# Nitrate loss from a tile-drained reclaimed marsh soil from SW Spain amended with different products

María Dolores Hurtado, Luis Andreu, José María Abril, Antonio Delgado

**Abstract** Tile drainage and soil amendments have been found to affect losses of nitrate N from agricultural soils. This work was aimed at measuring nitrate N losses in a tile-drained marsh soil from SW Spain under traditional fertilization and irrigation practices, and how these losses were influenced by the application of soil amendments. To this end, a randomised block experiment with three replications was performed during two consecutive growing seasons—2003 to 2004 with cotton and sugar beet, respectively—involving four different amendment treatments: (1) control without amendment, (2) phosphogypsum (PG), (3) manure, and (4) sugar factory refuse lime (SFRL). Flow-weighted (FW) nitrate–N concentrations in drainage water, estimated as the slope of the regression of the instantaneous nitrate–N flow as a function of drain flow rate, was decreased by PG in some drainage events in the 2003 season and in the four last events of the 2004 season when compared with control without amendment. The increased FW nitrate–N concentrations in drainage from SFRL in comparison to control in a drainage event of 2003 season, and in the four last events of 2004, can be explained by the contribution of N present in the amendment. These effects did not account for significant differences in nitrate–N loss among treatments over the whole season in 2003, when they ranged from 19.3 to 24.9 kg N $ha^{-1}$, accounting for 6–8% of applied N, nor in 2004, when they ranged from 4 to 6 kg N $ha^{-1}$, accounting for 3–4% of applied N. The decrease in mean FW nitrate–N concentration after the third drainage event in 2003 was not the consequence of the depletion of total soil nitrate–N because soil mineral N was increased on average by 205 kg N $ha^{-1}$ during the season. The high N extractions by sugar beet and the subsequent decrease in total soil nitrate–N can contribute to explain the decrease of mean FW nitrate–N concentrations along the 2004 season. Greater absolute nitrate–N loss in 2003 than in 2004 was explained by the lower efficiency of the furrow irrigation when compared with sprinkler irrigation. Results also revealed that traditional management of N fertilizer was inadequate: rates applied to cotton were excessive, increasing the risk of N losses not only during the cotton season, but also at the beginning of the following season.

**Keywords** Drainage · Furrow · Sprinkler · Nitrate · Phosphogypsum · Manure

María Dolores Hurtado died in February 2010. The present work was a part of her unfinished Ph. D. Thesis. Her colleagues and friends wish to dedicate this article to her memory.

M. D. Hurtado · L. Andreu · A. Delgado (✉)
Department of Ciencias Agroforestales, Universidad de Sevilla, ETSIA, Ctra Utrera Km 1, 41013 Seville, Spain
e-mail: adelgado@us.es

J. M. Abril
Department of Física Aplicada I, Universidad de Sevilla, ETSIA, Ctra Utrera Km 1, 41013 Seville, Spain

**Abbreviations**

| | |
|---|---|
| PG | Phosphogypsum |
| SFRL | Sugar factory refuse lime |

## Introduction

Although nitrogen is essential for crop production, intensive agriculture management has led to nitrogen concentrations in surface and subsurface waters above water quality guidelines (Ng et al. 2000; Dinnes et al. 2002; Nangia et al. 2008, 2009), even under semiarid conditions (Hadas et al. 1999; Keller et al. 2008) as in Southern Spain (Moreno et al. 1996; Lentini et al. 2009). In fact, agriculture is the primary source of N pollution in European aquatic environments (Lassaletta et al. 2009). Nitrogen fertilization promoting high amounts of N accumulated in the soil (high rates or fertilization non-distributed during the crop season) contributes to N losses (Jaynes et al. 2001; Wang et al. 2010). Besides fertilizer management, other agricultural practices, such as amendments (Chang and Entz 1996; Diez et al. 1997), tillage (Ng et al. 2000), water management (Diez et al. 1997; Hack-ten Broeke 2001), and drainage (Randall et al. 1997; Huggins et al. 2001; Drury et al. 2009), may influence nitrogen loss from agricultural soils.

Tile drainage is a common water management practice in agricultural areas with poorly drained soils or/and high water tables (Randall et al. 1997; Kladivko et al. 2004). Also, an artificial drainage system is usually required to convert marshes to arable land (Hodgkinson and Thorburn 1995; Peck and Hatton 2003), not only to avoid flooding, but also to ensure that the highly saline water table does not encroach into the root zone (Moreno et al. 1995, 2001). Despite their agronomic benefits, tile drains have been found to increase losses of nitrate N through the enhancement of leaching of the soil profile (Gilliam et al. 1999; de Vos et al. 2000; Kladivko et al. 2004). Nitrate-contaminated drainage waters from artificial drainage systems have been found to be a primary source of nitrate loadings to surface waters within the Midwest US (David et al. 1997; Randall et al. 1997; Dinnes et al. 2002; Goswami et al. 2009). Even more, in cracking soils, such as those in the marsh soils from southwest Spain, cracks connect the upper nutrient-rich horizon with drain lines, shortcutting any buffer effect of subsurface horizons and enhancing nutrient losses (Delgado et al. 2006). An appropriate balance between increasing drainage intensity to improve soil conditions, and the decrease of its intensity to reduce N losses, is one of the most relevant aspects regarding the control of these losses in artificially drained soils (Kladivko et al. 1999, 2004; Nangia et al. 2009).

Nitrogen loss through tile drainage has been poorly described in reclaimed marsh soils from Southwest Spain (Guadalquivir Valley). In the area, an intensive production of cotton, sugar beet, corn, and horticultural crops (tomato, broccoli, and pepper) is done, usually involving high N rates (>300 kg N $ha^{-1}$). These soils represent a particular case of tile drained soils, because they are irrigated, and the main function of tile drains is to avoid the rising of the saline water table. Thus, drainage intensity can be affected not only by the design of the drainage system, but also by the irrigation water management (Delgado et al. 2006; Hurtado et al. 2011).

Besides drainage, other relevant factor in the management of reclaimed marsh soils is Ca-amendments, such as phosphogypsum (PG) and sugar factory refuse lime (SFRL), to reduce sodicity (Domínguez et al. 2001; Abril et al. 2008; Hurtado et al. 2011). These amendments contribute to enhance soil aggregation thus affecting solute and water transport in soil (Jarvis et al. 2007). The application of these products has been progressively replaced by manure as the sodicity of the soils decreased. Organic amendments can also affect nitrogen losses, not only by their effects on aggregation, but also by their nitrogen content (Chang and Entz 1996; Bakhsh et al. 2005), particularly under non-efficient irrigation (Diez et al. 1997).

The main objective of this work was to measure nitrate–N losses in an irrigated tile-drained marsh soil from southwest Spain under usual irrigation and fertilizer management in the area, and to study how these losses are influenced by the application of usual soil amendments in the area, such as PG, manure, and SFRL. Results will be also useful in the evaluation of the traditional fertilization and irrigation practices with a view of decreasing N loss from soil.

## Materials and methods

### Location

The experiment was conducted from April 2003 to September 2004 on a commercial farm, located in the

"Marismas de Lebrija", in the reclaimed marsh soils of the estuarine region of the Guadalquivir river, Sothwest Spain (37°01′N, 6°7′W). This area was reclaimed at the end of the 1970s by constructing artificial drainage with tile drains spaced 10 m apart at 1 m depth approx., leaching, and applying phosphogypsum (PG), a by-product of the P-fertilizer industry at usual rates of 25 Mg $ha^{-1}$ each 2–3 years to reduce Na saturation (Delgado et al. 2002, 2006). After reclamation, these marsh soils can be classified as Aeric Endoaquepts (Soil Survey Staff 2010). More detailed information about the area, soils, reclamation practices, and agricultural use can be found elsewhere (Moreno et al. 1981, 1995; Domínguez et al. 2001; Laudicina et al. 2009). Soil properties were homogeneous in the experimental site (Delgado et al. 2006), drainage flow has the same pattern in all the plots, and drainage water composition did not show significant differences between plots in the experimental site (Hurtado et al. 2011). The effect of the different irrigation systems on drainage flows has been described elsewhere (Hurtado et al. 2011). Abril et al. (2008) estimated, based on PG-associated $^{226}Ra$ enrichment, that the soil has received six phosphogypsum applications at a rate of 25 Mg $ha^{-1}$ since its reclamation started.

The mean temperature ranges from 10.0°C in January to 25.5°C in August. The annual total rainfall was 694 and 407 for years 2003 and 2004, with corresponding potential evapotranspiration of 1,423 and 1,444 mm.

## Experimental design

A randomised block design with three replications, each one corresponding to 250 m × 20 m plots, was performed during two consecutive growing seasons, 2003–2004, with four different amendment treatments: (1) control without amendment application, (2) phosphogypsum (PG) generated in a phosphate-industry in Huelva (SW Spain), (3) manure obtained from a commercial dairy farm, and (4) sugar factory refuse lime (SFRL), a Ca-rich by-product essentially composed of $CaCO_3$ also used in acid soils. Amendments were applied at the beginning of the first growing season (in April 2003) at 25 Mg $ha^{-1}$ after sun dried, and following current practices in this area: spreading them over a previously tilled soil, with additional deep tillage after their application, what provoked dilution of the amendment in a soil horizon down to 40 cm depth. Treatments were intended to evaluate the usual practice in the area, where in a typical crop rotation cotton-sugar beet there is more time to apply and to improve soil properties before cotton sowing in spring than before sugar beet.

The drain system consisted of ceramic drainage pipe-lines spaced 5 m apart that were placed at a depth of ca. 1 m. Tile drains were originally spaced 10 m when the reclamation of the area started. However, drain spacing was reduced in the nineties to increase drainage intensity. Each plot was longitudinally crossed by three pipe-lines. The two longest sides of the plots (East and West sides) corresponded to drainage lines that were not included in the study to prevent cross-contamination among different plots. The drainage flow was monitored in 2 of the 3 central tile-drains of each plot which were connected by a pipe. This drainage system controls the water table level, which remains at a depth of approximately 0.9 m. The electrical conductivity of the water table is >80 dS $m^{-1}$ (Moreno et al. 1995; Hurtado et al. 2011).

The South side of all plots was adjacent to a small channel that removed the drainage water to the Guadalquivir River. Drain lines had a 0.15% slope towards the channel in such a way that the long axis of the plot ran slopewise. Also, the surface of the plots had a 0.1% slope towards the channel in order to facilitate furrow irrigation and to avoid flooding in rainy years, without allowing surface runoff in normal years. The North side of the plots corresponded to the boundary with another commercial farm. In order to minimize the potential influence of such a farm on the experimental plot, a 5 m non-cropped border was inserted. On the other farm, the surface and tile-drain slope were towards another drainage channel running in the opposite direction. Crop management had to be adapted to commercial use of the farm, so that dose and frequency of irrigation, fertilizer rate and other practices was common in the area for these crops. In the 2003 season, cotton (*Gossypium hirsutum* L.) was grown under sprinkler the first irrigation, at 10 mm $h^{-1}$, and after, under furrow irrigation with furrows parallel to the longest side of each plot at a rate of 7.5 mm $h^{-1}$. Due to limitations in the availability of irrigation water under the furrow system, only one-third of the experimental site was irrigated at the same time; thus, irrigation was organized in three shifts.

Cotton was sown in April (11th) after amendment application and harvested in October—a typical cycle in Mediterranean region. During this growing season, total rainfall accounted for 76 mm, and irrigation applied for 1,096 mm. Fertilizer applications were done following usual recommendations in the area: 52 kg N $ha^{-1}$, 68 kg P $ha^{-1}$, and 43 kg K $ha^{-1}$ were applied at pre-plant as a mixture of $(NH_4)H_2PO_4$, urea, and $KNO_3$, and 268 kg N $ha^{-1}$ at sidedress as $NH_4NO_3$ in two applications (31st May and 28th July). In the 2004 season, sugar beet (*Beta vulgaris* L.) was grown under sprinkler irrigation at 5 mm $h^{-1}$ from January (sown 13th) to the end of June 2004, which is a typical cycle in South Spain. The total rainfall in this season was 491 mm and irrigation 399 mm. Pre-plant fertilizer rates for sugar beet were 41 kg N $ha^{-1}$, 54 kg P $ha^{-1}$, and 34 kg K $ha^{-1}$; besides this, 100 kg N $ha^{-1}$ at sidedress (18th February) as $NH_4NO_3$ were applied. Cotton residues were burnt and sugar beet residues removed; thus non-significant release or immobilization of N due to residue incorporation to soil could be expected.

## Soil, amendment, and plant analysis

Soil in the experimental site was sampled taking twelve soil cores at three different depths (from 0 to 30, 30 to 60 and 60 to 90 cm) from each plot. All the cores from each plot and same depth were mixed to make a single sample per plot and depth. Samples were taken before amendment and fertilizer application in the first growing season in January 2003, after the first growing season in November 2003, and after the second growing season in September 2004. Soil samples were air dried and ground to pass a 2 mm screen. With the samples taken at the beginning of the first growing season, a complete soil characterization was done, involving: particle size analyses by using the hydrometer method (Gee and Bauder 1986), organic carbon by dichromate oxidation (Walkley and Black 1934), total N by the Kjeldahl method in the surface horizon, pH in 1:5 soil:water extracts, nitrate- and ammonium–N after extraction with 2 M KCl according to Mulvaney (1996), and P availability index according to the Olsen method (Olsen et al. 1954). In the soil saturation extract obtained using the method of Rhoades (1996), electrical conductivity (EC), and Na, Ca and Mg concentrations were determined to calculate the Na adsorption ratio (SAR); Na was determined by flame photometry and Ca and Mg by atomic absorption spectroscopy after filtering through a 0.22 μm membrane filter. With samples taken after the first and the second growing season, only nitrate- and ammonium-N was determined as described above.

Organic matter in amendments was determined by loss weight after combustion, total N by the Kjeldahl method, total P, S, Ca, Mg, K, and Na by emission spectroscopy coupled with inductively coupled plasma (ICP-OES) after nitric acid digestion in microwave, and pH and electrical conductivity in a 1:5 amendment:water ratio.

At the end o each growing season, biomass production (aboveground in the case of cotton) and N concentration of plants were determined. Biomass production of cotton was evaluated by harvesting 30 $m^2$ of crop in each plot. After this, from collected plants, 5 plants of cotton were randomised sampled and divided in stems, leaves and fruits/seeds. Plant material was dried in a forced-air oven at 65°C until constant weight and mill to pass a 1-mm screen. After that, total N in samples was determined by the salicilate modified Kjeldahl method to include nitrates. Sugar beet production was evaluated by harvesting 20 $m^2$ (two subplots of 10 $m^2$) from each plot. Plants were divided in leaves and roots. A representative sample of leaves and roots was taken and processed for N analysis as described above.

## Drainage monitoring and water analysis

Rainfall and sprinkler irrigation were recorded with pluviometers; furrow irrigation was measured by flow meters installed in the furrow heads. Drain flow was monitored by manually measuring the discharge in all pairs of drains studied continuously from the beginning to the end of each irrigation and rainfall event; drain flow rates were measured through the time required to fill up a known volume. With these data, the drainage hydrograph for each rain/irrigation event was constructed. The total drainage during the season was estimated by integrating the drainage hydrographs during the crop season. Regular sampling of drainage water was done manually in each rain or irrigation event during the growing season. At least five samples per event and plot were taken. After sampling, drainage water was stored at 4°C before analysis.

Nitrate–N in drainage water samples was determined by the ultraviolet absorbance at 220 nm corrected by the absorbance at 275 to avoid organic matter interferences (APHA et al. 1985). In all the cases, the low organic matter of water allowed to apply this method. Ammonium- and nitrite-N was negligible in drainage water in comparison with nitrate–N concentrations. Instantaneous nitrate–N flow from soil was determined by multiplying the measured nitrate–N concentration and its corresponding measured drain flow rate at the time of sampling. The nitrate–N loss during the time interval $\Delta t$ between two consecutive samplings was calculated as:

$$[\text{Nitrate-N loss}(t) + \text{Nitrate-N loss}(t + \Delta t)]\Delta t/2$$

For each plot, the total nitrate–N loss during the season was calculated as the sum of losses during each time interval between samplings during the season.

### Statistical analysis

The analysis was intended to expose the effects of the amendment application on drainage and nitrogen losses, and nitrogen balance components. To this end, the General Linear Model procedure in Statgraphics Plus 5.1 (StatPoint 2000) was used. This software was also used for regressions analyses.

Nitrate–N concentration is expected to change during the experiment. Thus, in order to compare the effect of the different treatments on nitrate–N concentration, flow-weighted (FW) nitrate–N concentrations is usually estimated for each treatment as the nitrate–N load divided by the corresponding drainage volumes (Goswami et al. 2009). In this work, we have calculated the FW nitrate–N concentration as the slope of the linear regression of the instantaneous nitrate–N flow (NF, calculated for a time *t* as the product *nitrate–N* × *drain flow rate* at this time) as a function of drain flow rate, including the data of the three replicates of each treatment for each irrigation event. This provided a representative nitrate–N concentration of each treatment and irrigation event. Figure 1 represents regressions for two drainage events after the first and the fifth furrow irrigation in control plots in the 2003—cotton—season. Interception points and slopes (FW nitrate–N concentrations) were compared using Statgraphics Plus 5.1 (StatPoint 2000). Slope comparison allows one to establish significant differences in FW nitrate–N concentration between treatments for each drainage event.

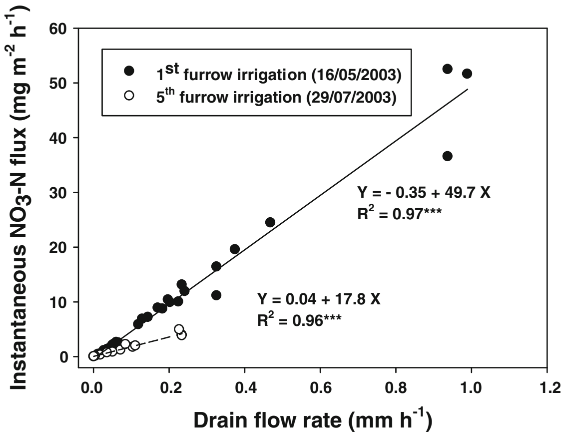


**Fig. 1** Relationship between instantaneous $NO_3$–N flux (calculated for a time *t* as the product *nitrate–N* × *drain flow rate* at this time) and drain flow rate for two drainage events after two irrigations in the 2003 (cotton) season. Regressions were calculated for all the data of each drainage event in control plots. ***Significant at $P < 0.001$

## Results and discussion

Properties of the soil were in the usual range described for soils of the area (Domínguez et al. 2001). Physico-chemical soil properties were fairly homogeneous between plots involved in the experiment (Table 1), with relative standard errors under 12% (except sand content). Electrical conductivity (EC) and Na adsorption ratio (SAR) in soil increased with depth (Table 1) due to reclamation practices, which reduced the salt content and Na saturation in the upper horizons. Also, the saline watertable can be a source of soluble salt for the deeper horizons, thus contributing to the gradient in EC and SAR observed. Amendments applied had very different properties. Phosphogypsum composition was essentially determined by its high content in gypsum, and SFRL by the high content in $CaCO_3$ (Table 2). The properties of manure revealed that it was a fairly mineralized product.

Drainage discharges from soils of the area have been described in previous works (Andreu et al. 1994; Moreno et al. 1995; Delgado et al. 2006), and more detailed in the experimental site by Hurtado et al. (2011), who demonstrated that drainage discharge was affected by irrigation methods, with higher drainage to

**Table 1** General soil properties

| Depth (cm) | Sand (g $kg^{-1}$) | Silt (g $kg^{-1}$) | Clay (g $kg^{-1}$) | OC (g $kg^{-1}$) | Total N (g $kg^{-1}$) | EC[a] (dS $m^{-1}$) | pH[b] | SAR[a] ($mmol_c^{1/2}$ $L^{-1/2}$) | Olsen P (mg $kg^{-1}$) | $NO_3$–N (mg $kg^{-1}$) | $NH_4$–N (mg $kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0–30 | 86 ± 33 | 373 ± 43 | 452 ± 22 | 8.2 ± 0.2 | 0.94 ± 0.02 | 1.7 ± 0.1 | 8.5 ± 0.02 | 2.4 ± 0.1 | 16 ± 1 | 17 ± 1.5 | 4.2 ± 0.1 |
| 30–60 | 95 ± 55 | 332 ± 31 | 574 ± 26 | | | 5.8 ± 0.1 | 8.3 ± 0.02 | 8.4 ± 0.5 | 9.0 ± 0.2 | 15 ± 0.4 | 4.2 ± 0.5 |
| 60–90 | 78 ± 7 | 341 ± 23 | 581 ± 16 | | | 12.5 ± 0.4 | 8.2 ± 0.02 | 18.9 ± 0.8 | 8.0 ± 0.3 | 14 ± 1 | 3.2 ± 0.3 |

Mean ± standard error for the 12 plots

*OC* organic carbon, *EC* electrical conductivity, *SAR* sodium adsorption ratio in the saturation extract

[a] Determined in the soil saturation extract

[b] Determined in the 1:5 soil extract

irrigation volume ratios for furrow than for sprinkler irrigation. In agreement with these evidences, in the present work, the drainage to irrigation + rain ratio was greater in the 2003 season than in the 2004 (Table 3). However, no significant effects of amendments on drainage volumes were observed within each growing season (Table 3). As it can be deducted from the slope of the cumulative drainage as a function of time (Fig. 2), the drainage to irrigation + rain ratio in each drainage event was higher at the beginning of both seasons than at the end, despite the lower water supply at the beginning. Different factors can contribute to explain this observation, such as lower crop evapotranspiration and the initial dryness of the soil and the consequent presence of cracks at the beginning of crop season (Hurtado et al. 2011).

Mean values of nitrate–N concentrations in samples ranged from 22 (PG) to 26 mg $L^{-1}$ (SFRL) in the 2003 season, and from 14 (PG) to 28 mg $L^{-1}$ (SFRL) in the 2004 season (Table 3). Nitrate–N concentrations tended to decrease along each growing season, such as it can be observed in Fig. 3 which shows data from two drainage events, one from an irrigation at the beginning of the season, and other from an irrigation at the end.

Nitrate–N concentration increased at increased drain flow rates at the beginning of both seasons (Fig. 3a shows an example for the 2003 season—cotton—, and Fig. 3b for 2004—sugar beet—); this was particularly evident at drain flow rates lower than 0.1 mm $h^{-1}$ in the 2003 season. These positive relationships can be the results of a rapid non-equilibrium water movement through macropores (root or earthworm channels, desiccation cracks) (Luxmoore et al. 1990; Stamm et al. 1998; Kladivko et al. 1999). Also, the relative capacity of the different sources of water contributing to drain discharge, such as irrigation or rain, soil water, and watertable discharge (particularly at peaks in drain discharge; de Vos et al. 2000; de Vos 2001) and their nitrate–N concentrations can explain different relationships between nitrate–N concentration in drainwater and drain flow rate (Evans and Davies 1998; Chanat et al. 2002; Rose 2003). At the end of both seasons, relationship between nitrate–N concentration and drain flow rate was less evident; in some cases this relationship was negative at the end of the 2003—cotton—season (Fig. 3). These changes in the relationship between nitrate–N concentration and drain

**Table 2** Properties of applied amendments

| Product | OM (g kg$^{-1}$) | Total N (g kg$^{-1}$) | P (g kg$^{-1}$) | S (g kg$^{-1}$) | K (g kg$^{-1}$) | Ca (g kg$^{-1}$) | Mg (g kg$^{-1}$) | Na (g kg$^{-1}$) | pH[a] | EC[a] (dS m$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Phosphogypsum | ND | ND | 3.5 | 150 | ND | 229 | ND | 0.3 | 2.9 | 2.6 |
| Manure | 300 | 10 | 3.1 | 23 | 18 | 100 | 10 | 5.8 | 6.6 | 8.3 |
| SFRL | 90 | 4 | 6.2 | 16 | 3 | 214 | 11 | 1.3 | 7.9 | 3.5 |

Data expressed over dry matter basis

*OM* organic matter, *SFRL* sugar factory refuse lime, *EC* electrical conductivity, *ND* not detectable

[a] Determined in the 1:5 extract

**Table 3** Effect of the different soil amendments on drainage, drainage to irrigation + rain ratio and components of the N balance in soil for each growing season

| Amendment | Drainage (mm) | Drain to irrigation + rain ratio (%) | $NO_3$–N concentration in water[a] (mg L$^{-1}$) | Change in soil $NO_3$–N (0–90 cm) (kg ha$^{-1}$) | Change in soil $NH_4$–N (0–90 cm) (kg ha$^{-1}$) | N crop exportation[b] (kg ha$^{-1}$) | $NO_3$–N lost by drainage (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Cotton (2003) | | | | | | | |
| Control | 80 ± 8 | 7 ± 1 | 26 ± 12 | 169 ± 19 | 18 ± 15 | 100 ± 22 | 24.9 ± 1.4 |
| Phosphogypsum | 93 ± 10 | 8 ± 1 | 22 ± 13 | 164 ± 79 | 1 ± 11 | 126 ± 41 | 20.3 ± 0.3 |
| Manure | 82 ± 8 | 7 ± 1 | 24 ± 12 | 223 ± 8 | 21 ± 5 | 103 ± 5 | 23.7 ± 2.5 |
| SFRL | 60 ± 9 | 5 ± 1 | 26 ± 12 | 216 ± 29 | 9 ± 9 | 61 ± 2 | 19.3 ± 1.5 |
| Sugar beet (2004) | | | | | | | |
| Control | 13 ± 2 | 1 ± 0.1 | 25 ± 23 | −209 ± 16 | −25 ± 12 | 345 ± 6 | 6.0 ± 0.9 |
| Phosphogypsum | 15 ± 1 | 2 ± 0.1 | 14 ± 18 | −239 ± 69 | −8 ± 12 | 327 ± 17 | 5.5 ± 1.1 |
| Manure | 15 ± 2 | 2 ± 0.1 | 20 ± 18 | −280 ± 8 | −24 ± 12 | 411 ± 38 | 4.0 ± 1 |
| SFRL | 13 ± 3 | 1 ± 0.1 | 28 ± 15 | −243 ± 25 | −11 ± 15 | 378 ± 23 | 5.1 ± 1.4 |

Mean ± standard error; non-significant differences between treatments were observed

According to Delgado et al. (2006), a bulk density of 1.25 kg L$^{-1}$ has been considered

[a] Mean ± standard deviation of all the observations during the season

*SFRL* sugar factory refuse lime

[b] N in aerial parts of cotton, and N in aerial parts and roots of sugar beet

flow during the season likely reveal changes in soil conditions affecting drainage, such as depletion of nitrate–N in the soil volume acting as source of nitrate–N for drainage water, closing of cracks, or a smaller contribution of the water table to drain discharge at peaks flow.

The evolution of the slope of the relationship between instantaneous N flow and drain flow rate, i.e. flow-weighted nitrate–N concentration (Table 4, 5), with time is determined by the change of nitrate–N concentration in drainage water and by the different relationship between this concentration and drain flow rate along the season. In the 2003 season, PG and manure showed significantly lower flow-weighted (FW) nitrate–N concentration than control in some events: two at the middle of the season in PG, and in the last event in PG and manure; on the contrary, SFRL showed a higher FW nitrate–N concentration than control in one event (Table 4). Differences could be explained at least partially by the effect of soil factors affecting water movement. According to Yu et al. (2003), PG improves soil aggregation even in non-sodic soils. This effect can promote an increased flow through macropores (Jarvis et al. 2007), which can contribute to an increased bypass of nitrate present in smaller pores, and thus to lower FW nitrate–N

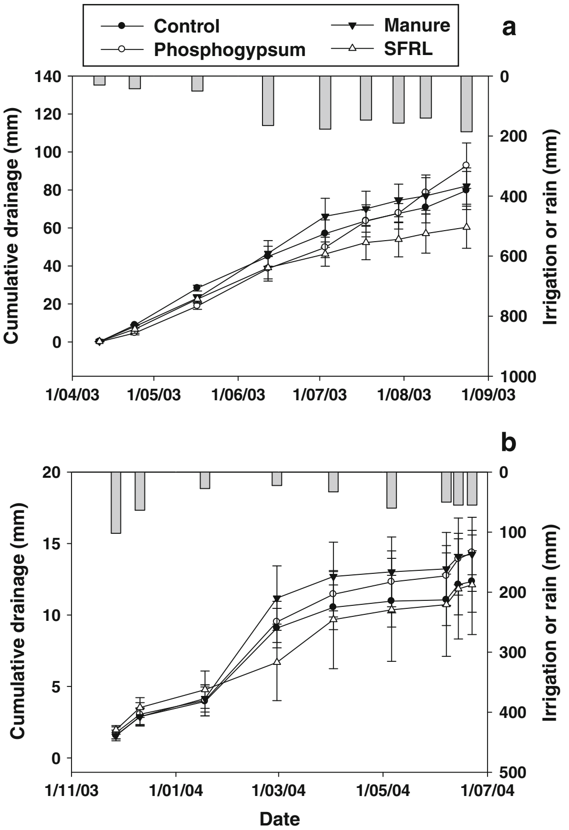


**Fig. 2** Irrigation + rain and cumulative drainage in each treatment; **a** for 2003 (cotton) season, and **b** for 2004 (sugar beet) season; *SFRL* sugar factory refuse lime. *Error bars* indicate one standard error

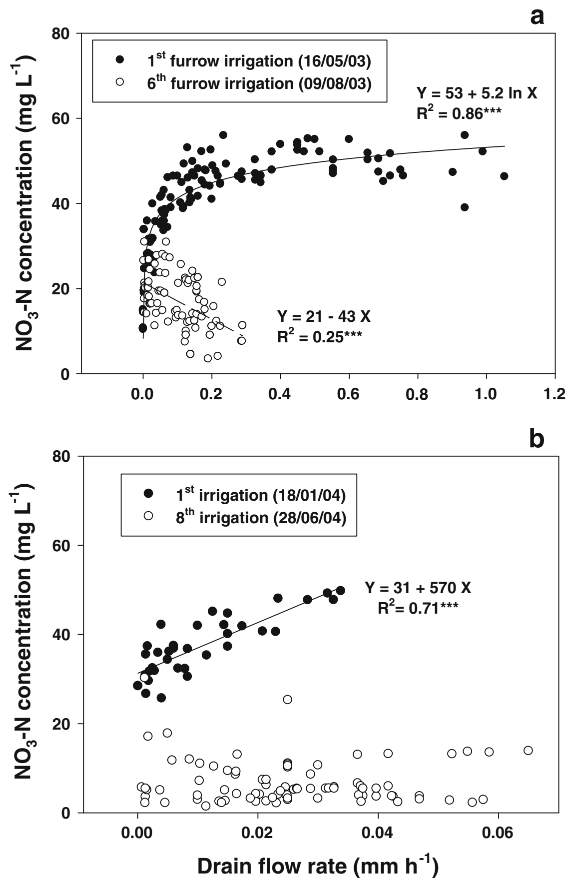


**Fig. 3** Relationship between nitrate–N concentration and drain flow rate in the drainage events after the second and sixth irrigation in the 2003 (cotton) growing season (**a**), and in drainage event after the first and the eight irrigation in the 2004 (sugar beet) season (**b**). ***Significant at $P < 0.001$

concentrations. However, these differences did not account for significant differences in total nitrate–N losses between treatments at the end of the season (Table 3). In general terms, considering mean for all the treatments in the 2003 season, maximum FW nitrate–N concentration was observed in the third event, before the two sidedress N fertilization, which accounted for 85% of the applied N (Fig. 4). The initial increase in FW nitrate–N concentrations was promoted at least partially by the dissolution of pre-plant N fertilizer. Crop extractions were much lower than applied N rate and a significant increase in soil nitrate–N was observed during the 2003—cotton—season (Table 3). Thus, the decrease in FW nitrate–N concentration after the third drainage event was not the consequence of the depletion of total soil nitrate because the amount of mineral N in soil increased during the season (Table 3). This reveals probably that nitrate–N leaching is restricted to part of the soil volume and that there is a depletion of nitrate only in the soil volume through which drainage water promotes nitrate leaching. The risk of nitrate leaching in each drainage event can be estimated by taking into account the FW nitrate–N concentration and the drainage volume in each event. In the 2003 season, this risk increased along the four first drainage events due to the increasing FW nitrate–N concentrations (three first events) and to the increasing drainage volumes (Fig. 4).

In the 2004—sugar beet—season, significant differences in FW nitrate–N concentration were also observed. Phosphogypsum tended to decrease FW nitrate-concentration at the end of the season (four last drainage events) when compared with control (Table 5). This was probably a consequence of its

**Table 4** Linear regressions of instantaneous nitrate–N flux, NF (mg $m^{-2}$ $h^{-1}$) as a function of drain flow, F (mm $h^{-1}$) (NF = mF + b) for the cotton (2003) season

| Irrigation/rain (date of start) | Control | | | Phosphogypsum | | | Manure | | | SFRL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | b | m | $R^2$ | b | m | $R^2$ | b | m | $R^2$ | b | m | $R^2$ |
| 11-04-2003 | 0.0 | 16.9 | 0.67 | 0.0 | 19.9 | 1.00 | 0.0 | 16.6 | 0.99 | 0.0 | 19.1 | 0.99 |
| 24-04-2003 | −0.25 | 46.6 | 0.99 | −0.12[b] | 36.0[a] | 0.99 | −0.35 | 49.2 | 0.98 | −0.20 | 44.1 | 0.98 |
| 16-05-2003[†] | −0.35 | 49.7 | 0.97 | −0.88 | 50.9 | 0.93 | −0.55 | 50.8 | 0.98 | −0.30 | 48.1 | 0.99 |
| 12-06-2003 | 0.85 | 33.3 | 0.88 | −0.08 | 34.2 | 0.87 | 0.44 | 35.8 | 0.97 | 0.66 | 34.8 | 0.98 |
| 03-07-2003 | 0.21 | 22.8 | 0.98 | −0.08[a] | 19.4[a] | 0.96 | −0.08 | 23.3 | 0.98 | 0.04 | 24.2 | 0.99 |
| 18-07-2003 | 0.09 | 13.9 | 0.97 | 0.57[c] | 6.2[b] | 0.43 | 0.07 | 14.7 | 0.98 | 0.04[a] | 17.3[a] | 0.99 |
| 29-07-2003[†] | 0.04 | 17.8 | 0.96 | −0.02 | 16.0 | 0.91 | 0.22 | 19.6 | 0.74 | −0.05 | 20.4 | 0.93 |
| 09-08-2003 | 0.80 | 9.3 | 0.41 | 0.67[c] | 3.9 | 0.42 | 0.28 | 13.1 | 0.76 | 0.33 | 11.2 | 0.53 |
| 23-08-2003 | 0.17 | 12.6 | 0.94 | 0.19[a] | 6.1[a] | 0.86 | 0.30 | 9.7[b] | 0.80 | −0.10 | 16.5 | 0.89 |

The slope (m) of the linear regression is considered the flow-weighted nitrate–N concentration

All the linear fits are significants at $P < 0.01$

*SFRL* sugar factory refuse lime

[†] Represented in Fig. 1

[a,b,c] Statistically significant differences at $P < 0.01$, 0.05, and 0.1, respectively (in comparison to control in the same irrigation event)

**Table 5** Linear regressions of instantaneous nitrate–N flux, NF (mg $m^{-2}$ $h^{-1}$) as a function of drain flow, F (mm $h^{-1}$) (NF = mF + b) for the sugar beet (2004) season

| Irrigation/rain (date of start) | Control | | | Phosphogypsum | | | Manure | | | SFRL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | b | m | $R^2$ | b | m | $R^2$ | b | m | $R^2$ | b | m | $R^2$ |
| 27-11-2003 | 0.01 | 55.2 | 0.77 | −0.08[b] | 39.7 | 0.76 | −0.03 | 48.7 | 0.97 | −0.16 | 56.1 | 0.95 |
| 11-12-2003 | 0.07 | 40.1 | 0.91 | −0.02 | 40.3 | 0.99 | −0.03 | 44.7 | 0.98 | −0.08 | 46.8 | 0.97 |
| 18-01-2004 | −0.01 | 48.4 | 0.88 | −0.02 | 41.0 | 0.95 | −0.03 | 44.8 | 0.99 | −0.05 | 44.9 | 0.98 |
| 29-02-2004 | −0.02 | 59.5 | 0.86 | −0.09 | 55.0 | 0.92 | −0.13[c] | 55.3 | 0.99 | −0.05 | 51.3 | 0.98 |
| 02-04-2004 | 0.00 | 52.9 | 0.75 | −0.12 | 50.1 | 0.81 | −0.09 | 51.9 | 0.97 | −0.04 | 48.1 | 0.99 |
| 06-05-2004 | 0.00 | 28.7 | 0.85 | 0.00 | 11.5 | 0.76 | 0.00 | 21.0[c] | 0.98 | 0.00 | 27.3 | 0.99 |
| 07-06-2004 | 0.01 | 7.85 | 0.84 | 0.00[a] | 2.77[a] | 0.74 | 0.01 | 9.20 | 0.50 | 0.04[a] | 19.7[a] | 0.95 |
| 14-06-2004 | 0.04 | 5.10 | 0.61 | 0.00[a] | 2.25[b] | 0.98 | 0.00 | 6.15 | 0.78 | 0.01[a] | 15.9[a] | 0.79 |
| 22-06-2004 | −0.01 | 6.78 | 0.66 | 0.00[a] | 2.02[a] | 0.99 | 0.00 | 5.44 | 0.93 | 0.00[a] | 16.1[a] | 0.98 |
| 28-06-2004 | 0.02 | 4.42 | 0.75 | 0.00[a] | 2.68[a] | 0.97 | −0.01 | 4.71 | 0.84 | −0.04[a] | 13.6[a] | 0.97 |

The slope (m) of the linear regression is considered the flow-weighted nitrate–N concentration

All the linear fits are significants at $P < 0.01$

*SFRL* sugar factory refuse lime

[a,b,c] Statistically significant differences at $P < 0.01$, 0.05, and 0.1, respectively (in comparison to control in the same irrigation event)

effect on soil structure as discussed above for the previous season which is more evident at the end of the season with less nitrate in the soil. On the contrary, in the same drainage events, SFRL promoted higher FW nitrate–N concentrations than control (Table 5), probably due to the contribution of N present in this material, most of it in organic form (Sims et al. 2010) with a higher mineralization rate at the end of the season with higher temperatures. Increased FW nitrate–N concentration with SFRL was observed in

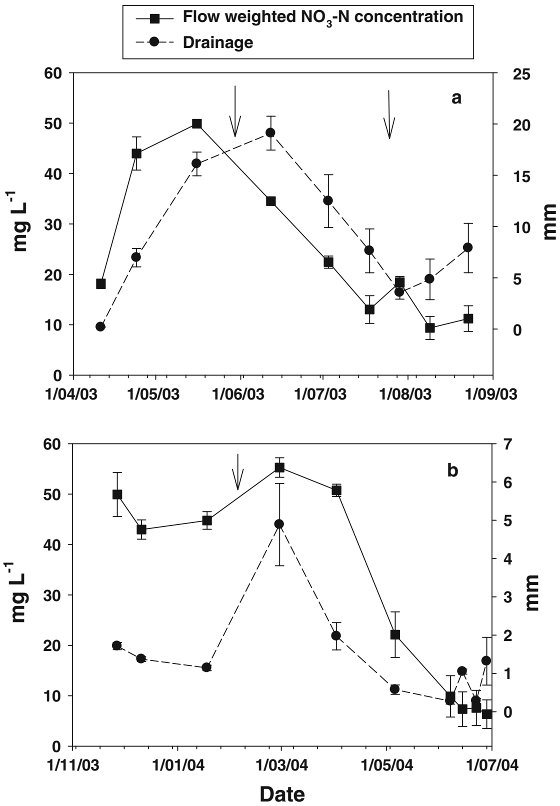


**Fig. 4** Flow weighted (FW) $NO_3$-N concentrations and drainage volumes for each drainage event in the 2003 (cotton) season (**a**), and in the 2004 (sugar beet) season (**b**). *Data* indicates mean for all the treatments, and *error bars* one standard error. *Arrows* indicate N fertilizer applications

the previous season only in one drainage event (Table 4). The absence of this effect with manure could be explained by two opposite processes affecting FW nitrate–N concentrations in drainage water: improvement of structure which contributes to decrease FW nitrate–N concentration as in PG, and N present in material which contributes to increase nitrate–N concentration. As in the 2003 season, these differences between treatments did not account for significant differences in total nitrate–N loss in the season due to the small contribution of the last four drainage events (lowest FW nitrate–N concentrations) to total nitrate–N loss (Table 3). Considering the mean of all the treatments, initial FW nitrate–N concentration in the 2004 season was much higher than in the 2003 season, and no significant differences were observed between the four first drainage events, even after the sidedress N fertilization (Fig. 4). This small change in FW nitrate–N concentration at the beginning of the 2004 season could be the consequence not only of the effect of the dissolution of preplant N fertilizer, but also of the high content of nitrate–N in soil before sowing which is mostly a residue N from the previous crop (Table 3); this residual N was much higher than in the previous season (Table 1). These observations were in agreement with previous works by Randall et al. (1997) and Kladivko et al. (1999) who observed that a high amount of residual nitrate in soil was a key factor explaining nitrate losses from soils. Contrasting with the previous season, the high N extractions by sugar beet and the subsequent decrease in total soil nitrate–N (Table 3) can contribute to explain the decrease of FW nitrate–N concentrations along the 2004 season. This decrease contributes to explain the drop in nitrate–N leaching risk along the season more than the evolution of drainage volumes (Fig. 4).

In the 2003 (cotton) season, nitrate–N losses through drainage accounted for 16–32% of the crop export (N in aboveground parts) and for 6–8% of the fertilizer rate; in 2004 (sugar beet), however, losses were less relevant, accounting for less than 2% of crop uptake (Table 3) and for 3–4% of the applied N. However, it should be taken into account that most of the N present in the soil in the 2004 season was a residue of the 2003 season (Table 3). Differences in absolute nitrate–N losses between both seasons can be explained by the different efficiency of irrigation systems, with a ratio of drainage volume to water supply ratio higher in the 2003 season (Table 3) than in 2004, which promotes a greater nitrate leaching. In the 2003 season, nitrate–N losses through drainage accounted for a small portion of the mineral N accumulated in soil during the season (Table 3). Thus, although N was applied in excess when compared with crop extraction, most of it was not lost through drainage. This can be explained probably as stated above by the leaching of nitrate only in part of the soil volume. However, this accumulation of N in soil during the first season contributes to high FW nitrate–N concentration at the beginning of the second season, thus increasing the risk of nitrate leaching as stated above.

Results reveal that the N fertilizer rate applied to cotton was excessive. This rate is usual in the area, and it should be mentioned also that sustainable production directives by regional government recommended rates until 280 kg N $ha^{-1}$, much higher than our measured crop exportations (Table 3). This high rate resulted in a high amount of nitrate–N in soil after cotton crop, which justifies the high N uptake by sugar beet when compared with usual uptake of this crop for optimum yields in the area (less than 260 kg N $ha^{-1}$; Bilbao et al. 2004). In fact, fertilizer applied to sugar beet accounted for less than 50% of the total crop uptake, thus indicating that most of this uptake was covered by N present in soil. Thus, lower N fertilizer rates in cotton could lead not only to smaller N losses through tile drainage during cotton season, but also to lower nitrate–N concentrations in drainage water at the beginning of the sugar beet season, and thus, to smaller N losses, with a likely increase of beet quality for sugar production (Bilbao et al. 2004).

## Conclusions

Phosphogypsum decreased flow-weighted (FW) nitrate–N concentrations in drainage water in some drainage events in the middle of the 2003 (cotton) season and at the end of the 2004 (sugar beet) season when compared with control without amendment. This can be the result of the enhancement of macropore flow, which can contribute to an increased bypass of nitrate present in smaller pores resulting in decreased FW nitrate–N concentrations. The increased FW nitrate–N concentrations in drainage from SFRL in comparison to control in a drainage event of 2003 season, and in the four last events of 2004 can be explained by the contribution of N present in the amendment. These differences did not account for significant differences in nitrate–N loss in both seasons, which ranged between 19.3 and 24.9 kg $ha^{-1}$ in the 2003 (cotton) season, and between 4 and 6 kg $ha^{-1}$ in the 2004 (sugar beet) season. The evolution of FW nitrate–N concentration in drainage waters along both seasons can be explained by the depletion of nitrate only in part of the soil volume; only in the 2004 (sugar beet) season, the depletion of total soil nitrate–N by crop extraction contributed to explain the decrease of FW nitrate–N concentration along the season. Greater absolute nitrate–N loss in 2003 than in 2004 was explained by the lower efficiency of the furrow irrigation when compared with sprinkler irrigation. The traditional management of N fertilizer was inadequate: rates applied to cotton were excessive, increasing the risk of N losses not only during the cotton season, but also at the beginning of the following season.

**Acknowledgments** This work was funded by the Spanish Ministry of Science and Innovation and by the Regional Development Funds of the European Union, through the National Research, Development and Innovation Program (Plan Nacional I+d+i, Projects AGL2000-0303-P4-0 and AGL2008-05053-CO2). Authors wish to thank "Cooperativa La Amistad" for making available some facilities and the experimental site.

## References

Abril JM, García-Tenorio R, Enamorado SM, Hurtado MD, Andreu L, Delgado A (2008) The cumulative effect of three decades of phosphogypsum amendments in reclaimed marsh soils from SW Spain: $^{226}Ra$, $^{238}U$ and Cd contents in soils and tomato fruit. Sci Total Environ 403:80–88

Andreu L, Moreno F, Jarvis NJ, Vachaud G (1994) Application of the model MACRO to water movement and salt leaching in drained and irrigated marsh soils, Marismas, Spain. Agric Water Manage 25:71–88

APHA, AWWA, WPCF (1985) Standard methods for the examination of water and wastewater, 16th edn. American Public Health Association, Washington

Bakhsh A, Kanwar RS, Karlen DL (2005) Effects of liquid swine manure application son NO3–leaching losses to subsurface drainage water from loamy soils in Iowa. Agric Ecosys Env 109:118–128

Bilbao M, Martínez JJ, Delgado A (2004) Evaluation of soil nitrate as a predictor of nitrogen requirement for sugar beet grown in a mediterranean climate. Agron J 96:18–25

Chanat JG, Rice KC, Hornberger GM (2002) Consistency of patters in concentration-discharge plots. Water Resour Res 38:1147–1157

Chang C, Entz T (1996) Nitrate losses under repeated cattle feedlot manure applications in southern Alberta. J Environ Qual 25:145–153

David MB, Gentry LE, Kovacic DA, Smith KM (1997) Nitrogen balance in and export from an agricultural watershed. J Environ Qual 26:1038–1048

de Vos JA (2001) Monitoring nitrate leaching from submerged drains. J Environ Qual 30:1092–1096

de Vos JA, Hesterberg D, Raats PAC (2000) Nitrate leaching in a tile-drained silt loam soil. Soil Sci Soc Am J 64:517–527

Delgado A, Uceda I, Andreu L, Kasem S, del Campillo MC (2002) Fertilizer phosphorus recovery from gypsum-amended, reclaimed calcareous marsh soils. Arid Land Res Manage 16:319–334

Delgado A, Hurtado MD, Andreu L (2006) Phosphorus loss in tile drains from a reclaimed marsh soil amended with manure and phosphogypsum. Nutr Cycl Agroecosyst 74:191–202

Diez JA, Roman R, Caballero R, Caballero A (1997) Nitrate leaching from soils under a maize-wheat-maize sequence,

two irrigation schedules and three types of fertilizers. Agric Ecosys Environ 65:189–199
Dinnes DL, Karlen DL, Jaynes DB, Kaspar TC, Hatfield JL, Colvin TS, Cambardella CA (2002) Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron J 94:153–171
Domínguez R, del Campillo MC, Peña F, Delgado A (2001) Effect of soil properties and reclamation practices on phosphorus dynamics in reclaimed calcareous marsh soils from the Guadalquivir Valley, SW Spain. Arid Land Res Manage 15:203–221
Drury CF, Reynolds WD, Welacky TW, Oloya TO, Gaynor JD (2009) Managing tile drainage, subirrigation, and nitrogen fertilization to enhance crop yields and reduce nitrate loss. J Environ Qual 38:1193–1204
Evans C, Davies TC (1998) Causes of concentration/discharge hysteresis ands its potential as a tool for analysis of episode hydrochemistry. Water Resour Res 34:129–137
Gee G, Bauder J (1986) Particle-size analysis. In: Klute A (ed) Methods of soil analysis: physical and mineralogical methods, 2nd edn. SSSA, Madison, pp 383–409
Gilliam JW, Baker JL, Reddy KR (1999) Water quality effects of drainage in humid regions. In: Skaggs RW, Van Schilfgaarde J (eds) Agricultural drainage, Agron. Monogr. 38. ASA, Madison, pp 801–830
Goswami D, Kalita PK, Cooke RAC, McIsaac GF (2009) Nitrate–N loadings through subsurface environment to agricultural drainage ditches in two flat Midwestern (USA) watersheds. Agric Water Manage 96:1021–1030
Hack-ten Broeke MJD (2001) Irrigation management for optimizing crop production and nitrate leaching on grassland. Agric Wat Manage 49:97–114
Hadas A, Sagiv B, Haruvy N (1999) Agricultural practices, soil fertility management modes and resultant nitrogen leaching rates under semi-arid conditions. Agric Water Manage 42:81–95
Hodgkinson RA, Thorburn AA (1995) Factors influencing the stability of salt affected soils in the UK—criteria for identifying appropriate management options. AgricWater Manage 29:327–338
Huggins DR, Randall GW, Russelle MP (2001) Subsurface drain losses of water and nitrate following conversion of perennials to row crops. Agron 93:477–486
Hurtado MD, Enamorado S, Andreu L, Delgado A, Abril JM (2011) Drain flow and related salt losses as affected by phosphogypsum amendment in reclaimed marsh soils from SW Spain. doi:10.1016/j.geoderma.2010.12.004
Jarvis N, Larsbo M, Roulie S, Lindahl A, Persson L (2007) The role of soil properties in regulating non-equilibrium macropore flow and solute transport in agricultural topsoils. Eur J Soil Sci 58:282–292
Jaynes DB, Colvin TS, Karle DL, Cambardella CA, Meek DW (2001) Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. J Environ Qual 30:1305–1314
Keller KC, Butcher CN, Smith JL, Allen-King RM (2008) Nitrate in tile drainage of the semiarid Palouse basin. J Environ Qual 37:353–361
Kladivko EJ, Grochulska J, Turco R, Van Scoyoc GE, Rigel JD (1999) Pesticide and nitrate transport into subsurface tile drains of different spacings. J Environ Qual 28:997–1004
Kladivko EJ, Frankenberger JR, Jaynes DB, Meek DW, Jenkinson BJ, Fausey NR (2004) Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system. J Environ Qual 33:1803–1813
Lassaletta L, García-Gómez H, Gimeno BS, Rovira JV (2009) Agriculture-induced increase in nitrate concentrations in stream waters of a large Mediterranean catchment ove 25 year (1981–2005). Sci Total Environ 407:6034–6043
Laudicina VA, Hurtado MD, Badalucco L, Delgado A, Palazzolo E, Panno M (2009) Soil chemical and biochemical properties of a salt-marsh alluvial Spanish area after long-term reclamation. Biol Fert Soil 45:691–700
Lentini A, Kohfahl C, Benavente J, García-Aróstegui JL, Vadillo I, Meyer H, Pekdeger A (2009) The impact of hydrological conditions on salinisation and nitrate concentration in the coastal Velez river aquifer (southern Spain). Environ Geol 58:1785–1795
Luxmoore RJ, Jardine PM, Wilson GV, Jones JR, Zelazny LW (1990) Physical and chemical controls of preferred path flow through a forested hillslope. Geoderma 46:139–154
Moreno F, Martín J, Mudarra JL (1981) A soil sequence in the natural and reclaimed marshes of the Guadalquivir River, Seville (Spain). Catena 8:201–211
Moreno F, Cabrera F, Andreu L, Vaz R, Martín-Aranda J, Vachaud G (1995) Water movement and salt leaching in drained sand irrigated marsh soils of southwest Spain. Agric Water Manage 27:25–44
Moreno F, Cayuela JA, Fernández JE, Fernández-Boy E, Murillo JM, Cabrera F (1996) Water balance and nitrate leaching in an irrigated maize crop in SW Spain. Agric Water Manage 32:71–83
Moreno F, Cabrera F, Fernández-Boy E, Girón IF, Fernández JE, Bellido B (2001) Irrigation with saline water in the reclaimed marsh soils of south-west Spain: impact on soil properties and cotton and sugar beet crops. Agric Wat Manage 48:133–150
Mulvaney RL (1996) Nitrogen-inorganic forms. In: Sparks DL (ed) Methods of soil analysis: chemical methods. SSSA, Madison, pp 869–920
Nangia V, Gowda PH, Mulla DJ, Sands GR (2008) Water quality modelling of fertilizer management impacts on nitrate losses in tile drains at the field scale. J Environ Qual 37:296–307
Nangia V, Gowda PH, Mulla DJ, Sands GR (2009) Modeling impacts of tile drain spacing and depth on nitrate-nitrogen losses. Vadose Zone J 9:61–72
Ng HYF, Drury CF, Serem VK, Tan CS, Gaynor JD (2000) Modeling and testing of the effect of tillage, cropping and water management practices on nitrate leaching in clay loam soil. Agric Water Manage 43:111–131
Olsen SR, Cole CV, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate, USDA Circ. 939. US Government Printing Office, Washington
Peck AJ, Hatton T (2003) Salinity and the discharge of salts from catchments in Australia. J Hydrol 272:191–202
Randall GW, Huggins DR, Russelle MP, Fuchs DJ, Nelson WW, Anderson JL (1997) Nitrate losses through tile drainage in conservation reserve program, alfalfa, and row crop system. J Environ Qual 26:1240–1247

Rhoades JD (1996) Salinity: electrical conductivity and total dissolved solids. In: Sparks DL (ed) Methods of soil analysis: chemical methods. SSSA, Madison, pp 417–436
Rose S (2003) Comparative solote-discharge hysteresis analysis for an urbanized and a "control basin" in the Georgia (USA Piedmont). J Hydrol 284:45–56
Sims AL, Windels CE, Bradley CA (2010) Content and potential availability of selected nutruents in field applied sugar beet factory lime. Commun Soil Sci Plant Anal 41:438–453
Soil Survey Staff (2010) Keys to soil taxonomy, 11th edn. USDA-NRCS, US Government Printing Office, Washington
Stamm C, Flüler H, Gächter R, Leuenberger J, Wunderli H (1998) Preferential transport of phosphorus in drained grassland soils. J Environ Qual 27:515–522
StatPoint (2000) Statgraphics plus 5.1. Rockville, Maryland
Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci 34:29–38
Wang H, Ju X, Wei Y, Li B, Zhao L, Hu K (2010) Simulation of bromide and nitrate leaching under heavy rainfall and high-intensity irrigation rates in North China plain. Agric Wat Manage 97:1646–1654
Yu J, Lei T, Shainberg I, Mamedov A, Levy GJ (2003) Infiltration and erosion in soils treated with dry PAM and gypsum. Soil Sci Soc Am J 67:630–636