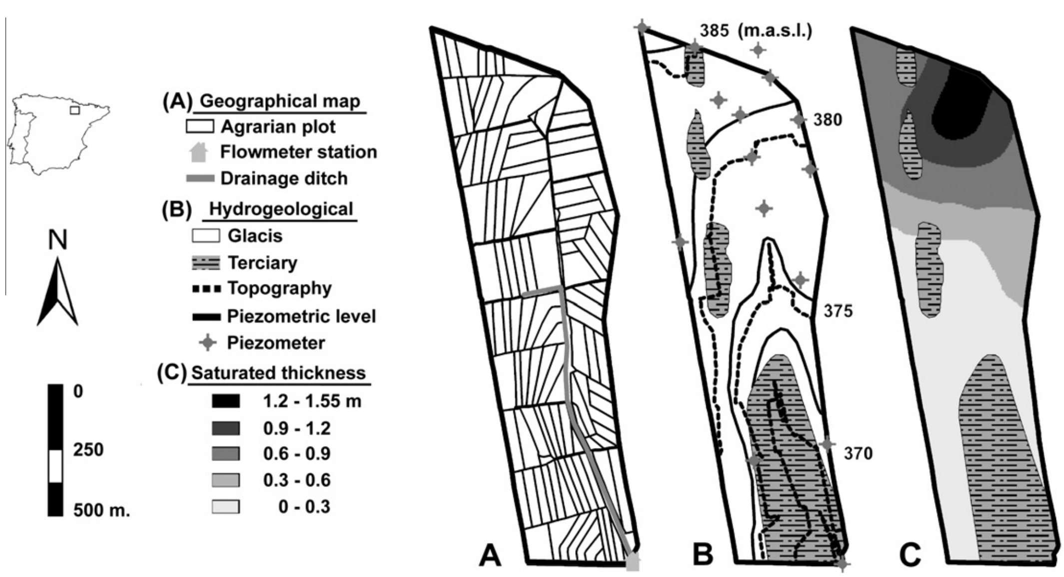

Fig. 1. Localization of the experimental hydrological basin drained by D-XIX-6 ditch: (A) Distribution of agrarian plots, gauging station and D-XIX-6 drainage ditch; (B) Geology, topography and piezometric level; and (C) Average saturated thickness in the aquifer.

from North to South, which affects the glacis by forming a valley where tertiary substratum surfaces.

Low-depth soils are developed on the glacis, with a high content of coarse elements, good drainage conditions, low water holding capacity (WHC = 60 mm), low salinity (Lecina et al., 2005) and classified as Calcixerollic Xerochrept according to the Soil Survey Staff (1992). Conversely, the soils of the valley are deeper soils developed on tertiary lutites with greater salinity, characterized by a higher WHC (182 mm; Lecina et al., 2005), and classified as Typic Xerofluvent (Soil Survey Staff, 1992).

Regarding the flood irrigation management of the study zone, García-Garizábal et al. (2011) quantified the benefits of the changes implemented by the Irrigation District based on assignment of irrigation allowances, on-demand flood irrigation system instead of rotation flood irrigation, and creation of water consumption accounts. The authors concluded that, between 2001 and the period 2005–2008, the changes implemented in the irrigation management resulted in a better use of water resources (a 26% increase in irrigation efficiency), with water consumption better adjusted to the water requirements of the crops. The response of nitrate contamination to the greater irrigation efficiency (percentage of irrigation water used by the crops) quantified in García-Garizábal et al. (2011) is the central objective of his investigation.

3. Methodology

3.1. Agronomic analysis

Annual surveys were conducted with each farmer to analyze the agronomic dynamics during the study years (2001 and period 2005–2008), including inquiries on the type of fertilizer, dates and rates applied (necessary data to analyze management and calculate the nitrogen applied).

The nitrogen fertilization necessities were estimated based on the average yields of the zone (GA, 2009b) and on the unit nitrogen extractions obtained from Orús and Sin (2006), except for the leguminous crops (alfalfa and pea), for which its capacity to fix atmospheric nitrogen was considered to be null (Table 1).

Based on the nitrogen fertilization necessities (NF) and nitrogen applied (NA), the nitrogen application index (NAI) was estimated as:

$$\mathrm{NAI}(\%) = \mathrm{NF}/\mathrm{AN} \cdot 100$$

3.2. Nitrogen balance

The nitrogen balance was developed for the basin for the five study years (2001 and period 2005–2008). To this end, concentrations were assigned to the different components of the water balance developed by García-Garizábal et al. (2011), except for evapotranspiration (assumed as pure water) and water stored in the soil (for its difficult quantification and extremely low contribution to the water balance). Other non- water related components of the nitrogen cycle were also considered, resulting in the following balance equation:

Table 1
Unit nitrogen extractions (Orús and Sin, 2006) and average yield in study area (GA, 2009b).

Crop	Extractions kg N/Mg yield	Yield Mg/ha
Corn	28.0	8.7
Winter wheat	25.6	4.3
Sunflower	50.0	1.6
Alfalfa	4.5	27.5
Ray grass	4.5	28.3
Leek	3.9	18.6

$$\text{Nitrogen Inputs(NI)} - \text{Nitrogen Outputs(NO)} - \text{Nitrogen Storage(NS)} = \text{Error}$$

$$(\mathrm{P} + \mathrm{I} + \mathrm{LSC} + \mathrm{Dep} + \mathrm{NA} + \mathrm{Fix}) - (\text{D-XIX-6} + \mathrm{E} + \mathrm{Vol} + \mathrm{Des}) - (\mathrm{Sa}) = \text{Error}$$

where the *inputs* of nitrogen through precipitation (P), irrigation (I), lateral subterranean contributions (LSC), atmospheric deposition (Dep), nitrogen applied by fertilization (NA), symbiotic fixation (Fix); minus the *outputs* of nitrogen through the ditch (D-XIX-6), crop extractions (E), volatilization (Vol) and denitrification (Des); minus the nitrogen *stored* in the aquifer (Sa); equals the *balance error*.

The only form of nitrogen analyzed in the components related to the water balance was nitrate, with the assumption that all nitrogen is found in this format - according to Causapé (2004), nitrate constitutes 98% of the total nitrogen in the study zone waters. The product of the volumes obtained in the water balance by its concentrations constituted the nitrogen masses associated with each water component.

The concentration of rain water was obtained from average values of the period 1988–2000 registered by the station of European Monitoring and Evaluation Program (EMEP, 2009) network in Logroño (Spain). Concentration of irrigation water was calculated by the average of three water samples collected from the Bardenas Canal.

Because of its greater variability, the concentration of the water of ditch D-XIX-6 at the exit of the hydrological basin was measured through daily samples collected by an automatic sampler (ISCO 3600) and analyzed in the laboratory (Autoanalyzer AA3).

Regarding the nitrogen present in the lateral subterranean contributions, the concentrations were obtained through monthly sampling of groundwater from a piezometer located on the Nothwest vertex of the basin, entry area of the subterranean flow (Fig. 1).

The nitrogen content of the aquifer in the initial and final stages of this study (necessary for the estimation of storage) was obtained as the average concentration of the aquifer through geostatistical techniques (Kriging) applied to the entire data of the piezometer network (Fig. 1).

Regarding the remaining nitrogen components in the water balance, the nitrogen originated from atmospheric deposition was considered to be an annual rate of 10 kg N/ha year based on Sanz et al. (2002) in Mediterranean areas and the nitrogen applied by fertilization was obtained from the annual surveys conducted with the farmers in each plot.

For the nitrogen contributions through symbiotic fixation of leguminous plants (alfalfa and pea), it was assumed that these plants fixed from the atmosphere the necessary nitrogen for its development, estimated as its extractions. For the other crops, this contribution was calculated from unit extractions (Orús and Sin, 2006) and the annual yields informed by the farmers for each plot.

Quantification of the volatilized nitrogen followed recommendations of literature (Baker et al., 2001; Sanz-Cobena et al., 2008; Ventura et al., 2008), which estimated values equal to 10% of fertilizers applied in ammonia form based on their surveys.

Finally, the denitrification rate was considered to be null because of the good permeability aeration conditions and of the soils in the basin (Isla and González, 2006).

The difference between inputs, outputs and storage of nitrogen in the aquifer constitute the balance error. This error was quantified in a percentile form as the unbalance calculated in accordance to the equation:

$$\text{Unbalance}(\%) = [(\mathrm{NI} - \mathrm{NO} - \mathrm{NS})/(\mathrm{NI} + \mathrm{NO} + \mathrm{NS})] \cdot 200$$

In addition to the small errors associated with the water balance (García-Garizábal et al., 2011), errors in the estimations of each component of the nitrogen balance and the components not included in the balance need to be accounted for.

Therefore, the assumption that all nitrogen present in the water is under the nitrate format, the assumption of an annual stationary regime in the nitrogen content of the soil, and the uncertainty associated with the information obtained from the farmers are some of the error sources for which unbalances lower than 10% are considered acceptable in this type of study.

3.3. Nitrate contamination produced by irrigation

Although the current environmental legislation is established based on final nitrate concentration in the waters, the nitrate contamination produced by irrigation was evaluated from the exported mass of nitrates in order to track specific contributions from irrigation, which increment the nitrate concentration of water systems that are supposed to be protected.

The mass of nitrates exported by the studied irrigation area ($N—NO_3^-$) was calculated as the difference between the mass exported from the ditch and the mass introduced by the lateral subterranean contributions that initially only circulated through the basin.

$$N—NO_3^- = \text{D-XIX-6} - \text{LSC}$$

The mass of nitrate exported by the irrigation area is conditioned by the fertilization necessities of the crops, hindering comparison of the agroenvironmental impact produced by different irrigation areas or different years of the same irrigated area. However, the nitrate contamination index (NCI) proposed by Causapé (2009) allows for such comparisons, differentiating the crop patterns with respect to other variables such as climate or agronomic management (irrigation and fertilization). This index allows for the analysis of the impact of agrarian activity and fertilization practice through the relationship between the nitrate exported via drainage and the nitrogen fertilization necessities of the area.

$$\text{NCI} = N—NO_3^-/\text{NF}$$

4. Results and discussion

4.1. Agronomic analysis

In the study basin, maize was the crop with highest fertilization necessities (243 kg N/ha year), followed by pasture herbs such as ray-grass and fescue (128 kg N/ha year) and winter cereals such as wheat or barley (111 kg N/ha year). The lowest nitrogen necessities were associated with sunflower and leek, which required between 78 and 73 kg N/ha year.

According to the surveys, nitrogen fertilization practices did not significantly vary during the study years. The highest fertilization rates were applied to maize (420 kg N/ha; VC = 17%), with pre-sowing accounting for 20% of the applied nitrogen in the form of solid complex fertilizers containing between 8% and 19% nitrogen. Subsequently, two emergence applications occurred: the first in June with urea (46% of N), which accounted for 65% of the total applied nitrogen, and the second in July–August with liquid fertilizer N-32 distributed in irrigation water, which accounted for the last 15% of the total applied nitrogen.

Significantly lower rates were applied to winter cereal (162 kg N/ha average; VC = 40), in an individual emergence application (83% of the total applied nitrogen) in the form of urea (46% of N) and in smaller quantity as ammonium nitrate (33% of N).

Surprisingly, despite the fact that alfalfa is a leguminous plant and thus does not have nitrogen fertilization necessities, it received average rates of 61 kg N/ha (VC = 91%) in the form of several low-content nitrogen complex fertilizers throughout spring.

Other crops such as sunflower, herbs, leek and pea, can be grouped due to their minor presence in the basin, with 68% of the nitrogen applied through nitrogen fertilization being in the form of urea, 21% as complex fertilizers, 6% as N-32 and 3% as ammonium nitrate.

During the five study years and for all crops, the applied fertilizer was superior to the necessities of the crops (Fig. 2). The year of 2001, with a greater surface of maize, was the year with highest fertilization necessities of the basin (113 kg N/ha) and highest rate of applied nitrogen (187 kg N/ha), of which 85% corresponded to maize fertilization.

The drought in 2005 influenced the distribution of crops, with more winter cereal being planted at the expense of maize and 8% of land becoming fallow land. This led to a decrease of 41% in the fertilization necessities (68 kg N/ha) and consequently in the application of nitrogen (122 kg N/ha). The climatic normalization in the period between 2006 and 2008 resulted in a slight increment of fertilization necessities (approximately 78 kg N/ha) although the surface dedicated to maize continued to decrease along with alfalfa. The surface dedicated to winter cereal increased and became the crop with highest applications, constituting 57% of the nitrogen applied to the basin in 2008.

Alfalfa, despite being a leguminous plant, was fertilized with considerable rates that oscillated between 27% of nitrogen applied

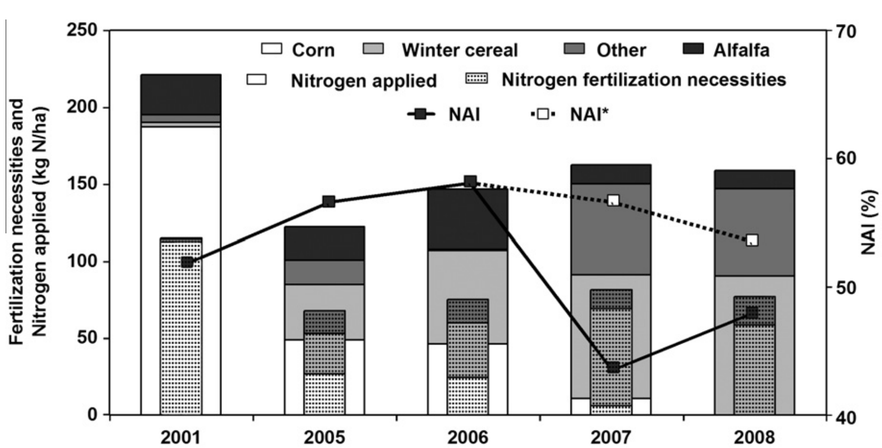

Fig. 2. Nitrogen fertilization necessities (dotted blocks) and nitrogen applied by farmers (solid blocks) in the hydrological basin drained by D-XIX-6 ditch during 2001 and the period 2005–2008. Nitrogen application index considering all agricultural plots (NAI) and disregarding two agricultural plots with high fertilization rates (NAI*).

in 2006 and 7% in 2008. This contributed to a low average nitrogen application index in the basin (52%) that was considerably less than those of main crops (winter cereal and maize). Among crops, winter cereal presented a nitrogen application index of 77%, which indicated a better fertilization than maize (NAI = 60%), where excessively high rates were applied.

The drought of 2005 and its effect in 2006 with low initial water reserves for the farmers, influenced the maximum nitrogen application index for 2006 (57%), while 2007 (NAI = 45%) and 2008 (NAI = 48%) presented the lowest indices. The years of 2007 and 2008 were affected by the abnormally high rates applied to an herb plot (960 kg N/ha) and a leek plot (475 kg N/ha). Without these two plots, the lowest nitrogen application index was presented in 2001 (52%), precisely the year with lowest irrigation efficiency.

Other flood irrigations areas with similar crops (Causapé et al., 2004b; Isidoro et al., 2006) presented nitrogen application indices of the same order (47–55%) compared to those obtained in the agrarian basin of ditch D-XIX-6 (52%). However, pressurized irrigated areas where fertigation is practiced (which allows for lower and more fractioned rates) presented nitrogen application indices of up to 80% (Cavero et al., 2003; Causapé et al., 2004b).

Therefore, despite the changes in irrigation management and oscillations in the prices of fertilizers and agrarian products (INE, 2009), the nitrogen fertilization practices in the study basin did not significantly vary in the study years. The main reasons are the excessive rates applied to maize (70% superior to the necessities) and the application of 61 kg N/ha year to alfalfa when the recommendations of the Government of Aragón in its agrarian practice code (BOA, 1997) are of 30 kg N/ha exclusively during the implementation year.

4.2. Nitrogen balance

Nitrogen fertilization is the component with the greatest amount of nitrogen applied to the basin in the five study years (Table 2). Surprisingly, in 2001, when the highest rates of nitrogenous fertilizer were applied (221 kg N/ha), the lowest percent contribution with respect to the inputs was recorded (54%; 2005–2008: 78% of inputs). This low contribution is due to the high lateral subterranean contributions (34% of inputs; 2005–2008: 5% of inputs).

Table 2
Nitrogen Inputs [NI: Precipitation (P), Irrigation (I), Lateral subterranean contributions (LSC), nitrogen applied by fertilization (NA), atmospheric deposition (Dep), symbiotic fixation (Fix)], Nitrogen Outputs [NO: drainage ditch D-XIX-6 (D-XIX-6), crop extractions (E), volatilization (Vol)] and Nitrogen Storage [NS: storage in aquifer (Sa)] of nitrogen in hydrological basin drained by D-XIX-6 ditch in 2001 and during the period 2005–2008.

	2001	...	2005	2006	2007	2008
	kg N/ha year					
Inputs						
P	3	...	1	3	2	2
I	5	...	3	3	2	3
LSC	139	...	10	15	8	6
NA	221	...	121	146	162	159
Dep	10	...	10	10	10	10
Fix	30	...	16	21	14	13
Outputs						
D-XIX-6	240	...	59	59	67	56
E	151	...	87	117	102	91
Vol	14	...	8	12	13	14
NS: Sa	−3	...	−3	4	2	−3
NI-Σ inputs	408	...	160	197	199	192
NO-Σ outputs	406	...	154	188	183	161
NS-storage	−3	...	−3	4	2	−3
Error (NI–NO–NS)	6	...	9	5	14	34
Unbalance (%)	1	...	6	3	7	19

During the period 2005–2008, nitrogen fertilization (147 kg N/ha year) was the greatest contributor of nitrogen to the basin (79%), in part associated with a sensible decrease in the lateral subterranean contributions.

The remaining input components were very minor, including highlights such as the 8% due to symbiotic fixation of alfalfa, the 4% from dry deposition in atmospheric nitrogen, and only 1% from irrigation and rain water (annual variations equivalent to the volume of its water contributions).

Regarding the outputs, the nitrogen exported through the ditch was the component with highest contribution in 2001 (59% of outputs), exporting 240 kg N/ha, although 58% of this nitrogen was introduced by lateral subterranean contributions and at first simply circulated through the basin.

From 2005 forward, the mass of nitrogen exported via drainage was reduced to one fourth (between 56 kg N/ha year in 2008 and 67 kg N/ha year in 2007) and the extractions of crops started to be the main output component (average 58%). Losses dues to volatilization were the least important component, accounting for only 6% of outputs (between 8 and 14 kg N/ha year).

Finally, the variation of nitrogen in the aquifer during one hydrological year accounted for only approximately 2% of the nitrogen intervening in the annual balances, considering storage and evacuations in accordance to the hydrological characteristics of the study years.

From the final result of the annual balances, it can be deduced that the nitrogen intervening in the 2001 balance was more than double the amount that intervened in the years 2005–2008. Moreover, with the exception of 2008, the inputs of nitrogen in the balance adjusted to the outputs, resulting in unbalances lower than 10%.

In 2008, the harvest of winter cereal (majority crop) was 20% inferior than what was expected. Therefore, part of the nitrogen applied via fertilization and not used by the crop could have accumulated in the soil, incrementing the error associated with this study year.

With respect to the balances calculated, it is noted that all years were positive, which could be associated with an overestimation of inputs or underestimation of outputs.

In this sense, symbiotic fixation of alfalfa could have been overestimated as alfalfa would not fix nitrogen until after what was applied via fertilization was consumed (Orús and Sin, 2006). Positive unbalances could also have been caused by not considering other forms of nitrogen beyond nitrate.

Nevertheless, the unbalances calculated were considered sufficiently significantly acceptable for the demands of this type of work, providing reliability to the quantification of each balance component that allows for a consistent analysis of the dynamics of nitrate contamination produced by the studied irrigation area.

4.3. Nitrate contamination produced by irrigation

The mass of nitrates exported from the basin in the period 2005–2008 (51 kg N—NO_3^-/ha year) was half of that of 2001 (101 kg N—NO_3^-/ha year). This reduction was mediated by a 34% reduction in fertilization necessities and 30% increase in irrigation efficiency (IE; García-Garizábal et al., 2011; Table 3), which not only decreased the nitrate content in the soil but also the drainage flows promoting leaching.

The decrease in fertilization necessities did not prevent evapo-concentrating effects from occurring as a result of an increase in irrigation efficiency. For example, the year of 2001 experienced the highest fertilization necessities (115 kg N/ha year), lowest irrigation efficiency (56%) and lowest nitrate concentration (82 mg/l),

Table 3
Irrigation efficiency (IE), drainage from hydrological basin (D), mass of nitrates exported with drainage (N–NO3–), concentration of drainage (N–NO3–/D), nitrogen fertilization necessities (NF) and nitrate contamination index (NCI) in the hydrological basin drained by D-XIX-6 ditch in 2001 and during the period 2005–2008.

Year	[a]IE %	[a]D mm	$N-NO_3^-$ kg $N-NO_3^-$/ha year	$N-NO_3^-/D$ $mgNO_3^-/1$	NF kg N/ha	NCI –
2001	56	544	101	82	115	0.88
⋮	⋮	⋮	⋮	⋮		⋮
2005	89	89	49	244	68	0.72
2006	84	85	44	229	75	0.59
2007	82	178	59	147	82	0.72
2008	78	160	50	138	77	0.65

[a] García-Garizábal et al. (2011).

while the period 2005–2008 had lower fertilization necessities (75 kg N/ha year), greater irrigation efficiency (83%), but presented double the concentration (176 mg/l average).

The variability in the annual masses exported for the period 2005–2008 (VC = 13%) was much inferior to the combined studied years (VC = 38%), due to the homogeneity in irrigation efficiency in the last four years. Nevertheless, it must be noted that 2007 and 2008 drained double the water of 2005 and 2006, which caused an increment in the exported mass and a more diluted drainage (Table 3).

Since 2005, a continuous drop has been detected in nitrate concentration, which can indicate the progressive leaching of the residual nitrate of previous years when the nitrogen contributions via fertilization was superior.

The masses exported from the 2001 study year (101 kg $N-NO_3^-$/ha year) were comparable to those exported in other irrigated areas with irrigation efficiencies around 50% (Causapé et al., 2004b; Isidoro et al., 2006), while during the period 2005–2008 the exported masses decreased to levels quantified in other irrigated areas with irrigation efficiencies over 70% (Cavero et al., 2003; Bustos et al., 2006). In these last referenced irrigated areas, the fertilization necessities were two or three times superior to those of this study's basin.

The relationship between the exported mass and fertilization necessities resulted in the highest nitrate contamination index for 2001 (NCI = 0.88), which was reduced by an average 24% (NCI = 0.67) during the period 2005–2008.

Analysis of the annual rolling average (Fig. 3) detected an abrupt drop in the fertilization necessities and mass of nitrates exported starting from 2001. The drop in fertilization necessities was much more gradual starting from 2005, while the mass of nitrates exported started to stabilize a year later (2006), emphasizing the time gap between the nitrogen applied through fertilization and its export through drainage.

It is remarkable that the difference between the fertilization necessities and exported nitrate progressively grows over the years (from 14 kg N/ha year in 2001 to 23 kg N/ha year at the end of the study period). Specifically, there was a continuous decrease in the nitrate contamination index until 2006 followed by a levelling off from there on, when the dynamics of the rolling averages seems to indicate a stability situation within the new irrigation conditions.

The decrease in the nitrate contamination index is directly related to the changes in irrigation management implemented by the Irrigation District, which has resulted in an increase in irrigation efficiency and therefore lower soil drainage and decrease in nitrate leaching (Spalding et al., 2001; Gehl et al., 2005; Li et al., 2007).

The values of the nitrate contamination indices in the study zone are close to those found in agrarian systems with an elevated use of irrigation water (IE = 73–90%). However, these agrarian systems presented NCI of approximately 0.25, values that were not reached by the study zone. This indicates that irrigation management has been improved but it is still necessary to adequate nitrogen fertilization management.

While modern well-managed irrigated areas can make the best use of the nitrogen applied (85%), in this agrarian basin, only 55% was utilized in 2001 and 65% on average during 2005–2008, with a maximum of 70% in 2006.

In summary, the changes in irrigation management implemented in the study basin have incremented the use of the nitrogen applied with fertilization by 10%, decreasing the mass of nitrates exported by half. Nevertheless, the exported masses are still extremely high for the fertilization necessities of the irrigated area, as indicated by the nitrate contamination index being double of that registered in modern well-managed irrigated areas.

Given the already high irrigation efficiency and limited margin for improvement, it remains paramount to optimize nitrogen fertilization. Optimization could begin by suppressing nitrogenous fertilizers in alfalfa (except for the small applications during first stages of the crop), which still amounts to an important share of the basin and has the capacity to fix its required nitrogen from the atmosphere. Regarding the remaining majority crops, maize

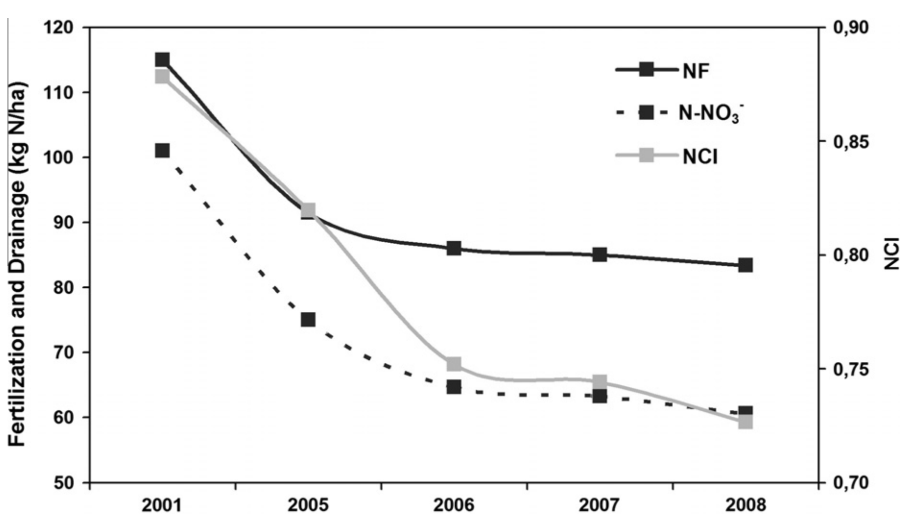

Fig. 3. Evolution of the annual rolling average of nitrogen fertilization necessities (NF), mass of nitrates exported with drainage ($N-NO_3^-$) and Nitrate Contamination Index (NCI) in the hydrological basin drained by D-XIX-6 ditch in 2001 and during the period 2005–2008.

(greatest fertilization necessities) presented the worst nitrogen application index. Its gradual disappearance from the crop pattern (substituted by winter cereal, with a higher nitrogen application index) has contributed to a progressive decrease in the nitrate contamination index.

In view of the highly probable return of maize to the crop pattern and the situation of the remaining crops, management of fertilization should be improved by applying nitrogen in accordance to the crop requirements (although not a simple task in such permeable soils with flood irrigation).

Given these challenges, several authors defend the utilization of slow-liberation fertilizers or nitrification inhibitors (Owens et al., 1999; Di and Cameron, 2005; Díez-Lopez et al., 2006). However, Isla and González (2006) carried out investigations in similar soils of the same Irrigation District and the use of the inhibitor 3,4-dimethylpyrazole phosphate (DMPP) did not significantly reduce the nitrate leaching and, therefore, this type of solutions should be appropriately contrasted first. Isla and González (2006) concluded their study by recommending that applications of fertilizer should be fractioned and total rates applied should be reduced. Investigation studies advise that in order to adjust application rates, the nitrogen present in the soil must be determined at the moment of sowing to control the nitrogen in the plant, which will indicate the necessity for further applications (Scharf et al., 2006; Hawkins et al., 2007; Isla and Blackmer, 2007).

Experiments in plot-lysimeters have demonstrated that the fractioning of fertilizer application reduces nitrogen leaching (Gehl et al., 2005; Quemada, 2005). However, nitrogen fertilization fractioning is not a simple task to carry out in flood irrigation systems, as access with machinery is impossible once the phenological state of the crop is advanced and application of fertilizer with irrigation water on permeable soils is subject to efficiency and uniformity of irrigation.

Nevertheless, the transformation of the study zone into pressurized irrigation is still in the planning stages. Such transformation will permit fertigation, which allows for a greater control in the distribution and adjustment of the fertilizer rates.

5. Conclusions

The changes in irrigation management implemented by the Irrigation District have not been accompanied by significant changes in nitrogen fertilization management for the crops.

Although changes in crop pattern reduced by 33% the nitrogen contribution from fertilization, the rates applied were still double the necessities. Maize went as far as receiving 70% more nitrogen than its requirements, while alfalfa received an average of 61 kg N/ha year, when an application of 30 kg N/ha is only recommended in its initial sowing stage.

Introduction of winter cereal (the crop with highest nitrogen application indices) at the expense of corn and alfalfa resulted in a reduction of the mass of nitrates exported from the agrarian basin of ditch D-XIX-6 during the period 2005–2008 by half of that exported in 2001 (101 kg $N—NO_3^-$/ha year).

The changes in irrigation management translated into an increase in irrigation efficiency with a correspondent decrease in leaching in such a way that the nitrate contamination index decreased by 24% in the period 2005–2008 compared to 2001.

Despite these contamination reductions brought about by improvements in irrigation management, the nitrate contamination indices are still approximately double of those found in other modern well-managed irrigation systems, demonstrating that it is still possible and necessary to improve nitrogen fertilization management,

Therefore, although the changes in irrigation management introduced by the Irrigation District have been effective, a greater effort is required to match nitrogen fertilization to the actual requirements of the crops, especially as the current levels of nitrogen application reaches 65% and lead to extremely high exports of nitrate masses.

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