Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield

Article *in* Agriculture Ecosystems & Environment · July 2013

DOI: 10.1016/j.agee.2013.04.018

Agriculture, Ecosystems and Environment 174 (2013) 1–10

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield

M. Quemada[a,*], M. Baranski[b], M.N.J. Nobel-de Lange[b], A. Vallejo[a], J.M. Cooper[b]

[a] School of Agricultural Engineering, Technical University of Madrid, 28040 Madrid, Spain
[b] Nafferton Ecological Farming Group, School of Agriculture, Food and Rural Development, Newcastle University, Devonshire Building, Newcastle upon Tyne NE1 7RU, United Kingdom

ARTICLE INFO

Article history:
Received 19 December 2012
Received in revised form 9 April 2013
Accepted 14 April 2013
Available online 28 May 2013

Keywords:
Diffuse water pollution
Effect size
Nitrogen
Nitrogen use efficiency
Water quality

ABSTRACT

Nitrate leaching (NL) is an important N loss process in irrigated agriculture that imposes a cost on the farmer and the environment. A meta-analysis of published experimental results from agricultural irrigated systems was conducted to identify those strategies that have proven effective at reducing NL and to quantify the scale of reduction that can be achieved. Forty-four scientific articles were identified which investigated four main strategies (water and fertilizer management, use of cover crops and fertilizer technology) creating a database with 279 observations on NL and 166 on crop yield. Management practices that adjust water application to crop needs reduced NL by a mean of 80% without a reduction in crop yield. Improved fertilizer management reduced NL by 40%, and the best relationship between yield and NL was obtained when applying the recommended fertilizer rate. Replacing a fallow with a non-legume cover crop reduced NL by 50% while using a legume did not have any effect on NL. Improved fertilizer technology also decreased NL but was the least effective of the selected strategies. The risk of nitrate leaching from irrigated systems is high, but optimum management practices may mitigate this risk and maintain crop yields while enhancing environmental sustainability.

1. Introduction

Irrigated agriculture represents 16% of total cropland in the world and over 40% of crop production (FAOSTAT, http://www.fao.org/nr/water/aquastat/main/index.stm). Mainly developed in arid and semiarid areas, irrigated agriculture benefits from the high solar radiation and extended frost-free periods to make these areas capable of high crop yields. Water application contributes to crop diversification and, provided proper crop production practices are used, may enhance sustainability of rural areas. However, irrigated agriculture has considerable potential for contaminating groundwater because crops are abundantly fertilized to achieve high yield potentials (Diez et al., 2000). Watershed studies have shown that return flows from irrigated agriculture are a major diffuse contributor of nitrate contamination in water bodies (Isidoro et al., 2006). Excess nitrate in water is one of the major environmental impacts of agricultural production, resulting in decreasing groundwater quality and increasing eutrophication of surface inland water and coastal marine environments (McIsaac et al., 2001). Current legislation in developed countries aiming at preserving good water quality has made it imperative to reduce quantities of nitrate delivered from cropland to ground and surface water (EC, 2000; Rabalais et al., 2002). Since nitrate leaching (NL) is frequently the most important loss process in irrigated agriculture (Follet et al., 1991) and imposes a cost on both the farmer and the environment, it is essential to quantify these losses and establish best management practices aimed at their reduction.

While the mechanisms of N losses in irrigated and rainfed agriculture are common, the strategies and options to secure ecological sustainability and economic viability may differ considerably. In irrigated agriculture, excessive water applications increase NL, leading to a vicious circle were low crop N availability is compensated by increasing fertilizer rates. As a consequence, when crops are overwatered it is common to observe low N use efficiency (NUE) and a deleterious impact on groundwater. Water and N availability remain globally the most limiting plant growth factors for non-leguminous crops, and water application is a management option in irrigated systems that interacts with the efficient use of N (Vázquez et al., 2006). Therefore, irrigated agriculture requires specific practices to increase water- and nitrogen-use efficiency that may differ from rainfed systems.

Improving the sustainability of intensive agricultural production by increasing water- and nutrient-use efficiency is a major challenge for ensuring food production during this century (Tilman

* Corresponding author at: Dept. Producción Vegetal: Fitotecnia, ETSI Agrónomos, Avd. Complutense s/n, 28040 Madrid, Spain. Tel.: +34 915491122; fax: +34 915449983.
E-mail address: miguel.quemada@upm.es (M. Quemada).

0167-8809/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agee.2013.04.018

et al., 2002). Pressure on water resources for irrigated agriculture is not confined to arid and semiarid regions, but is an increasing problem in more humid areas where irrigation is supplemental (Knox and Weatherhead, 2005). The degree of the irrigation-induced nitrate pollution varies among irrigated areas but the negative effects of intensive agriculture threaten the expansion of irrigation in many areas of the world. Despite the large body of research in irrigated agricultural systems, it is still not clear which practices most effectively reduce NL while maintaining crop yield. A comprehensive analysis is needed to clarify which management practices may contribute to a more sustainable future for crop production in irrigated areas.

Adjusting water to meet crop requirements can diminish NL (Diez et al., 2000), however, it is not clear if further control of water application can further reduce NL. Deficit irrigation, defined as a reduction in water application with respect to crop needs that leads to a significant yield reduction (Fereres and Soriano, 2007), is a common practice when water availability is limited. It implies less water percolation below the root zone but also a decrease in crop growth and N uptake, therefore, the final effect on the mass of nitrate leached below the root zone remains unclear. Improved irrigation management by scheduling might enhance NUE, particularly, when fertilizer injection to the irrigation system (fertigation) is facilitated.

Mineral N fertilizer is regarded as a main contributor to NL, but there is little likelihood that we can maintain adequate food supplies without fertilizers (Tilman et al., 2002). In most cases where fertilizer causes NO_3^- pollution, it is due to excessive application or to poor management practices (Follet et al., 1991). A deeper analysis of the published results may help to quantify the levels of N application at which NL becomes a problem and the management techniques that may help to control it.

The role of cover crops (CC) in semiarid zones where establishment can be ensured by irrigation has been highlighted in recent articles (Gabriel and Quemada, 2011). Main crops usually recover less than 50% of the fertilizer N applied, and large amounts of residual N are left in the soil at harvest (Bundy and Andraski, 2005). This residual N is prone to leaching during the intercrop period and replacing the fallow with a non-legume CC is a known biological tool to control NL (Thorup-Kristensen et al., 2003). However, the role of legume CC in reducing NL is uncertain. While legumes benefit subsequent crops by supplying N to the system, a deleterious effect has been reported in areas were NL is a concern (Campiglia et al., 2011).

A meta-analysis (MA) of the available information on strategies to reduce NL losses from agricultural irrigated systems was conducted. The main objective was the identification of those strategies that have proven effective at reducing NL losses and quantification of the scale of reduction in N losses that can be achieved by the various strategies. In addition, the following questions concerning the fate of N in irrigated systems were addressed: (i) do deficit irrigation or scheduling reduce NL with respect to adjusting water application to crop requirements? (ii) at which level of N application does the relationship between yield and NL become most favorable? and (iii) how does including a cover crop, either a grass or a legume, during winter affect NL relative to the conventional winter fallow?

2. Materials and methods

2.1. Article search and selection criteria

A survey of peer-reviewed published literature was conducted to identify articles that reported NL in irrigated agricultural systems using the ISI-Web of Science and CAB Abstracts (Ovid) from 1910 to 2012. The following search terms and their variations were used: irrigation, nitrogen, nitrate leaching, leachates, losses (from soil), percolation, eutrophication, nonpoint source or diffuse water pollution. This provided 234 articles published from 1963 to 2012 in scientific journals from the Journal Citation Report. More relevant papers were found by searching through the reference lists of papers already selected for the MA. Papers were scrutinized and included if they met the following selection criteria: (i) study of NL in an irrigated agricultural cropping system; (ii) study for at least one growing season; (iii) conducted under field conditions; (iv) NL was measured in terms of mass of N lost (i.e. NO_3-N concentration and the volume of water leached were both considered). Studies that determined the risk of NL through soil or soil solution NO_3-N concentrations, were not considered as these might give a skewed view of NL. Even if the study relied on computer modeling to simulate components of the water balance or solute transport, the studies were selected if data collected under field conditions were the major component of the results. We found a total of 90 articles that met these criteria. A further selection was conducted by critical examination of these papers for inclusion and exclusion from the data-set, following quality criteria that ensure statistical power avoiding unconscious bias (Hedges et al., 1999). These criteria were that: (i) the experimental design had to be sufficiently detailed to determine all critical aspects of the treatments, plot size and recent history, irrigation systems and fertilizer management; (ii) studies reflected typical regional practice; and (iii) in most cases included treatment replicates. In some cases exceptions were made to this final criterion. For example, Sharma et al. (2012) remained in the data-set even though it did not have actual replicates. This study compared two fields with different irrigation systems by taking a large number of samples from each treatment and analyzing them in different pools to reflect field variability. Some lysimeter studies without replicates (e.g. Moreno et al., 1996) were included because it was considered that the data obtained from these studies could be considered relatively accurate, even without replication. For all studies, a general site and environment description was required to ensure proper location, soil and climate type and crop identification. Articles were also discarded from the MA either because they did not follow an experimental design with a control (17 articles) or because mixed treatments impeded obtaining pair comparison observations (11). After the final screening of articles, we identified a total of 44 that were used in the MA (meta-analysis references are available in Appendix, supporting information).

2.2. Building the data-sets

Information was compiled from the selected articles to characterize the environmental and management factors for each field study. Environmental variables included as factors were soil type and climate while management factors were crop and irrigation system. Soil type was defined by texture following USDA classification (Soil Survey Staff, 2003) and grouped in three categories: clay (clay, sandy clay, silty clay) loam (loam, clay loam, silty clay loam, silt loam, sandy loam, sandy clay loam), and sand (sand, loamy sand) for analysis purposes. Climate was grouped in the various thermal climate zones of the world (tropics, subtropics-summer rainfall, subtropics-winter rainfall, temperate-oceanic, temperate-subcontinental, temperate-continental) defined by FAO and IIASA (2007). Crops were originally categorized as cereals, vegetables and perennial trees. Only one article on perennial trees passed the selection criteria and so this group was excluded meaning only 'cereals' and 'vegetables' groups remained. When a CC was introduced in a cropping system, the main cash crop remained as the factor for the observation. Depending on water management technology, systems were grouped as surface (including furrow and flooding), sprinkle, central pivot and drip (including all types of trickle irrigation, surface or subsurface) irrigation. Further characterization of observations was attained by introducing the country and region of the experiment, the year when the field experiment was conducted, the number of replicates and the article reference.

Data on the variable NL were extracted from the selected articles that compared the various mitigation strategies. When available, data on crop yield (Y), N applied as fertilizer (Nap), and soil mineral N at planting (Nmin) were also collected for each observation. In addition, we calculated NUE as the Y per unit of Nap (kg kg^{-1} N), and nitrate leaching-scaled yield (NLSY) as Y divided by the quantity of nitrate leached (kg kg^{-1} N-NO_3 leached). NLSY provides an index of the tradeoff between Y and environmental impact that is often associated with pollution mitigation strategies in agriculture. High values for NLSY are considered indicative of optimizing this tradeoff since they result when Y is high and NL is low.

The period of an observation in which NL was measured varied between a growing season and a full year. In order to avoid bias toward short term experiments, studies conducted in different years or growing seasons were considered independent (Hedges et al., 1999). So for each observation, data were presented as an average of all comparable data within a species and growing season or year. The only exception was the article by Tarkalson et al. (2006) in which data from a two-year experiment are presented; since both years were highly related they could not be considered as independent and the average of both years was considered as a single observation. When possible, Y was introduced as dry matter per unit area but in the observations in which the cash crop was a vegetable (102 data pairs) fresh weights were considered. As we will see when describing the MA, as the magnitude of the effect for each observation is expressed relative to the control, the variable units do not affect the results.

The total number of observations on NL in the database was 279, which is more than the number of studies because many studies investigate more than one experimental factor. From these observations, 166 contain data on Y and were used to calculate NUE and NLSY.

2.3. Categorizing the literature: strategies and treatments definition

Four main strategies for NL control were identified based on a systematic review, and further subdivided, when justified, into various treatments (Table 1). Each observation in the data-set was assigned to one strategy and treatment.

Improved water management included all studies where the strategy used to reduce NL dealt directly with water application. If crop water requirements were defined and compared to a control with excessive irrigation, the pair was assigned to the treatment *Adjust water application to crop needs*. If water application was reduced with respect to crop needs, either to control NL or because of water restrictions, the pair was assigned to *Deficit irrigation*. In other studies, there was no difference in the amount of applied water, but a further increase in N or water efficiency was pursued by either an *Improved irrigation schedule* (e.g. optimal timing of water application) or *Improved irrigation technology* (e.g. using more efficient systems for water delivery) and pairs were assigned to the corresponding treatment. In these cases the control for each pair was the schedule or technology that resulted in higher NL. Because plastic mulching affects crop evapotranspiration, studies comparing bare versus *mulched soil* were grouped in a new strategy. Care was taken to select for the MA the data pairs in which the only difference between a control and its pair corresponded with the treatment definition. As an example, if a comparison of two irrigation technologies (i.e. drip versus sprinkle) was performed using different water rates, only the pairs with equal water rates were considered for the MA while the others were discarded because they were considered as mixed treatments (i.e. irrigation technology and water application).

Table 1
Categories (strategies and treatments) to control nitrate leaching in irrigated land defined from the systematic analysis of selected peer reviewed articles.

Strategies	Treatments	Observations
Improved water management (IWM)		82
	Adjust water application to crop needs	24
	Deficit irrigation	16
	Improved irrigation schedule	25
	Improved irrigation technologies	12
	Mulched soil	5
Improved fertilizer management (IFM)		106
	Use recommended fertilizer rates	40
	Reduction in the recommended fertilizer rate	40
	Optimized timing of fertilizer application	16
	Fertigation	10
Use of cover crops (UCC)		59
	Replacing winter fallow by a non-legume CC	39
	Replacing winter fallow by a legume CC	20
Improved fertilizer technologies (IFT)		32
	Controlled release fertilizer	13
	Nitrification inhibitor	19

The strategy *Improved fertilizer management* was subdivided into treatments that *Use recommended fertilizer rates*, or that apply a *Reduction in the recommended fertilizer rate*. In these treatments, we included only studies that, in addition to NL losses, reported or allowed calculation of a recommended nitrogen fertilizer rate. Calculation of the recommended rate when not reported was based on the Y response presented in the paper. The “recommended fertilizer rate” was chosen from among those tested and was assumed to be the rate above which no further increase in Y occurred. Recommended rates not reported in the same article but in others published by the same research group, or by a recognized experimental station for the same crop under similar soil-climatic conditions, were also accepted. The control for data pairs that used the recommended fertilizer rate was excessive application, while the control for those with reduced application rates was the recommended rate. When several rates were applied in excess of the recommended rate in the same experiment, we only included the rate immediately superior to the recommended rate in the analysis to avoid bias from experiments with very excessive rates. In addition, two more treatments were included under this strategy: these focused on *Optimizing timing* of fertilizer application and the very specific category of *Fertigation*. We did not attempt to differentiate between organic and inorganic fertilizers, as insufficient data-pairs did not allow a comparison between these sources of fertilizers on the effect on NL. Therefore, articles in this strategy included application of mineral (33), organic (1) or a combination of both fertilizers (9).

Use of cover crops to replace the conventional winter fallow was further subdivided into legumes and non-legumes CC, with mixed CC (legume/non-legume) considered as legumes. The winter fallow was the control for these treatments. Initially, management of the CC residue (soil incorporation or left on the soil surface) was defined as a treatment, but as it did not have an effect on NL, it was not included in the final MA.

New developments in the fertilizer industry to obtain synthetic fertilizers that enhance NUE constitute the strategy *Improved fertilizer technologies*. The treatment *Controlled release fertilizers* (CRF) refers to technologies used to delay the release of available N (i.e. semi-permeable coatings and chemical forms of different solubility). *Nitrification inhibitors* (NI) are substances that inhibit the biological conversion of ammonium to nitrate, and are another fertilizer technology used to reduce NL. The control for CRF and NI treatments was the application of the same quantity of N as a 'rapidly available nutrient fertilizer'. As only one article on no-till versus conventional tillage passed the criteria for MA, this was not included as a separate strategy.

2.4. Data analysis

Data were analyzed using MA techniques to study the response of NL and the other variables to the strategies and treatments that had been identified. All data were analyzed using the R statistical software package (www.r-project.org) (R Development Core Team, 2011). For each observation data were presented as averages of the replicates in the field study and the number of replications was not used for weighting. The effect size for each observation was calculated as the response ratio ($r = Xe/Xc$), where Xe is the experimental treatment mean and Xc is the control mean of each variable. To perform the MA, a square root transformation of the response ratio was used, $R = sqrt(r) = sqrt(Xe/Xc)$, to normalize the data distribution. Therefore, the mean of the R distribution should be approximately equal to the true response ratio (Johnson and Curtis, 2001). The transformed values were used to compare the effect sizes across all the strategies and treatments using resampling (Hedges et al., 1999). Back transformation of these average values provided an estimate of the difference in the magnitude of the effect sizes. Because we defined treatments as practices that should reduce NL, negative effect size meant greater effectiveness. However, positive effect sizes in Y, NUE and NLSY indicated that the practice improved the studied variable. Mean effect sizes were calculated for each variable of interest and data-set category, and bias-corrected 95% confidence intervals (CIs) were generated by a bootstrapping procedure (5000 iterations). Mean effects were considered significantly different from zero if the 95% CI did not overlap zero, and different from one another if their 95% CIs were non-overlapping (Hedges et al., 1999). We also analyzed the mean response ratios of the environmental (soil type and climate) and management (crop and irrigation system) factors describing the field experiments of the data-set.

A subset of the database from the observations in treatments *Use recommended fertilizer rates* (40 observations) and *Reduction in the recommended fertilizer rate* (40 observations) was created to conduct a more detailed analysis into the relationship between NL and rates of N fertilizer application. The number of data pairs (NL versus fertilizer N applied) remaining in the analysis after separating observations was 150. N fertilizer rates were divided into 6 groups with the first group including the data pairs from treatments that did not receive N fertilizer ($n = 45$). The rest of the data pairs were first ranked according to total fertilizer-N applied and then split up into groups of approximately the same size every 100 kg N ha^{-1} up to 400 kg N ha^{-1} applied. The average Nap rates for groups 2–5 were 92, 167, 256 and 359 kg N ha^{-1}. Application rates above 400 kg N ha^{-1} were pooled in a sixth group with an average application rate of 548 kg N ha^{-1}. Data pairs with 800 kg N ha^{-1} applied were kept in the database and included observations from the same field study in the Central Plain of China where various rates were applied to a high N demand wheat-maize rotation (Li et al., 2007). In an attempt to relate Nap and crop demand, in the same data subset the fraction of recommended N rate applied was calculated by dividing the actual N applied by the recommended rate for the study. The data pairs were split into five groups according to the fraction of recommended N rate applied: no N fertilizer, less than the recommended rate, the recommended rate, less than twice the recommended rate, twice the recommended rate or more. When Y data were available ($n = 166$), data pairs of the fraction of recommended N rate applied and relative Y were introduced to complete the database. Relative Y was calculated as the Y obtained at a particular Nap rate divided by the Y obtained at the recommended N rate for the experiment. Means were calculated for all database subsets and 95% CI around the means were generated by a bootstrapping procedure using the R statistical software package (www.r-project.org) (R Development Core Team, 2011).

3. Results

3.1. Overview of the data-set

Irrigated land is present in many regions of the world, and the scientific literature selected represented a global data-set. The geographical distribution of the selected articles was as follows: North America (44%), Europe (38%), Asia (14%) and South America (4%). Most data came from the European Mediterranean basin (35%) and from the Midwest of the United States (30%).

The NL observations focused on the strategies improved water (82) and fertilizer management (106) dominated the literature (Table 1). Studies focused on water management were evenly distributed between treatments, except for *Mulched soil* where only 5 observations were assigned and *Improved irrigation technologies* with 12 observations. *Improved fertilizer management* is a strategy that received attention in many studies; specifically, most efforts were focused on adjusting Nap to the recommended fertilizer rate or reducing it. *Optimized timing of fertilizer application* and *fertigation* were also studied in relation to controlling NL, but to a lesser extent.

The *Use of cover crops* was the only crop diversification approach to reducing NL included in the analysis. This does not mean that there are not other approaches based on cropping systems diversification that are used in irrigated systems, but direct effects on NL have never been proven for these techniques. The data-set produced enough pairs (69) to conduct a more detailed analysis to answer some specific questions about the use of CC. *Improved fertilizer technologies* received moderate attention in the literature, but articles dealing with this topic were very clearly defined and conducted, so most of studies found in the literature passed the criteria to be included in the data-set. All the studies were about technologies related to synthetic fertilizers, with none about the direct application of NI to organic byproducts as has been reported in other agricultural systems (Ledgard et al., 2008).

No significantly different effect sizes on NL for any of the environmental factors describing the field experiments were detected. Studies were conducted mainly in loam (71% of observations) and sandy soils (27%), with a small fraction in clay soils (2%). The different soil textures had overlapping CI, meaning that the relative effect of the strategies with respect to the control was similar in the various soil types. Observations were distributed between four climate zones: temperate-subcontinental (38%), subtropical-winter rainfall (29%), subtropical-summer rainfall (18%), and temperate-oceanic (15%), with the mean effect size for climate on NL not significantly different for any of these zones. Most studies were conducted in temperate-subcontinental and subtropical-winter rainfall zones as these are the thermal climate zones that include most of the semiarid climates. As the effect of environmental factors was of little relevance for our data-set, we focused on the mean effect size of the management strategies to control NL that were identified in the comprehensive analysis.

3.2. Nitrate leaching

All management strategies selected for the MA reduced NL, but with varying degrees of success (Fig. 1). The largest effect was achieved by *Improved water management* (58%) which was significantly different from the other strategies. *Improved fertilizer management* (39%) had a larger effect than *Improved fertilizer technologies* (24%), and the effect of *Use of cover crops* was in between these two strategies. The potential of specific practices to reduce NL is confirmed by these results, with *Improved water management* highlighted as the most effective strategy and the treatment *Adjust water application to crop needs* having the largest effect with reductions in NL of 78% relative to the excessive water control (Fig. 2). *Deficit irrigation* and *Improved irrigation schedule* also decreased NL but to a lesser extent. *Improved irrigation technologies*, a technique that in most cases allows a better adjustment of water to crop needs, decreased NL by 22%. Few observations (5) compare the effect of plastic mulching but all of them indicated a beneficial effect on NL relative to non-mulched controls.

Overall, *Improved fertilizer management* reduced NL by 39% (Fig. 1). *Use recommended fertilizer rates* reduced NL relative to excessive application by 43% (Fig. 3). A *Reduction in the recommended fertilizer rate* produced a further decrease in NL of 50% compared to using the recommended fertilizer rate. The number of available observations in these two treatments was about half the total in the *Improved fertilizer management* group and sufficient for a more detailed analysis to improve understanding of the relationship between adjusting N fertilizer rates and NL. The mean NL from treatments that did not receive N fertilizer was 16 kg NO_3-N ha^{-1} per measurement period, and then it increased with Nap up to a mean NL of 106 kg NO_3-N ha^{-1} for application rates above 400 kg N ha^{-1} (Fig. 4a). When NL was analyzed versus the percentage of recommended N rate applied, there was a linear increase up to applications equal to the recommended rate, but if Nap> recommended rate then the NL losses were enhanced (Fig. 4b).

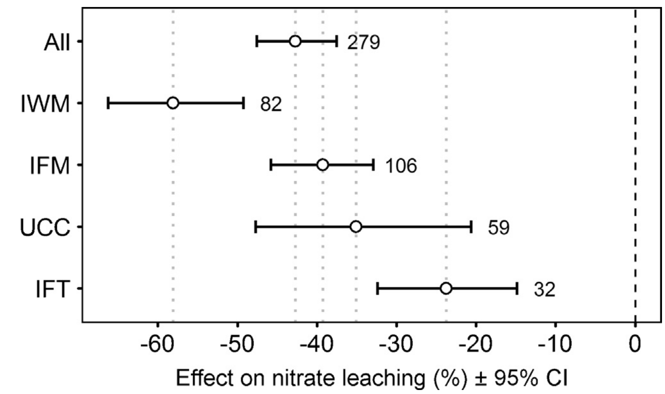

Fig. 1. Overall effect of all management strategies (All) and effect of each category of management strategy on nitrate leaching in units of percent change from the control. Mean values and 95% confidence intervals of the back-transformed response ratios are shown. IWM: improved water management; IFM: improved fertilizer management; UCC: use of cover crops; IFT: improved fertilizer technologies. Sample sizes (i.e. the number of control–treatment pairs) are shown on the right of the confidence intervals.

The treatment *Optimized timing of fertilizer application* reduced NL by 22% (Fig. 3). Surprisingly, *fertigation*, a practice specific to irrigated systems that allows improved timing of fertilizer application, did not have a significant effect on controlling NL. The CI of the *fertigation* effect on NL ranged from −22 to 10% with 4 observations out of 10 showing an increase in NL from this practice. The observations came from 4 articles, but many (5) articles were discarded because there were mixed treatments where application of N and water varied at the same time, impeding pair comparisons based on Nap.

Use of cover crops reduced NL by 35% on average (Fig. 1). The effect was clearly affected by the CC type. While replacing fallow with a non-legume CC decreased NL by 50% on average, using a legume CC did not reduce NL relative to the control (Fig. 5). A closer look at the effect distribution shows that in only one observation out of 39 was NL greater for a non-legume CC than for the fallow. In contrast, the results for a legume CC are not conclusive with an increase in NL when legumes were used as CC in nine out of 20 observations, while for the other 11 observations NL was decreased even when the CC was a legume. *Improved fertilizer technologies* decreased NL by 27% on average with no differences observed between CRF and NI (Fig. 6a).

3.3. Yield, NUE and NLSY

Improved water management did not reduce Y relative to excessive irrigation (Fig. 2). *Mulched soil* had a beneficial effect on Y and achieved an average of 40% higher Y than the control. A few studies reported the effect of improving irrigation technology on Y (4), which they showed can increase Y by 10%. The effect was clearly different when comparing *Deficit irrigation* and *Improved irrigation schedule* relative to *Adjusting water to crop needs*. While most crops under deficit irrigation decreased their Y by an average of 23%, the proper scheduling of water application increased Y in 9 out of 11 observations (Fig. 7).

The mean Y from treatments that did not receive N fertilizer was 63% of the Y obtained in the recommended N rate treatments (Fig. 4b). Above the recommended rate, only a very slight crop response to Nap was observed (in the order of a 4% increase at twice the recommended rate). As a consequence, in the strategy *Improved fertilizer management* the largest mean effect on NUE was observed for the treatment *Use recommended fertilizer rates*, in which an increase of over 80% can be achieved relative to excessive applications (Fig. 3c). Reducing the Nap with respect to the recommended rate allowed a further increase of 60% NUE. Treatments *Fertigation* and *Optimized timing of fertilizer application* did not have an effect on total Y or NUE.

Replacing a fallow with a legume CC had a positive effect on Y in all observations, with a mean increase of 25% (Fig. 8a). If the fallow was replaced by a non-legume CC,

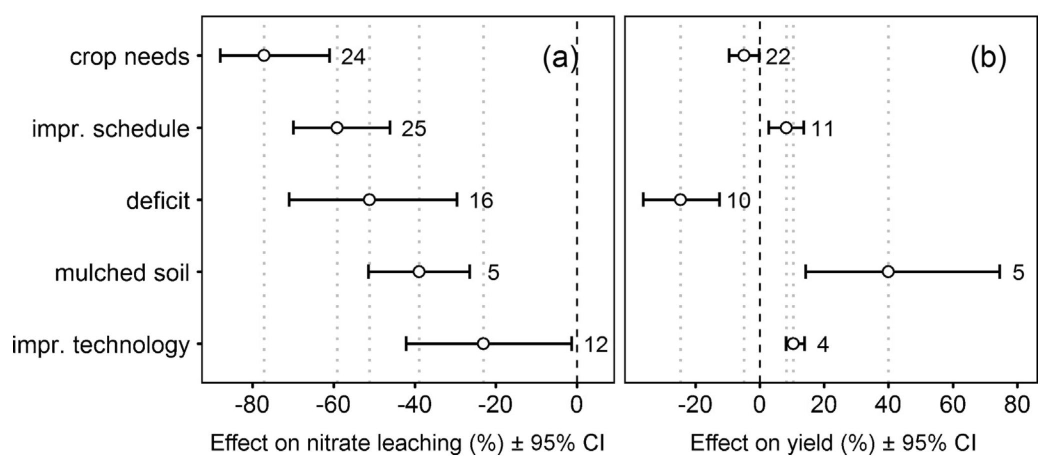

Fig. 2. Effect of the strategy Improved water management and various treatments within the strategy on nitrate leaching (a) and crop yield (b) in units of percent change from the control. The control for crop needs is excessive irrigation; the control for all other treatments is crop needs. Mean values and 95% confidence intervals of the back-transformed response ratios are shown. Sample sizes (i.e. the number of control–treatment pairs) are shown on the right of the confidence intervals.

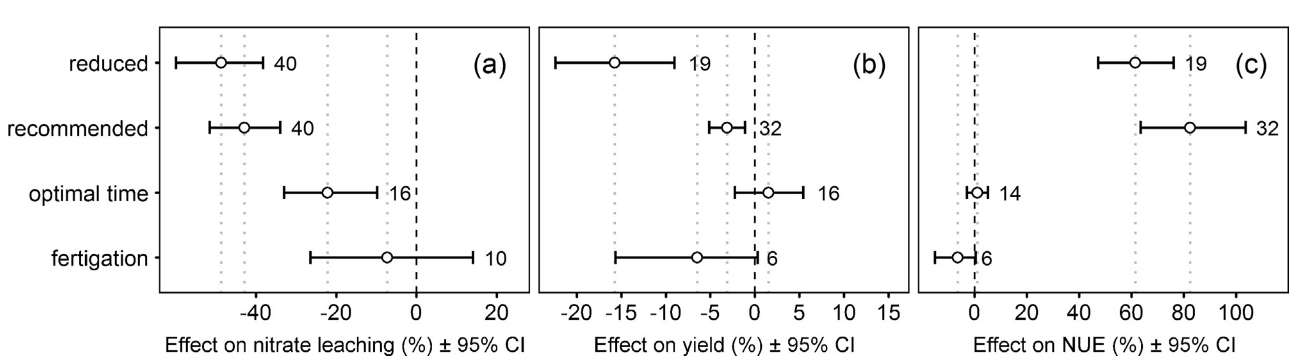

Fig. 3. Effect of treatments from the strategy Improved fertilizer management: Use recommended fertilizer rate (recommended), Reduction in the recommended fertilizer rate (reduced), Optimized timing of fertilizer application (optimal time) and Fertigation on the control of nitrate leaching (a), crop yield (b) and N use efficiency (c). The control for recommended rate is excessive fertilization; the control for all other treatments is recommended rate. Sample sizes (i.e. the number of control–treatment pairs) are shown on the right of the confidence intervals.

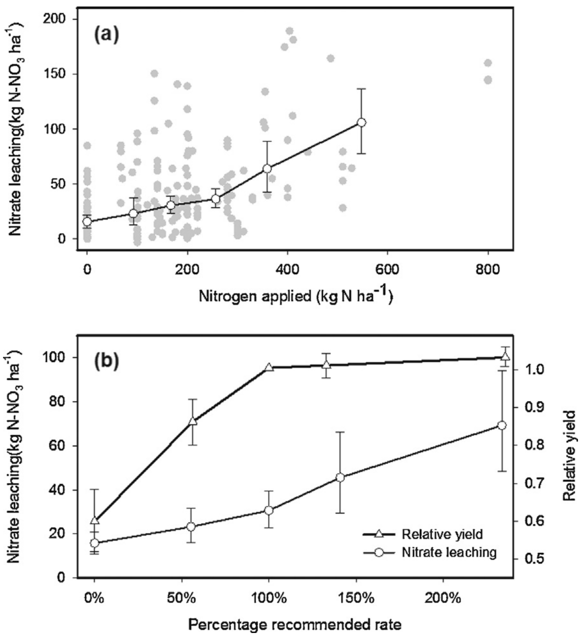

Fig. 4. Nitrate leaching from observations in the treatments *Use recommended fertilizer rate* and *Reduction in recommended fertilizer rate* versus the nitrogen applied as fertilizer (a) or the percentage of the recommended N rate (b). Plot (a) points represent the raw data from all treatments included in the database (150) and the circles show mean values for each fertilizer rate class. Plot (b) shows mean nitrate leaching (circles) and relative yield (triangles) at each class of percentage of recommended rate. Bars on all plots are the 95% confidence intervals around the mean effects generated by bootstrapping.

in more than half of the observations there was a Y decrease in the subsequent cash crop and the mean effect on Y was not significant. Not many data were available to analyze the effect of CC on NUE but the trend was similar to Y; while a legume CC had a positive mean effect the non-legume had no effect (Fig. 8b). Non-legume CC had a clearly positive effect on NLSY (i.e. kg of yield per kg of NO_3-N leached), which means that the benefits of non-legume CC for reducing NL far outweighed the cost of Y reductions associated with this practice(Fig. 8c). The effect of legume CC on NLSY was not always positive and the mean effect was not different from the fallow.

Overall, the strategy *Improved fertilizer technologies* did not have an effect on Y (Fig. 6b). The use of CRF even had a negative effect on Y, while the effect of NI was not significant. Nevertheless, both treatments increased NLSY with an average mean effect size for both treatments of 38%.

3.4. Crop type and irrigation system effects

Crop type also affected NL. A total of 16 different cash crops were studied in the experiments selected for the data-set, with 63% of observations assigned to cereals and 37% to vegetables. The mean effect of the strategies to control NL was larger for the cereals than for the vegetables. On average, a 48% reduction in NL was achieved by applying the strategies in cereal crops while a 33% reduction occurred in vegetables.

Observations were distributed between the various irrigation types: 23 for surface, 24 for sprinkle, 14 for central pivot and 54 for drip irrigation. Within a given irrigation type adopting a strategy to control NL had a positive effect, with largest

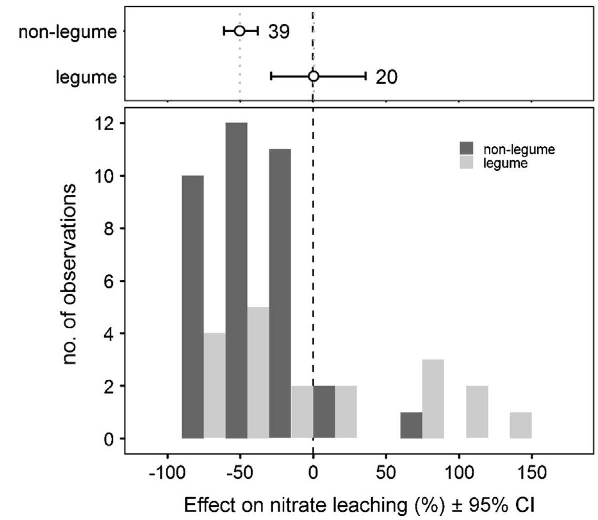

Fig. 5. Effect of cover crop type (legume versus non-legume) on nitrate leaching relative to bare fallow. Upper panel plot shows mean values and 95% confidence intervals of the back-transformed response ratios. Lower plot: frequency distribution of observations for percentage of nitrate leaching relative to the control for each cover crop type.

effects achieved when mitigating strategies were implemented for surface irrigation and smallest effects when drip irrigation was used. This means that on average there is more potential for controlling NL in surface than in drip irrigated systems, with sprinkle and central pivot systems presenting intermediate opportunities for reductions in NL.

4. Discussion

The strategy *Improved water management* was the most effective for controlling NL and it did not imply a decrease in Y or NUE. Therefore, in irrigated areas where policies to control nitrate pollution are to be implemented the focus first should be on optimizing water management. The reduction in NL attained by *Adjust water application to crop needs* depends on the original degree of excessive application, but according to our results it is the treatment with a larger effect and can lead to reductions in NL of over 80%. In the six articles for this treatment, excessive irrigation varied from 10% to 30% over crop needs, and in only one of them (Diez et al., 1997) the effect of water management on grain Y was significant. This article reported the results of three years, and in one of them wheat from excessively irrigated plots presented lower Y than from irrigation adjusted to crop needs. The authors explained that excessive irrigation deprived the topsoil of available N and lead to lower Y. Overwatering is a common practice to compensate for soil variability and soil salt accumulation (Gabriel et al., 2012a), but because N losses are enhanced it is often accompanied by over fertilization which leads to a vicious circle with deleterious environmental effects. Water and N use efficiency were highly related in all

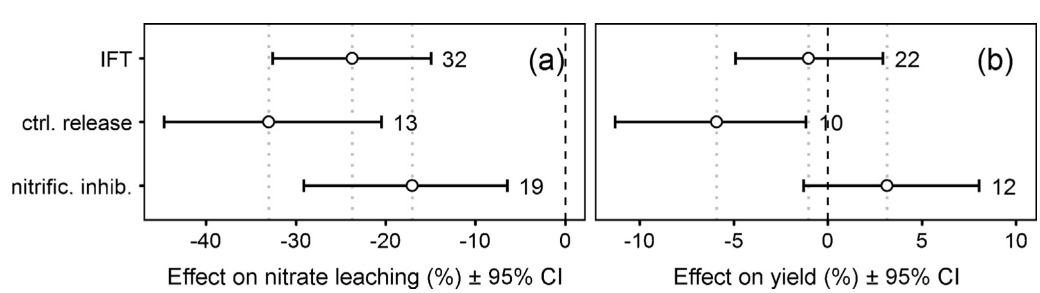

Fig. 6. Effect of the strategy Improved fertilizer technology and the treatments Controlled release fertilizer and Nitrification inhibitor on nitrate leaching (a) and yield (b). Mean values and 95% confidence intervals of the back-transformed response ratios are shown.

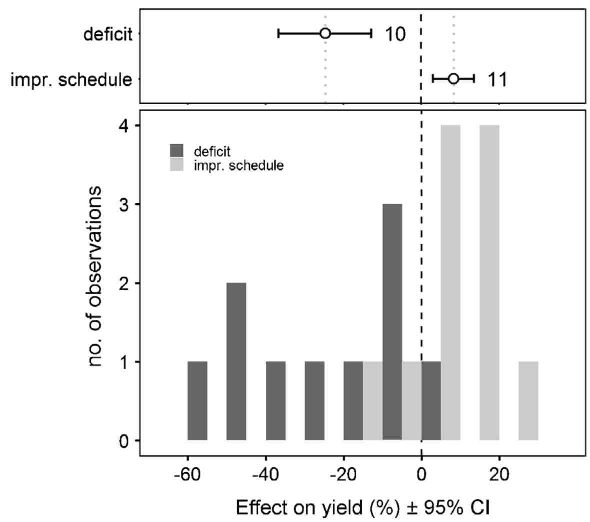

Fig. 7. Effect of deficit irrigation and improved irrigation schedule on crop yield relative to adjusting water to crop needs (upper panel plot). Mean values and 95% confidence intervals of the back-transformed response ratios are shown. Lower panel plot: the frequency distribution of observations for percentage of yield effect relative to the control for each treatment.

articles from this treatment and adjusting water to crop needs had the largest effect of all practices on NLSY, indicating that this is a good strategy to optimize environmental quality without sacrificing Y.

Deficit irrigation, a common practice where water is scarce, allowed for a further reduction in NL relative to adjusting water application to crop needs. A good example is recent work conducted in Iran (Sepaskhah and Tafteh, 2012) with rapeseed, where two methods of alternate furrow irrigation (i.e. partially root drying) were compared to ordinary furrow irrigation. Both methods decreased NL and Y with respect to the control, as a consequence NUE was equal to the control when Y was only slightly reduced and lower when it was drastically reduced. In our MA, the mean effect of the treatment *Deficit irrigation* on NLSY was low, because while it reduced NL, it also reduced Y, making this a strategy that incurs an economic cost to the farmer. When Y is reduced because of deficit irrigation, N fertilizer application should also be reduced to match the reduced crop demand; otherwise enhancement of residual N could increase NL risk during the non-growing season.

Even if water application was not reduced with respect to crop needs, *Improved irrigation schedule* allowed for NL control and increased Y, enhancing NLSY. This practice is particularly relevant in vegetable crops (22 out of 25 observations) and with drip irrigation (20 out of 25 observations) where programming facilitates irrigation scheduling. In vegetable crops, NL is particularly important during the crop establishment period when irrigation is applied to maintain low soil water potential to ensure survival of plantlets (Vázquez et al., 2006). Irrigation frequency is a major management variable that may lead to increased water and N use efficiency during the crop establishment period and sustain high Y. A further reduction in NL can be attained with appropriate use of soil or plant moisture sensors to control irrigation that may allow better adaptation of water application to crop demand (Zotarelli et al., 2011).

The few studies on *mulched soil* are consistent and all of them showed a large effect on NL control (mean effect of 40% reduction) and Y enhancement, therefore NLSY increased compared to bare soil. Mulching, apart from numerous other agronomic advantages, enhanced crop N uptake due to an increase in soil temperature and water use efficiency leading to a reduction in NL (Vázquez et al., 2005). In addition to that, mulching protects the bed from direct infiltration of rainfall during the cropping season that may cause occasional NL. Various mulching materials exist (black PE films, cellulose, etc.) and the effect of them differs depending on permeability, biodegradability and other characteristics, but overall Romic et al. (2003) reported that mulched surfaces showed lower NL than unmulched treatments.

It was hard to find many paired comparisons for the treatment *Improved irrigation technologies*, because changes in the irrigation system were often associated with different water or fertilizer application rates. The effect on controlling NL and increasing Y was associated with a better adjustment of water application to crop needs, and has been reported for comparisons of drip irrigation versus surface (Sharma et al., 2012) and sprinkle (Waddell et al., 2000). Comparisons between different drip irrigation techniques (subsurface versus surface drip) did not have a large effect on NL (Bruin et al., 2010; Zotarelli et al., 2009). These results are in agreement with the outcome of irrigation as a main factor in the MA, where differences between surface and drip irrigation appear to be different only at the 10% significance level. The results suggest that the strategies proposed were more successful at reducing NL in furrow and flooding systems than in drip irrigated systems, probably because the leaching in the baseline situation was much larger for surface irrigated systems so there was more room for improvement.

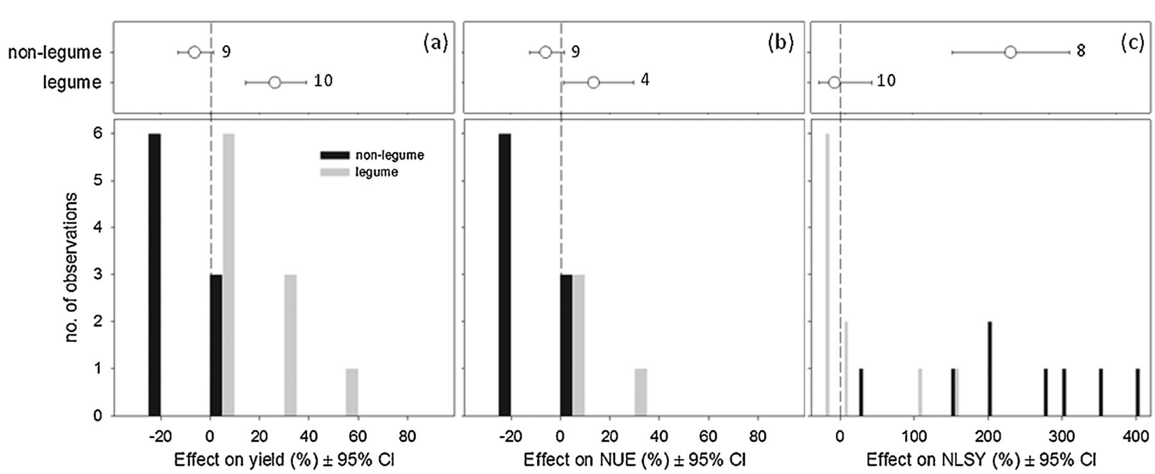

Fig. 8. Effect of using legume and non-legume cover crops on yield (a), N use efficiency (b) and nitrate leaching-scaled yield (c). The control for both cases is bare fallow. Upper panel plots show mean values and 95% confidence intervals of the back-transformed response ratios. Lower plots show the frequency distribution of observations for each percentage range with respect to the control for each treatment.

Improving the irrigation system technology is a tool that may help to reduce NL by effectively increasing N and water use efficiency. However, these technologies generally require a higher level of management input and expertise. If these technologies are not well implemented, they may not result in a reduction in NL. This is an important point because it highlights the need for funding and policy decisions that address equally improvements in technology and farmers' education.

The strategy *Improved fertilizer management* was less efficient at controlling NL than *Improved water management*, but nevertheless attained a reduction in NL of almost 40%, making it an additional priority when implementing policies to control nitrate pollution. The scientific community seems to be aware of this, as most of the observations obtained from the literature focused on this strategy.

Application of N fertilizer to an irrigated system increased NL, even applying N at the recommended rate doubled NL compared with unfertilized controls. There was a broad range of NL when Nap was below the recommended rate (from less than 10 to 150 kg NO_3-N ha^{-1}), which indicates that factors other than Nap are also affecting nitrate losses to water. This is in agreement with the general result of this MA which has shown that a range of practices apart from fertilizer management can impact on NL. Van Groenigen et al. (2010) observed in a MA that N_2O gas emissions from agricultural soils increased exponentially with additions of N fertilizer above 180 kg N ha^{-1}. In our results, the threshold of Nap after which NL drastically increased was 256 kg N ha^{-1}, higher than the value reported for N_2O emission. Nevertheless, considering the uncertainties of analysis involving multiple studies, these values are of the same order of magnitude and show that over fertilization can drastically increase pollution problems. These results also show that the best relationship between Y and NL is obtained when applying the recommended N fertilizer rate. Values below the recommended rate, while reducing leaching, also reduce Y. Fertilizing above the recommended rate will lead to an increase in NL without a significant increase in Y. The estimation of recommended fertilizer rates in our study helped us to explain some of the observations in our MA. For instance 400 kg N ha^{-1} may look like a very high Nap but it is the recommended fertilizer rate for the high N demand wheat-maize rotation of the fertile soils in the Central Plain of China, and actually it is related to low NL values (Li et al., 2007). Therefore, even with the limitations associated with defining a recommended fertilizer rate for each experiment, it was a useful parameter to help interpret the results. Nevertheless, it is advisable for future articles to report crop N uptake and the different sources of N supply (deposition, irrigation water, soil) when studying NL, so an approach based on N surplus could be conducted in addition to the recommended rate (Perego et al., 2012).

Surprisingly, *fertigation* did not reduce NL in comparison with side-dressing granular N fertilizer application. Frequent *fertigation* of vegetables (i.e. associated with drip irrigation) has often been recommended in the literature with the aim of increasing NUE and reducing losses, due to better synchronization between N availability and crop N uptake (Vázquez et al., 2006). However, in our study we selected data-pairs that used identical amounts of irrigation water and N, and in most cases, the conventional fertilizer control with granular N fertilizer was also split 2–4 times, producing relatively even N availability during the crop period; therefore, no significant effects on NL, Y or NUE were found for *fertigation*. Our strict selection criteria for *fertigation* experiments in this MA may have resulted in an underestimation of the potential of this technology to reduce NL. Therefore, the results are not conclusive and studies with valid comparisons of fertigation and conventional applications are needed.

The reductions in NL that resulted from replacing a fallow with a CC may have been related to some or all of the following factors: increased evapotranspiration, decreased water percolation below the root zone, a modification of nitrate concentration in the soil solution moving down the soil profile, and N uptake by the CC (Gabriel et al., 2012b). As expected, non-legume CC had a greater effect and their performance was very consistent. Grasses were the non-legume CC most used in the articles reviewed (95% of observations) followed by rape (5%). A closer look at the data is required to understand the legume effect. In nine out of 20 observations replacing the fallow with a legume decreased NL (Fig. 5). In five out of 20 observations the difference between the mean value of NL for the legume and the fallow was not significant. These observations are mainly occasional seasons of multi-year studies (Feaga et al., 2010; Gabriel et al., 2012b). There were 6 observations coming from the same study (Campiglia et al., 2011) in which a consistent increase in NL was observed when replacing a fallow with either hairy vetch, subclover or a hairy vetch/oats mix. In these observations nitrate concentration in the leachates greatly increased relative to the fallow and this was associated with a fast N release from legume residues that was not taken up by the cash crop. The risk of NL in this experiment was particularly high for two specific reasons. Firstly, it was conducted on a volcanic soil with more than 53% sand with high permeability and low N retention capacity. Secondly, the pepper cash crop following the CC grew slowly and was only able to absorb the N released from the legume residue during the final growth period. In the rest of the studies, replacing fallow with a legume CC increased soil N retention without a significant increase in NL, suggesting an enhancement of organically bound soil N. The high retention of N in soil stable organic matter pools in legume systems is related to re-coupling C and N cycles and increases the opportunity for fertilizer N savings without increasing NL potential risk (Gabriel et al., 2012b). In accordance with this process the results of this MA show that in irrigated systems the use of legume CC can increase Y and NUE without enhancing NL risk, if subsequent crops are fast-growing and able to exploit the N released from legume CC residues. A MA by Tonitto et al. (2006) focusing mainly on rainfed temperate systems found a negative or no effect on Y when replacing a fallow with a legume CC, with the negative effect increasing when crops were over-fertilized. In the studies in our MA involving a legume CC treatment, the mean N fertilizer application rate was 150 kg N ha^{-1} which was either equal to or below the recommended rate. This may explain the difference between our findings and the results of Tonitto et al. (2006). The effect of non-legume CC on Y was similar in our study and in Tonitto et al. (2006), with no difference between fallow and non-legume CC at recommended fertilizer levels.

The use of new N fertilizer technologies, such as NI and CRF, contributes to mitigating NL. The main reason is the slower release of nitrate to the soil solution achieved via these new compounds when compared with conventional fertilizers. The MA included some currently non-commercial NIs, such as nitrapyrin (which has been prohibited in the EU because of its pollutant effect), as well as commercial products (i.e. dicyandiamide – DCD, 3,4-dimethylpyrazole phosphate – DMPP). The efficiency of NIs and CRF is generally higher under conditions that favor high drainage or under high inputs of N fertilizer (Cui et al., 2011), and effects in our study were highly variable. Nitrification is inhibited by NIs for a short period (4–8 weeks depending on environmental conditions); therefore, their possible effect on NL and Y depends on the conditions during that period. If during the days following fertilizer application, there is a risk of intensive rainfall or high applications of irrigation water, NI could be very effective. Two different types of CRF fertilizers were included: low solubility compounds, such as isobutylidene diurea (IBDU) or urea-form, and soluble N granular fertilizer coated with an insoluble compound, such as polymeric resin or sulphur. Taking into account that most of these products release N for >3 months, fertilizer application timing is very important and affects the results. To compare NI and CRF with conventional fertilizers, the studies applied all the fertilizers at the same time. Consequently, the synchronization of N release and crop N uptake could have been affected. To avoid bias, studies comparing NI and CRF with conventional fertilizers should include different combinations of application time so the actual effect of the fertilizer technology can be isolated from other factors. The incorporation of fertilizer into the soil or the application on the surface may also affect efficiency. Walters and Malzer (1990) only found significant differences using nitrapyrin + urea when fertilizer was not incorporated into the soil. As a whole, the use of *Improved fertilizer technologies* was moderately effective for controlling NL and increasing NLSY, and even for CRF resulted in slightly reduced Y. Currently prices for NI and CRF are substantially greater than those for standard fertilizers (i.e. 20–30% for NI and >400% for CRF in the EU) and may add an additional cost for the farmer (Trenkel, 2010). The cost gap depends on raw material prices and varies greatly, but while NI is in a range that is attractive for agricultural use, the CRF are economical in agriculture only under exceptional conditions. Additional benefits of new fertilizer technologies, as NI contribution to reduce N oxides emissions (Merino et al., 2005), must be also taken into account in order to decide the best option for each agro-ecosystem.

In order to avoid bias toward short term experiments, the minimum measurement period considered was a growing season and the maximum 12 months. The minimum length was 2.5 months for horticultural crops (Zotarelli et al., 2007, 2009, 2011) and the maximum comprised either a full year cash-cover crop or fallow cycle (9 articles) or a two cash crop rotation (Li et al., 2007). It could be argued that in some of the multi-year studies a cumulative effect might influence the results, even though we considered that the potential bias derived from these studies was compensated for by the benefit of long-term measurements. Another potential bias derived from the experiment length might come from short studies focused on the growing season that did not measure NL after harvest. Taking into account that the fallow is frequently the most important leaching period, differences in annual leaching losses may be underestimated when NL is not monitored for a full year (Gabriel et al., 2012b). For example, a NI successfully used to control NL during the growing season may leave a larger residual Nmin at harvest. If no measurements are taken during the months following harvest then the mitigating effect could be overestimated. The recommendation for future studies is that NL measurements should be conducted for a full year, even if the growing period is shorter than this.

The methodology used to measure NL varied among the studies and could have had an effect on the determination. Nitrate leaching was based on direct measurements on lysimeter studies, or on a combination of nitrate concentration determined in soil solution samplings with either a simplified water balance or computer modeling to simulate water percolation beyond the root zone. Nevertheless, as the MA was based on the effect size calculated as a response ratio for each pair observation, differences linked to the measurement method tended to compensate (Hedges et al., 1999).

One of the goals of the MA was to learn from the experiences in areas already using irrigation to avoid repeating pollution problems in newly irrigated areas or areas that will be irrigated in the future. Care should always be taken when extrapolating results, but the MA allows for results to be extrapolated with more confidence than is possible when looking at individual studies (Jeffery et al., 2011). The inclusion of data from four zones of climate has helped to reduce bias, and even if most studies come from North America and Europe, the scientific literature selected represented a global data-set. In the same way, the inclusion of different soil textures should reduce bias in the present MA and enhance the reliability of the results. Nevertheless, other soil characteristics that may be relevant in NL or Y studies such as depth, stone content or soil organic matter content have not been included in the MA. Also, topography and hydrological characteristics of the field sites are rarely described in detail in the studies and have not been included. Consequently, care should be taken when extrapolating the results and attention paid to local conditions and information.

5. Conclusions

This study has highlighted the relative potential of four different strategies for reducing NL from irrigated cropping systems, providing information for policy development designed to mitigate nonpoint source N pollution. It is unique because it provides these comparisons at the broad level of strategy and also provides insight into the best technique within a given strategy to achieve reductions in NL. We have also analyzed the impacts of these approaches on yields, thus providing an important indication of the financial implications of these methods for the farmer.

Clearly, improving water management practices offers the greatest potential for reductions in NL to groundwater, and matching irrigation supply to crop needs should be the primary water management technique implemented. Further reductions in NL can be achieved if scheduling is improved, with a concurrent slight increase in crop yields. Deficit irrigation comes at the cost of crop yield but it also reduces NL.

Improved fertilizer management reduced NL by a mean of 40% relative to management where fertilizer use was not optimized, indicating that this should also be a priority when designing policies to mitigate NL. Our results suggest that a combination of optimal water management and applying recommended fertilizer rates should also be the most profitable choice for the farmer: crop yields for both approaches are reduced by less than 5% relative to the controls. Therefore, optimizing water and fertilizer management practices appear to be “win-win” choices for reducing NL.

Other strategies, while providing some benefits in reducing N losses, should only be recommended once the primary approaches of improving water and fertilizer management are implemented. The use of leguminous CC does not reduce NL with respect to the fallow but increases Y and NUE, opening the option of reducing N fertilizer application. The use of non-leguminous CC offers some potential with reductions of NL by 50% compared with bare fallow. However, cover cropping requires an additional labor and seed input by the farmer, which may not be compensated by the minor gains in yield obtained by CC use. Likewise, the use of fertilizer technologies like NI and CRF, while reducing NL by 20–30% compared with standard fertilizers, may incur an additional cost for the farmer. CRF may slightly reduce yields while the use of NI does not increase them relative to standard fertilizer, making the economic case for using improved fertilizer technologies to reduce NL less convincing.

Acknowledgements

We would like to acknowledge the work conducted by the researchers whose published results were used for this MA. This work was part of the N-TOOLBOX project (N-TOOLBOX-227156) which was co-funded by the European Commission, Directorate General for Research, within the 7th Framework Programme of RTD, Cooperation Theme 2 – Biotechnology, Agriculture & Food. Thanks also to the CICYT from Spain (project AGL2011-24732) and the Comunidad de Madrid (project S2009/AGR-1630).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2013.04.018.

References

Bruin, A.J., Coelho, B.R.B., Beyaert, R.P., Reeleder, R.D., Roy, R.C., Capell, B., 2010. High value crops in coarse-textured soil and nitrate leaching – how risky is it? Can. J. Plant Sci. 90, 515–528.

Bundy, L.G., Andraski, T.W., 2005. Recovery of fertilizer nitrogen in crop residues and cover crops on an irrigated sandy soil. Soil Sci. Soc. Am. J. 69, 640–648.

Campiglia, E., Mancinelli, R., Radicetti, E., Marinari, S., 2011. Legume cover crops and mulches: effects on nitrate leaching and nitrogen input in a pepper crop (*Capsicum annuum* L.). Nutr. Cycl. Agroecosyst. 89, 399–412.

Cui, M., Sun, X., Hu, C., Di, H.J., Tan, Q., Zhao, C., 2011. Effective mitigation of nitrate leaching and nitrous oxide emissions in intensive vegetable production systems using a nitrification inhibitor, dicyandiamide. J. Soils Sediments 11, 722–730.

Diez, J.A., Caballero, R., Roman, R., Tarquis, A., Cartagena, M.C., Vallejo, A., 2000. Integrated fertilizer and irrigation management to reduce nitrate leaching in Central Spain. J. Environ. Qual. 29, 1539–1547.

European Commission, 2000. Council directive of 23rd October 2000 establishing a framework for community action in the field of water policy (2000/60/ec). Official Journal of the European Community (22/12/2000 L2327/2001 to 2073).

F.A.O., I.I.A.S.A., 2007. Mapping biophysical factors that influence agricultural production and rural vulnerability. Environmental and natural resources series, Rome, Italy.

FAOSTAT, 2012. Aquastat. http://www.fao.org/nr/water/aquastat/main/index.stm (verified on 05.12.12).

Feaga, J., Selker, J., Dick, R., 2010. Long-term nitrate leaching under vegetable production with cover crops in the pacific northwest. Soil Sci. Soc. Am. J. 74, 186–195.

Fereres, E., Soriano, M.A., 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58, 147–159.

Follet, R.F., Keeney, D.R., Cruse, R.M., 1991. Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Science Society of America, Madison, WI, USA.

Gabriel, J.L., Almendros, P., Hontoria, C., Quemada, M., 2012a. The role of cover crops in irrigated systems: soil salinity and salt leaching. Agric. Ecosyst. Environ. 158, 200–207.

Gabriel, J.L., Munoz-Carpena, R., Quemada, M., 2012b. The role of cover crops in irrigated systems: water balance, nitrate leaching and soil mineral nitrogen accumulation. Agric. Ecosyst. Environ. 155, 50–61.

Gabriel, J.L., Quemada, M., 2011. Replacing bare fallow with cover crops in a maize cropping system: yield N uptake and fertiliser fate. Eur. J. Agron. 34, 133–143.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150–1156.

Isidoro, D., Quilez, D., Aragues, R., 2006. Environmental impact of irrigation in La Violada district (Spain). II. Nitrogen fertilization and nitrate export patterns in drainage water. J. Environ. Qual. 35, 776–785.

Jeffery, S., Verheijen, F.G.A., Van Der Velde, M., Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric. Ecosyst. Environ. 144, 175–187.

Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. Forest Ecol. Manage. 140, 227–238.

Knox, J.W., Weatherhead, E.K., 2005. The growth of trickle irrigation in England and Wales: data, regulation and water resource impacts. Irrig. Drain. 54, 135–143.

Ledgard, S.F., Menneer, J.C., Dexter, M.M., Kear, M.J., Lindsey, S., Peters, J.S., Pacheco, D., 2008. A novel concept to reduce nitrogen losses from grazed pastures by administering soil nitrogen process inhibitors to ruminant animals: a study with sheep. Agric. Ecosyst. Environ. 125, 148–158.

Li, X., Hu, C., Delgado, J.A., Zhang, Y., Ouyang, Z., 2007. Increased nitrogen use efficiencies as a key mitigation alternative to reduce nitrate leaching in North China plain. Agric. Water Manage. 89, 137–147.

McIsaac, G.F., David, M.B., Gertner, G.Z., Goolsby, D.A., 2001. Eutrophication – nitrate flux in the Mississippi river. Nature 414, 166–167.

Merino, P., Menéndez, S., Pinto, M., González-Murua, C., Estavillo, J.M., 2005. DMPP reduces nitrous oxide emissions from grassland after slurry application. Soil Use Manage. 21, 53–57.

Moreno, F., Cabrera, F., Murillo, J.M., Fernandez, J.E., Fernandez-Boy, E., Cayuela, J.A., 1996. Nitrate leaching under irrigated agriculture. Sustainability of irrigated agriculture, Vimeiro, Portugal, pp. 407–415.

Perego, A., Basile, A., Bonfante, A., De Mascellis, R., Terribile, F., Brenna, S., Acutis, M., 2012. Nitrate leaching under maize cropping systems in Po Valley (Italy). Agric. Ecosyst. Environ. 147, 57–65.

R Development Core Team, 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rabalais, N.N., Turner, R.E., Scavia, D., 2002. Beyond science into policy: gulf of Mexico hypoxia and the Mississippi river. Bioscience 52, 129–142.

Romic, D., Romic, M., Borosic, J., Poljak, M., 2003. Mulching decreases nitrate leaching in bell pepper (*Capsicum annuum* L.) cultivation. Agric. Water Manage. 60, 87–97.

Sepaskhah, A.R., Tafteh, A., 2012. Yield and nitrogen leaching in maize field under different nitrogen rates and partial root drying irrigation. Int. J. Plant Prod. 6, 93–114.

Sharma, P., Shukla, M.K., Sammis, T.W., Adhikari, P., 2012. Nitrate-nitrogen leaching from onion bed under furrow and drip irrigation systems. Appl. Environ. Soil Sci. 2012, Article ID 650206, 17 pages.

Soil Survey Staff, 2003. Keys to Soil Taxonomy. USDA, Natural Resources Conservation Service, Madison, WI, USA.

Tarkalson, D., Payero, J.O., Ensley, S.M., Shapiro, C.A., 2006. Nitrate accumulation and movement under deficit irrigation in soil receiving cattle manure and commercial fertilizer. Agric. Water Manage. 85, 201–210.

Thorup-Kristensen, K., Magid, J., Jensen, L.S., 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79, 227–302.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.

Tonitto, C., David, M.B., Drinkwater, L.E., 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: a meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ. 112, 58–72.

Trenkel, M.E., 2010. Slow- and Controlled-release and Stabilized Fertilizers: An Option for Enhancing Nutrient Efficiency in Agriculture. IFA, Paris, France.

Van Groenigen, J.W., Velthof, G.L., Oenema, O., Van Groenigen, K.J., Van Kessel, C., 2010. Towards an agronomic assessment of N_2O emissions: a case study for arable crops. Eur. J. Soil Sci. 61, 903–913.

Vázquez, N., Pardo, A., Suso, M.L., Quemada, M., 2005. A methodology for measuring drainage and nitrate leaching in unevenly irrigated vegetable crops. Plant Soil 269, 297–308.

Vázquez, N., Pardo, A., Suso, M.L., Quemada, M., 2006. Drainage and nitrate leaching under processing tomato growth with drip irrigation and plastic mulching. Agric. Ecosyst. Environ. 112, 313–323.

Waddell, J.T., Gupta, S.C., Moncrief, J.F., Rosen, C.J., Steele, D.D., 2000. Irrigation- and nitrogen-management impacts on nitrate leaching under potato. J. Environ. Qual. 29, 251–261.

Walters, D.T., Malzer, G.L., 1990. Nitrogen management and nitrification inhibitor effects on N-15 urea. 1. Yield and fertilizer use efficiency. Soil Sci. Soc. Am. J. 54, 115–122.

Zotarelli, L., Dukes, M.D., Scholberg, J.M.S., Femminella, K., Munoz-Carpena, R., 2011. Irrigation scheduling for green bell peppers using capacitance soil moisture sensors. J. Irrig. Drain. Eng. 137, 73–81.

Zotarelli, L., Dukes, M.D., Scholberg, J.M.S., Munoz-Carpena, R., Icerman, J., 2009. Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agric. Water Manage. 96, 1247–1258.

Zotarelli, L., Scholberg, J.M., Dukes, M.D., Munoz-Carpena, R., 2007. Monitoring of nitrate leaching in sandy soils: comparison of three methods. J. Environ. Qual. 36, 953–962.