UNIVERSITA' DEGLI STUDI DI PADOVA

SCUOLA DI DOTTORATO DI RICERCA IN

SCIENZE DELLE PRODUZIONI VEGETALI

INDIRIZZO AGRONOMIA AMBIENTALE - CICLO XXI

Dipartimento di Agronomia Ambientale e Produzioni Vegetali

ACHIEVING THE NITRATE DIRECTIVE: FIELD MEASUREMENTS AND SIMULATION APPROACH

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DATA CONSEGNA TESI

(25/01/2010)

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SUMMARY

RIASSUNTO

Una produzione sostenibile richiede inputs di azoto (N) e fosforo (P) per compensare sia le asportazioni che le perdite a livello campo. Spesso però, le perdite di azoto sono positivamente correlate alle quantità di azoto distribuito. A tutto ciò va poi sommato l'effetto del clima (piovosità) e della caratteristiche del suolo, nel promuovere o limitare le perdite di N. In linea generale, le perdite di nutrienti, in particolare di N, dovrebbero essere minimizzate in quanto, identificate come causa principale dell'inquinamento dei corpi idrici. La relazione tra l'incremento della densità animale nelle aziende zootecniche e la qualità delle acque su scala europea, ha spinto la Comunità Europea con la legge EU 91/676 a fissare un limite massimo di N di origine zootecnica pari a 170 kg N ha^{-1}, come valore massimo precauzionale per aree individuate come "sensibili all'inquinamento da nitrati". Sebbene i fertilizzanti di origine zootecnica possano contribuire all'inquinamento dei corpi acquiferi, va però, sottolineato che l' "effetto inquinante" delle fertilizzazioni azotate va determinato considerando inputs e outputs isieme, invece che del solo input. E' comunque, innegabile che gli insediamenti zootecnici sia legato ad un maggior rischio di eccedere i limiti imposti dalla Direttiva Nitrati di 11.3 mg^{-1}, specialmente perché le deiezioni zootecniche, generalmente, sono difficili da gestire. La tesi ha valuta i) la capacità dei limiti imposti dalla EU Direttiva Nitrati, nel limitare le perdite di azoto in falda ii) la determinazione delle migliori pratiche agricole applicabili a parte della Regione Veneto per controllare le perdite di N e iii) la valutazione dei limiti EU 91/676 nel contenere i rilasci, sotto l'effetto dei cambiamenti climatici durante il periodo 2010-2100. I risultati ottenuti mostrano che i nitrati nell'acqua di drenaggio sono influenzati sia dagli inputs di N e acqua (irrigazioni+pioggia). Alte concentrazioni di NO_3-N sono state osservate nelle tesi concimate con le più alte quantità di fertilizzante (400 kg N ha^{-1}), mentre le più basse a quantità minori (145 kg N ha^{-1}). L'acqua distribuita ha influenzato la concentrazione di nitrato nell'acqua di drenaggio. Alte

concentrazioni (>40 ppm) sono state misurate in tesi irrigate con 800 mm acqua, mentre molto basse nelle tesi irrigate con le quantità più alte di acqua (1700 mm). Il limite di 11.3 ppm è stato superato solo il 5% delle misurazioni ad 1700 mm mentre, per il 30% ad 800 mm. I risultati della modellizzazione ha messo in luce un ottima capacità del limite 170 kg N ha^{-1} nel prevenire il superamento di 11.3 ppm NO_3-N, all'interno delle aree vulnerabili. Inoltre, la concentrazione di 11.3 ppm non è mai stata superata in nessuno dei numerosi scenari testati a differente quantità di acqua (irrigazione+pioggia). Il limite di 340 kg N ha^{-1}, (aree non vulnerabili), ha mostrato buona capacità nel controllare le lisciviazioni solo ad l'input d'acqua inferiori a 1100 mm/anno. Oltre, 1200 mm, al fine di rispettare i limiti UE, si consiglia di ridurre le concimazioni a 230-250 kg N ha^{-1}.

I cambiamenti climatici potrebbero avere un forte impatto sia sullo sviluppo delle piante che sul ciclo dell'azoto, sotto la spinta di un incremento dei giorni di siccità e delle temperature. La concentrazione di NO_3-N nell'acqua di drenaggio potrebbe aumentare del +11.3% al 2080, mentre la produzione di mais potrebbe diminuire del -10.5 % al 2080. Nonostante le simulazioni abbiano messo in luce un trend di incremento delle lisciviazioni nel prossimo futuro, il limite UE 170N, non ha mai ecceduto la concentrazione di 11.3 ppm a tutte gli inputs di acqua simulati. Il limite UE 340N ha ecceduto sempre il limite di 11.3, anche se il superamento del limite è più consistente alla fine del periodo della simulazione. I risultati, suggeriscono altresì, che una riduzione delle inputs azotati da 340 a 230 kg N ha^{-1}, consentirebbe sia di limitare i rilasci di nitrati (soprattutto ad input superiori a 400 mm annui) che di ottenere produzioni, lievemente inferiori, ma economicamente remunerative.

La tesi fornisce risultati interessanti sul comportamento dei rilasci dei nitrati misurati alle dosi massime di N organico ammissibili dalla Direttiva Nitrati. Questo studio ha altresì, fornito indicazioni molto importanti nell'uso nelle quantità massime di N utilizzabili per limitarne le lisciviazioni, nel breve periodo che nel lungo (sotto l'effetto dei cambiamenti climatici). Nondimeno questa tesi fornisce basi scientifiche per decisioni governative.

SUMMARY

Sustainable crop production requires nitrogen (N) and phosphorus (P) inputs to compensate for the elements removed from the system by plant uptake and losses. Often, however, Losses of N are positively related to input levels. Also the effect of climate (precipitation) and soil properties can promote or limit N loss. Agricultural losses should be minimized as they largely determine the quality of water bodies. The relationship between animal density and water quality in Europe, has lead the European Union, throughout the Nitrates Directive, to set a limit of 170 kg N manure ha per year as a precautionary application threshold for regions that are vulnerable to N leaching. Also, although application rates can affect environmental quality of the water bodies, the effective environmental effects are determined by all inputs and outputs together instead of the manure input only. Farming in general is undeniably associated with the risk of exceeding the EU target of 11.3 ppm, especially because manures are inherently difficult to manage. The purposes of this thesis were to i) evaluate the performances of the N limits, imposed by the EU nitrate Directive, in limiting N loss in groundwater, ii) identify the best agricultural practices applicable in the Veneto Region in order to control the nitrate pollution, and iii) evaluate the performance of the EU Nitrate Directive limits under the effect of the climate change, from 2010 to 2100.

Results show that nitrate in drainage water was influenced by N and water inputs. Higher concentrations were measured theses fertilized with the higher amount of N (400 kg N ha^{-1}) while lower ones at lower N rates (145 kg N ha^{-1}). Water inputs clearly affected NO_3-N concentration in the drainage water. Higher concentrations were measured in plots irrigated with the lower amount of water (800 mm), while lower concentrations were found in plots with higher water inputs (1700 mm). The EU target of 11.3 ppm was exceeded for the 5% of the total measurements under 1700 mm, while 30% at 800 mm yr^{-1}.

Simulations that the EU Nitrate Directive threshold of 170 kg N ha^{-1} did not exceed the 11.3 ppm at any water inputs considered in our scenarios. Also it has never exceeded the EU target 11.3 ppm at any water inputs considered in our scenarios. Maize on loamy soil in the north of Italy can utilize fertilizer N up to 340 kg ha^{-1} without exceeding a target value of 11.3 mg l^{-1} in the groundwater. However, the water input should not exceed 1100 mm annually. However, our results suggest fertilizations should be reduced to between 235 and 270 when water inputs are greater than 1100 mm.

Simulations revealed that N-cycle and crop grain yield may be sensitive to gradually increasing temperature, days of drought and decreasing of precipitation. Nitrate-N concentration could increase about +11.3% at the end of the simulation, while crop maize production could decrease about -10.5% at the end of simulation. Despite simulations showed that N loss could increase in the future, the EU limit of 170N has never exceed the threshold of 11.3 ppm at any water inputs considered in our scenarios. In contrast, the EU limit of 340N exceeded always the concentration of 11.3 ppm NO_3-N, however, 340N was less effective in limiting N loss at the end of the simulation. Results, also suggest when annual water inputs (irrigation) are lower than 400 mm a reduction of the N fertilizations from 340 to 230 kg N ha^{-1} should allow to limit N loss and, at the same time, reach high crop maize production,

This thesis provide useful information about the behavior of the N loss at the N rate allowed to the EU Nitrate Directive. Our results provide interesting information that can be useful in order to improve the management of N fertilizations and maximize crop productivity, in view of complying with the European environmental policy both during an initial phase and a long term period. Nonetheless our results provide scientific basis and references for governments' decision-making from the view of regional climate change response.

“Alla mia famiglia, le persone

che hanno saputo, con amore, guidarmi

verso ciò che fieramente sono oggi”

CHAPTER 1

PERMISSIBLE N FERTILIZATION AND IRRIGATION RATES UNDER MAIZE CROP IN THE VENETO REGION TO COMPLY WITH THE NITRATE DIRECTIVE AIMS

ABSTRACT

The north of Italy is characterized by intensive livestock faming systems and land applications of manures and slurry remain a traditional practice. Sustainable agriculture management requires assessment of N fertilization and the potential for nitrate losses. Moreover, the EU Nitrate Directive imposes limitation on the use of manure and mineral fertilizer to specified limits. We used an experimental facility with 20 lysimeters to investigate the loss of nitrate in drainage water from maize crops grown under a range of rates of water and N applications in two soils of the Veneto Region, Italy. Four levels of water inputs (800, 1100, 1400 and 1700 mm yr^{-1}) were combined with four levels of N from manure (85, 170, 225 and 340 kg ha^{-1} yr^{-1}). Maize grain yield and above ground biomass were consistently increased by N fertilizations and water inputs. Grain yields were near maximum with 1400 mm yr^{-1} of water. In contrast, the response of grain yield and AGB to N inputs was positive up to 340 kg N ha^{-1}. Productivity yield efficiency tended to decrease with increasing applied nitrogen. In contrast, water inputs slightly increased the efficiency. Higher efficiency at higher water regimes was attributed to the higher ET which increased N transported to the roots. NO_3-N concentrations in drainage water increased in response to the increase of applied N. Water inputs markedly affected NO_3-N concentrations in the drainage water. Higher concentrations were measured in lysimeters irrigated with the smallest amount of water. Lower nitrate concentrations, but higher N loss, in heavily watered lysimeters were probably due to water dilution effects and higher denitrification losses. High nitrate concentration in drained water were measured in treatments that lost a lower amount of NO_3-N, while lower NO_3-N concentration were observed in whose lysimeters that lost high amount of nitrate-N.

INTRODUCTION

In the Veneto region of north eastern Italy the protection of water resources is of particular importance. The deep aquifers are used for drinking water supplies and shallow ones have an impact on the lagoon of Venice and the Adriatic Sea (Borin et al., 1997). The greatest groundwater pollution risk in the Veneto Region is nitrate leaching which is linked to agricultural management practices (Marchetti et al., 2001), high rainfall (average annual precipitation 800 to 1200 mm), and subsurface hydrological properties. Agricultural nitrogen losses in form or nitrate leaching should be minimised as they largely determine the quality of water bodies in this region (Rambalais, 2002; Schröder et al., 2007;).

Growing concern about the effects of agricultural practices on the environment led the European Union (EU) to develop new strategies to balance economic efficiency and negative effects on the environment. The EU nitrate directive (91/676 CEE) aims to reduce water pollution caused by nitrate from agricultural sources by obliging every member state to identify and designate Nitrogen Vulnerable Zones (NVZ) (Anonymous, 2006) and to introduce Action Programmes (AP) in these areas (Mantovi et al., 2006; Ventura et al., 2008). The EU nitrate directive set 170 kg N ha^{-1} as a precautionary application threshold for regions that are vulnerable to N leaching, and 340 kg N ha^{-1} for all remaining regions that are not vulnerable to N leaching (Mantovi et al., 2006; Schröder et al., 2007; Ventura et al., 2008; Capri et al., 2009).

Several studies have addressed various aspects of nutrient pollution in the Veneto region (Borin et al., 2001; Morari et al., 2004; Polese et. al., 2007) and they highlighted that intensive agricultural practices may be lead to N pollution of ground water. Farming and livestock production in particular is associated with the risk of exceeding the EU target of

11.3 mg l^{-1} nitrate in water (Schröder et al., 2007), especially because manures are inherently difficult to manage (Schröder, 2005).

Manure management for maize production represents an important issue which deserves special analysis. This crop occupies almost the 51% of the agricultural area in the Veneto (Anonymus, 2000) region and it is grown on loamy and loamy-sandy soils that are sensitive to N leaching. Moreover, variability of hydrology, climate and management of land use may result in large N losses to groundwater. For instance, at the foot of the Alps the soils are characterized by gravelly loam textures and a deep heterogeneous gravel layer, within 1-2 m of the soil surface, that is directly connected with the groundwater. This area is very important for the recharge of groundwater used as sources of drinking water and for agricultural uses. Pollution of groundwater in this area would affect the water quality of the rest of the Veneto region. The coarse-textured soils have a high nitrate leaching potential because they retain less water than fine textured soil (Maddux and Halvorson, 2008). In addition, the soils of the Venetian Lagoon Watershed are also well drained and sandy, and often have water tables within 4 m of the surface. Because of the high N fertilization rates applied, the sandy texture, and the short distance to the water table, this area is also subject to excessive nitrate pollution of aquifers.

The Veneto region was identified as an NVZ in 2006 (Anonymous, 2006), and concentrations above 50 mg N l^{-1} in groundwaters have been measured over a three year period (ARPAV, 2002, 2003, 2004, 2005), so that the risk of exceeding the EU Directive Nitrate concentration threshold for drinking water (UEL) of 11.3 mg Nitrate-N l^{-1} is particularly high. Groundwater pollution by agricultural activities need to understood in order to identify strategies to improve the Action Programme and to optimize the efficiency of irrigation and fertilization. It is anticipated these will take the form of best management practices (BMPs) to minimize environmental impacts of nitrate leaching while maintaining agricultural productivity (Mostaghimi et al., 1997).

The main objective of this study is to investigate the combinations of water and N fertilizations inputs that can be applied to maize crops grown on sandy-loamy and loamy soils and their influence on nitrate leaching. In particular we aimed to evaluate whether local farming practices are likely to result in nitrate leaching and whether the target limits of 170 and 340 kg N ha^{-1} set by the EU Directive are appropriate in the Veneto region. We investigated the fate of nitrogen in soil in 20 reconstructed lysimeters that had received a range of N fertilization in the form of pelletized poultry manure at rates and volumes of irrigation used in the region. We investigated two locally important soils types with diverse hydrological and pedological characteristics. Maize was used as it is the predominant crop of the Veneto NVZ.

MATERIAL AND METHODS

The lysimeters were installed on a 60 m^2 flat area at the experimental farm of the faculty of Agronomy of the University of Padova (Veneto Region) in an area designated a Nitrogen Vulnerable Zone (Anonymous, 2006) (45°20'26'' N, 11°58'0'' E, elev. 8 m), (Fig. 1). Twenty gravimetric lysimeters were established at the site in the early 1970s. The lysimeters have a sliding roof that can cover the lysimeters automatically in case of rain. The site provides facilities to accurately measure nutrient and water dynamics throughout the year as well as the yield and above ground biomass of crops. Each lysimeter is a 1 m square cement tank, 1.5 m deep. A funnel at the bottom of each lysimeter is connected with an underground chamber by a tube. This allows the collection of the leachate and measurements of the watertable (Fig. 2).

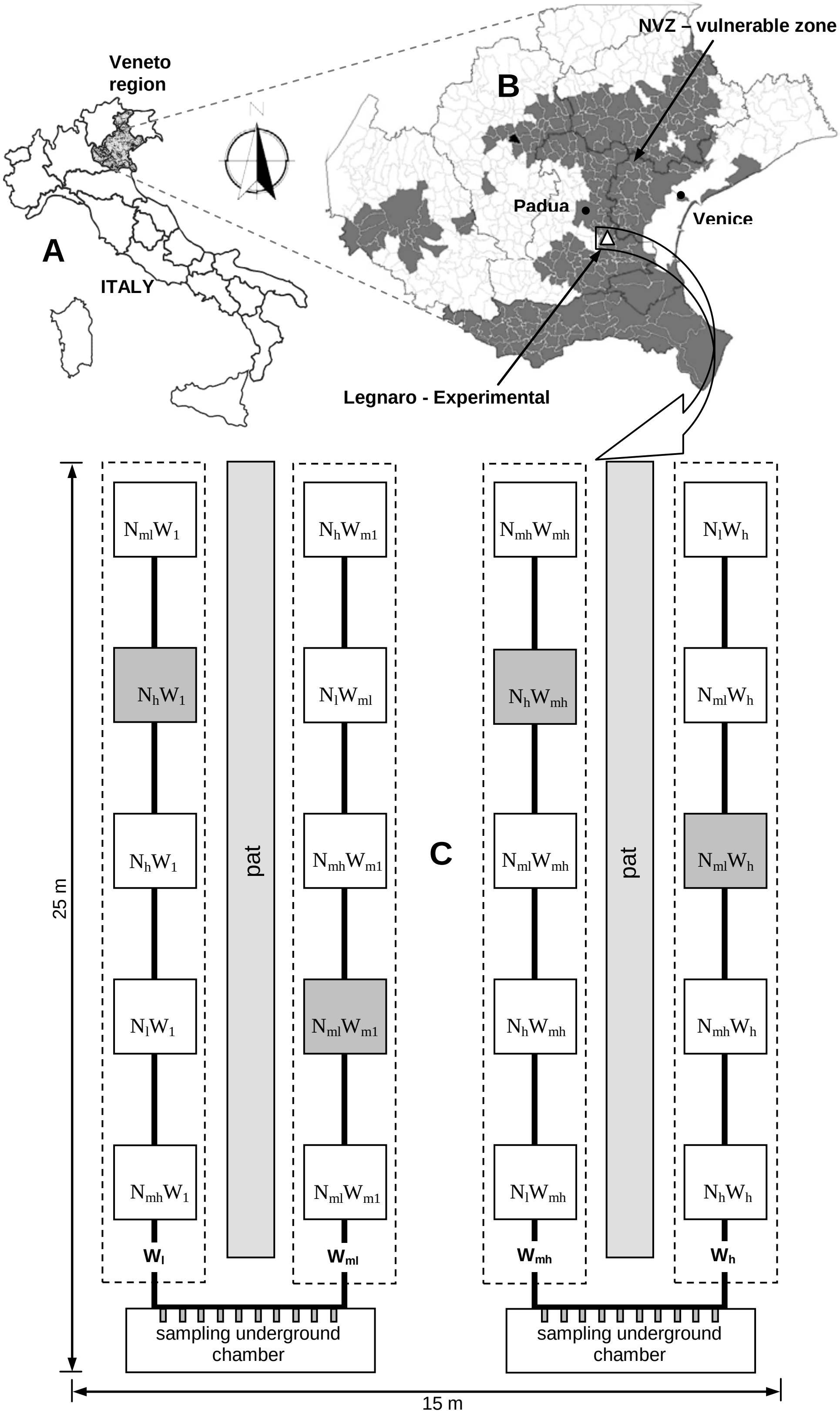

Figure 1. Location of Veneto region (A), its Nitrogen Vulnerable Zone (B) and experimental site (C). The map of the experimental site shows the treatments applied for each lysimeter: "N" identifies the amount of Nitrogen applied whilst "W" the amount of irrigation and precipitation. Loamy soils are represented by the white squares, sandy-loamy by grey ones.

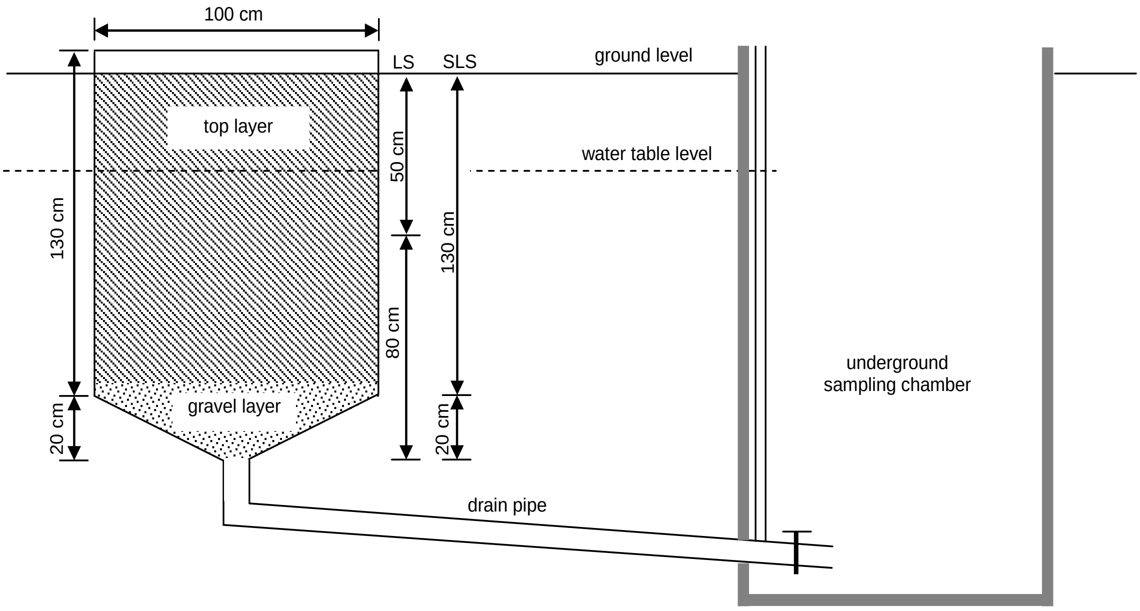

Figure 2 – Diagram of the lysimeter installations.

Two soils, collected from arable fields, were chosen to represent the predominant textures found within the Veneto NVZ: A loamy soil (LS) from the area at the foot of the Alps and a silty loam soil (SLS) from the Venetian Plain NVZ area. Physical and chemical properties of each soil are shown in Table 1. The SLS soil was used to a depth of 130 cm, whereas the depth used for the LS soil was 50 (Fig. 2). When filling the lysimeters a layer of gravel (2-4 Ø cm), was first placed in the funnel at the bottom of each container. Gravel allowed drainage through the sampling tube and avoided blockage of the drainage flow.

Table 1. chemical and physical characteristics of SLS and LS soils.

soil	depth	sand	silt	clay	soil moisture	bulk density	organic matter	pH	CEC	total $CaCO_3$	active $CaCO_3$	N
	(cm)	(%)	(%)	(%)	(% weight)	(t/m^3)	(%)		(meq/ 100 g)	(%)	(%)	(‰)
SLS	130	31	54	15	19.79	1.496	1.41	8.13	47.22	20.1	4.1	1.0
LS	50	36	44	20	15.14	1.316	1.14	8.25	24.29	32.8	3.4	0.9

The filling was done very carefully by packing layers of about 10-20 cm of soil at a time in order to obtain a bulk density as close as possible to *in situ* field conditions. After packing each lysimeter was irrigated with 35 mm to assist settling.

The climate of the area is subhumid (FAO-UNEP, 1977) with highest temperatures during July and August and precipitation mainly distributed in spring and autumn. Climate data were collected at the experimental site for the duration of the experiment and the monthly data are shown in Figure 3. The average air temperatures were, 13.5, 13.9 and 13.6 °C respectively in 2006, 2007 and 2008. Rainfall, at the lysimetrical area, was 699, 640 and 958 mm for the corresponding years. In 2008 almost the total amount of rain fell in the 4 months from September to December. Precipitation was about 400 mm in 2008 whilst in 2006 and 2007, for the same 4 month periods, it was 195 and 272 mm (Fig. 3).

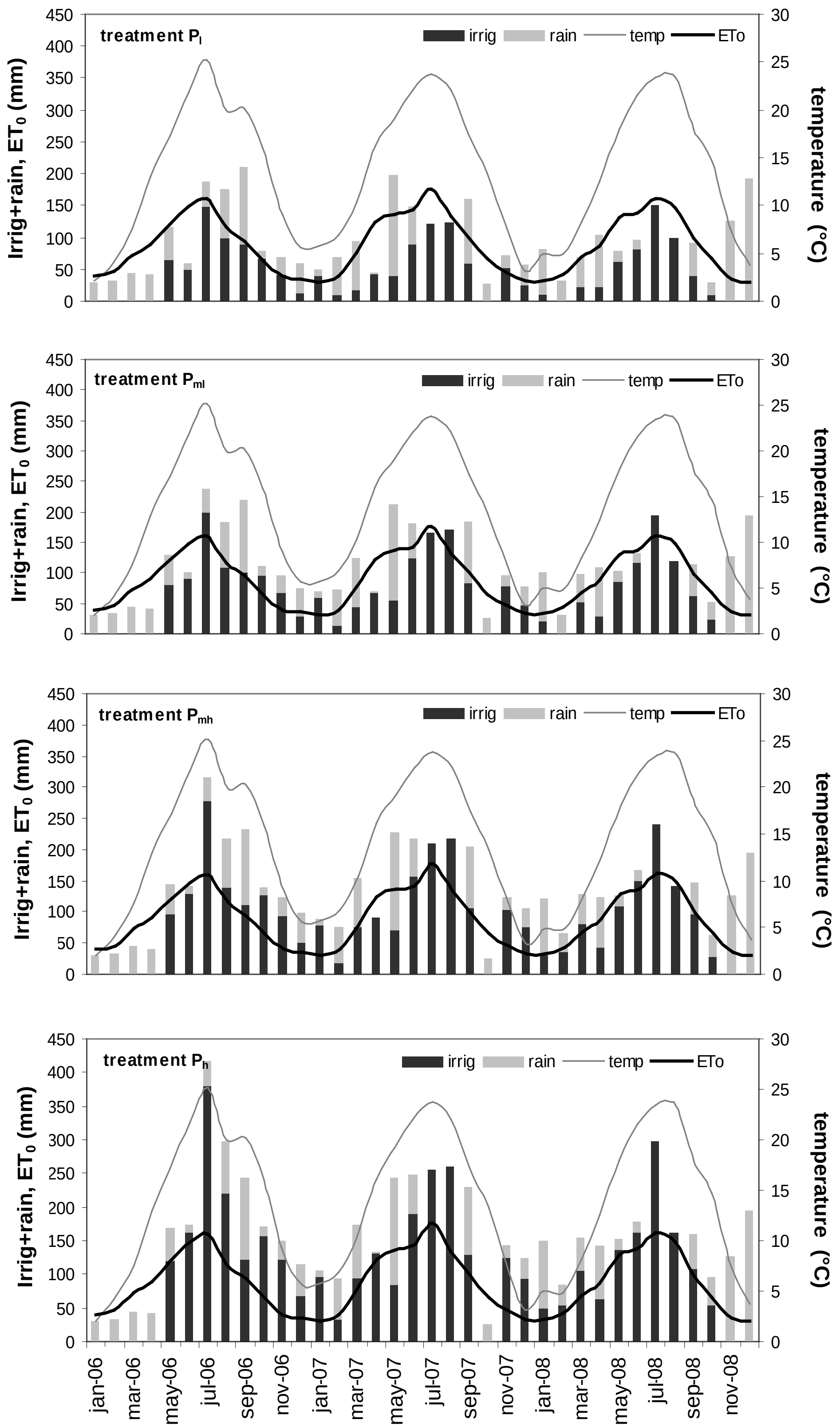

Figure 3. climatic conditions at the lysimeter site. Monthly precipitation (rain), monthly irrigation (irrig), potential evapotraspiration (ET_0 calculated with Penman-Monteith method) and air temperature (temp).

TREATMENTS AND SAMPLING

Four levels of water inputs (irrigation and precipitation) (800, 1100, 1400 and 1700 mm yr^{-1}) were combined with four levels of nitrogen application from manure (85, 170, 225 and 340 kg ha^{-1} yr^{-1}) in the SLS soil whilst four levels of irrigation (800, 1100, 1400 and 1700 mm) and 2 levels of nitrogen (170 and 340 kg ha^{-1} yr^{-1}) were used for the LS soil (Fig. 1). Given that the total number of lysimeters available was 20 units, only 2 fertilizations rates were tested in the LS soil. Emphasis was given to the SLS soil which is more representative of the NVZ.

No replication was used because due to the high variability of fertilized used in the NVZ (Anonymous, 2006) the experiment tried to reflect such high variability with the limited number of lysimeters available. Fisher, 1999 argued that studies conducted on experimental units without rigorous design (no replications) may be appropriate for conducting experiment that are very difficult or expensive to manage. Our logistical constrains, such as the high cost of new installations and the limited number of lysimeters, prevented a rigorous application of a statistical experimental design. Also the lysimeters in NVZ are used for up scaling at regional level the effects of such high variability fertilization practices, which is replicated in each lysimeter. Statistical analysis was performed by using of regression analysis. This method in grazing research is an alternative to replicating treatments with experimental units. (Fisher, 2000). This approach in fact, uses the deviation from regression to estimate experimental error (Fisher, 2000).

Nitrogen was applied as pelletized poultry manure (PPM) at 4 rates, in treatment N_l (N_l=low) the N rate was 85 kg N ha^{-1} yr^{-1} , whilst in the N_{ml} (N_{ml}=medium-low) it was 170 kg N ha^{-1} yr^{-1}. In N_{mh} (N_{mh}=medium-high) the rate was 225 kg and in N_h (N_h=high) 340 kg N ha^{-1} yr^{-1}. These rates of N were chosen because 170 and 340 kg N ha^{-1} yr^{-1} are the maximum that it can be spread in NVZ and non NVZ areas, respectively. PPM was applied each year just before sowing (on 05/05/2006, 14/04/2007, and 03/04/2008) and immediately incorporated into the surface 30 cm in order to minimize volatilization losses. An additional fertilization with 60 kg N ha^{-1} yr^{-1} urea (split over 3 dates, 20 kg N each) was applied 1 week after sowing, and 30 and 60 days after emergence (05/05, 05/07, 03/08 in 2006; 17/05, 22/05, 27/06 in 2007 and 07/05, 05/06, 24/06 in 2008). All treatments were supplied with the adequate amounts of P and K, so these nutrients were not yield-limiting (200 kg ha^{-1} yr^{-1} P_2O_5 and 150 kg ha^{-1} yr^{-1} K_2O).

Irrigations were started on 01/05/2006. Maize was irrigated during the growing season whilst during the off season, from October to April, the lysimeters were irrigated only when rainfall did not reach a determined amount of water per month (Table 2). The crops were irrigated by drippers once a week. Four rates of water inputs were chosen: W_l (W_l =low), 800 mm which is the yearly average rainfall in Padova province, W_{ml} (W_{ml}=medium-low), 1100 mm, W_{mh} (W_{mh}=medium-high), 1400 mm and W_h (W_h=high), 1700 mm which is the yearly average rainfall for the flat area of the spring and groundwater recharge areas at the foot of the Alps. The purpose of the irrigation was to reach a pre-determined rate of water per month (Table 2). When the amount of monthly precipitation was not reached the required volume shown in Table 2, was applied in order to compensate. However, when rainfall was heavy and exceeded the monthly limit irrigation was stopped until the next month. When precipitation was very heavy (over 100 mm d^{-1}) the automatic-sliding roof covered the experimental site to prevent excessive watering. We chose these amounts of water because we wanted to simulate the range of precipitation typical of the Veneto Region. In the 2006 and 2007 irrigation was increased to compensate for the high rate of evapotranspiration of maize during the summers. The treatments are hereafter reported as combination of the nitrogen and water inputs for example N_lW_h (lowest N applied and highest irrigation).

Table 2. Monthly amount of water applied (mm) (irrigation+rainfall)

month	a	b	c	d
Jan	50	69	88	106
Feb	40	55	70	85
Mar	70	96	123	149
Apr	70	96	123	149
May	80	110	140	170
Jun	90	124	158	191
Jul	80	110	140	170
Aug	50	69	88	106
Sep	60	83	105	128
Oct	80	110	140	170
Nov	70	96	123	149
Dec	60	83	105	128
total	**800**	**1100**	**1400**	**1700**

Cultivation was carried out following the traditional local practices. Maize (*Zea mais* L.) was sown on 05/05/2006, 10/04/2007 and 03/04/2008 using. In 2006 and 2007 cv Costanza, FAO class 600 was used whilst in 2008 Pioneer hybrid P88, FAO class 500, was sown. The crops were sown in rows (8 plants/m^2) with a plant density of 80,000 plants ha^{-1}. However, density was reduced to 70,000 plants ha^{-1} 1-2 weeks after emergence to even out variations due to unevenness of in the emergence of maize seeding (in both 2007 and 2008). Maize was also sown in the 60 m^2 area surrounding the lysimeters at the same density (excluding the paths) to reproduce the climatic and physiological conditions typical of the cultivated crops in the open field.

The following sampling and measuring activities were regularly carried out on the site:

1. *precipitation and irrigation*: precipitation as well as maximum, minimum, average temperature, wind speed and radiation were measured three times a day by a meteorological station located 50 m from the site whilst irrigation was directly measured in the tanks. Rain that fell when the sliding roof was closed was not considered.

2. *drainage*: water drainage from each lysimeter was measured once a week by weighing it with an electronic balance. During some periods (autumn-winter) when precipitation did not reach high levels (for example on 18-20 September 2006, 170 mm of rain) an extra sampling was made in order to prevent saturation of the lysimeters. Once collected, samples were immediately stored at -25 °C and analyzed for nitrate-N within 15-20 days.
3. *soil moisture*: Soil was sampled two times each year, before sowing (01/05/2006 and 19/03/2007) and after harvesting (08/09/2006 and 29/10/2007). Samples were taken at intervals of 20-25 cm up to 120 cm. Soil-moisture was calculated after drying at 105° for 48 hours. In addition, soil samples were air-dried and sieved to 2 mm for chemical analysis. In 2008, a TDR (Moisture Point® MP-917) were used to measure the soil moisture. 4 TDR probes (Moisture Point® PRB-F) were installed in the lysimeters $N_{ml}W_{l}$, $N_{ml}W_{ml}$, $N_{ml}W_{mh}$ and $N_{ml}W_{h}$ to measure the soil moisture profile at 0-15, 15-30, 30-60, 60-90, plus a 30 cm TDR probe (Moisture Point® SDP) per each lysimeter. Soil moisture in 2008 was measured every 1-2 days.
4. *soil physical characteristics*: in 2006, just before sowing, bulk density was measured by in metallic cylinders (5cm x 5cm). In addition, water retention curves were obtained using Richard's ceramic suction cups and measuring the water content at wilting point (WP, 15 bar) and at field capacity (FC, 1/3 bar), in order to determine the plant available water (PAW=FC-WP).
5. *yield and biomass*: Maize was harvested at the physiological maturity when the humidity of the grains was about 14%. The above-ground biomass was completely harvested and weighed. In addition, leaves, husks, grains, stalks and cobs were weighed and analyzed for nitrogen separately. All samples were oven-dried at 60°C and the above ground biomass (AGB) and yield obtained.

Nitrate in drainage, rainfall and irrigation water, was determined by the salicylic acid method described by Cataldo et al. (1975). The N TKN was analyzed in manure, soils and plant products using the Macro-Kjeldahl digestion-distillation-titration methods (standard method 4500-N_{org}B, APHA, 1995).

RESULTS AND DISCUSSION

CROP YIELD DEVELOPMENT

Grain yield of maize harvested from each lysimeter ranged from between 9.8 (N_lW_h) and 18.0 ($N_{mh}W_h$) t ha^{-1} and the above ground biomass (ABG) ranged from between 20.2 (N_lW_l) and 40.0 (N_hW_h) t ha^{-1}. Average grain yields and AGB were higher in 2006 than in 2007 and 2008. This was probably due to the higher water inputs during the first year. The response of maize to irrigation is shown in figure 4.

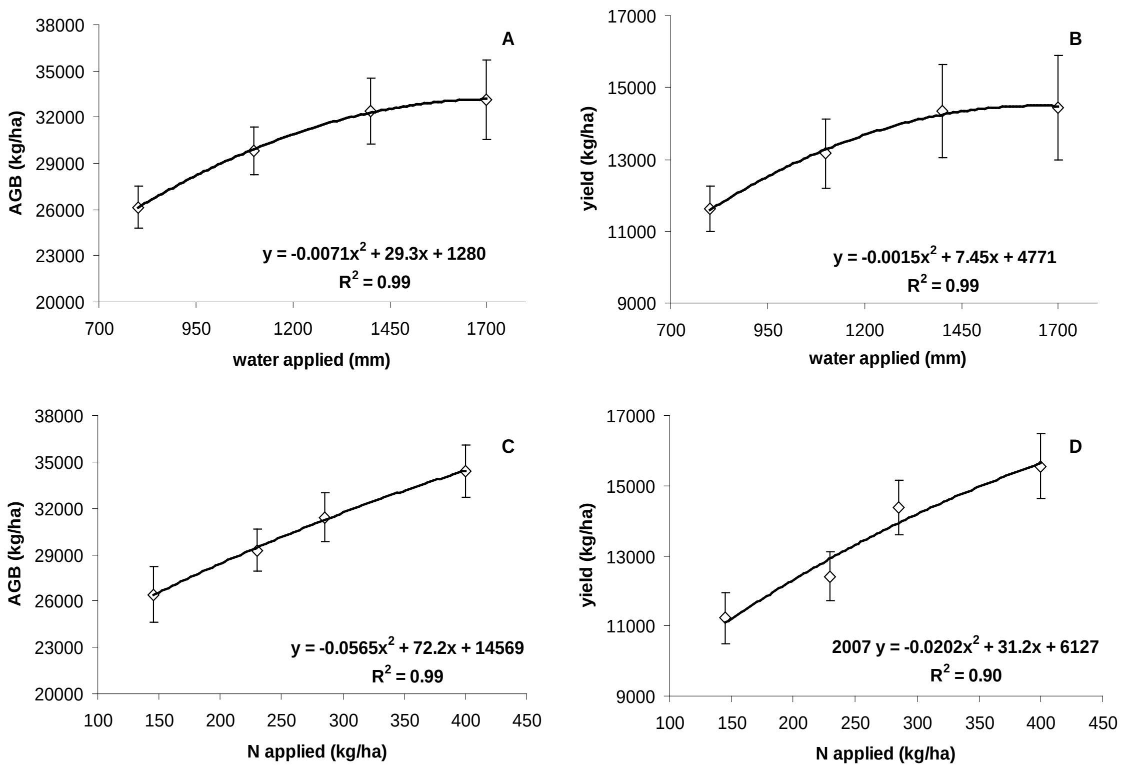

Figure 4. Above ground biomass (a, c) and yield (b, d) response to the 4 rates of N and water applied averaged over years from 2006 to 2008. Bars show the standard error among years and over the other treatment in SLS soils.

Although seasonal precipitation and irrigations varied slightly among the 3 years, there was a consistent effect, in both SLS and SL soils, of the water treatments on grain yield and AGB (Fig. 4, Table 3, 4).

On average, in SLS soils, yield and AGB increased around 24 and 27%, respectively, with higher versus lower water levels. Likewise, N applications in the form of PPM increased grain yield and AGB as well. On average the grain yield and AGB increased around 30 and 39% in response to PPM+urea application. Similar findings were made by O'Neill et al., (2004) and Ki-In Kim et al., (2008). The interaction of water and N applied was consistent (Table 3, 4). The increasing amount of water inputs leads to an increase of grain yield of +1.5 and +2.0 t ha^{-1} in N_l and N_{ml}, respectively while at N rates of N_{mh} and N_h of +4.6 and +4.2 t ha^{-1} (Table 3). Furthermore, the increasing amount of N rates leads to an increase of grain yield of +2.5 and +4.0 t ha^{-1} in W_l and W_{ml}, respectively while at W inputs of W_{mh} and W_h of +5.2 and +5.7 t ha^{-1} (Table 3). This clearly shows a positive interaction N x W inputs in grain yield.

Table 3. Maize grain yield production (t ha-1) averaged over the study (2006-2008) in SLS soils.

treatment	W_l	W_{ml}	W_{mh}	W_h	$\bar{X}$
N_l	10.4	11.3	11.9	11.3	**11.2**
N_{ml}	11.2	12.3	13.2	13.0	**12.4**
N_{mh}	12.0	13.8	15.2	16.6	**14.4**
N_h	12.9	15.3	17.1	16.9	**15.6**
$\bar{X}$	**11.6**	**13.2**	**14.4**	**14.4**	

The increasing amount of water inputs leads to an increase of AGB of +5.3 and +5.4 t ha^{-1} in N_l and N_{ml}, respectively while at N rates of N_{mh} and N_h of +9.2 and +9.0 t ha^{-1} (Table 4). Furthermore, the increasing amount of N rates lead to an increase of grain yield of +6.2 and

+6.3 t ha^{-1} in W_l and W_{ml}, respectively while at W inputs of W_{mh} and W_h of +9.0 and +10.5 t ha^{-1} (Table 4). Even in this case, these results clearly show a positive interaction N x W inputs in maize AGB.

Table 4. Maize AGB production (t ha^{-1}) averaged over the study (2006-2008) in SLS soil.

treatment	W_l	W_{ml}	W_{mh}	W_h	$\bar{X}$
N_l	22.9	26.9	28.2	27.6	**26.4**
N_{ml}	26.0	28.7	31.4	31.0	**29.3**
N_{mh}	26.6	30.5	32.7	35.8	**31.4**
N_h	29.1	33.2	37.2	38.1	**34.4**
$\bar{X}$	**26.1**	**29.8**	**32.4**	**33.1**	

These results are in agreement with whose reported by Ki-In Kim et al., (2008) who attributed the higher productivity of maize to the additive effect that water and N inputs have on maximizing productivity.

Water inputs increased both grain yield and AGB. However, crop yield production reached its maximum around 1400 mm water (Table 3). After that, additional application of water seems not to affect grain yield of maize. In contrast, a linear and positive behaviour were observer in AGB in response to the increase of water inputs. N inputs increased both grain yield and AGB as well (Table 3, 4). In addition, the relationship between AGB and yield versus N applied was always linear. Probably, as reported by Ki-Li Kim et al., (2008) the synergistic effect of N and water, combined with the high evapotranspiration measured throughout the trial, have affected the crop response by increasing the ability of maize to use the N derived from PPM fertilizations. A possible explanation is provided by Ki-Li Kim et al., (2008) who argued that “a large percentage of the N transported to the root is in the water transpiration stream”. These results are also in agreement with whose found by Pandey et al., (2000) and O’Neill et al., (2004).

It was not possible to highlight any interaction between N and W inputs because of the limited number of treatments available for SL soil. Results of grain yield and AGB, averaged over the study, are reported in Table 5.

In LS soils the grain yield ranged from between 1.25 (N_hW_l) and 11.8 (N_hW_{mh}) t ha^{-1} and AGB between 14.0 (N_hW_l) and 25.4 (N_hW_h) t ha^{-1} (Table 6). The highest yields were been obtained in 2008 than 2007 and 2006. The LS soils had on average a lower AGB and yield even though, and contrary of what was observed in SLS soils. This behaviour has due to the shallow profile (50 cm). These results, in fact, are in agreement with whose reported by Calviňo et al., 2003, who found that shallow soils had lower yield than deep soils even under rainfall greater than ET_{max}. Shallow soils restrict water use during the critical periods (vegetative period and flowering) by more than 50%, this consequently affects grain yield (Calviňo et al., 2003).

Table 5. Maize grain yield (A) and AGB (B) crop production (t ha^{-1}) averaged over the study (2006-2008) in LS soils.

(A) treatment	W_l	W_{ml}	W_{mh}	W_h
N_{ml}	-	8.0	-	9.6
N_h	6.5	-	11.1	-

(B) treatment	W_l	W_{ml}	W_{mh}	W_h
N_{ml}	-	20.3	-	26.0
N_h	23.2	-	30.2	-

Table 6. annual yield and above ground biomass (dry weight), harvest index, water inputs (irrigation and precipitation) and water drainage during 2006, 2007 and 2008. SLS results have been averaged for the nitrogen and irrigation treatment.

treatment	soil type	yield ($t\ d.m.\ ha^{-1}$)			AGB ($t\ d.m.\ ha^{-1}$)			harvest index			rain+irrig. (mm)			drainage (mm)			NO_3-N leached ($kg\ ha^{-1}$)		
		'06	'07	'08	'06	'07	'08	'06	'07	'08	'06	'07	'08	'06	'07	'08	'06	'07	'08
W_l	SLS	11.4	11.4	11.9	26.5	25.9	25.9	0.43	0.42	0.41	955	1173	1127	64	275	148	7	65	36
W_{mh}	SLS	13.9	12.6	12.9	31.4	28.6	29.3	0.43	0.43	0.42	1162	1464	1334	155	366	414	16	65	29
W_{ml}	SLS	16.1	13.1	13.7	35.3	31.1	30.7	0.45	0.45	0.47	1428	1774	1582	288	535	530	29	68	33
W_h	SLS	15.9	13.9	13.4	36.0	31.3	31.5	0.45	0.46	0.46	1757	2098	1823	410	787	713	22	60	38
N_l	SLS	12.9	10.4	10.3	29.8	24.0	25.3	0.43	0.44	0.46	1325	1627	1135	315	512	486	15	52	36
N_{ml}	SLS	13.8	11.3	12.0	31.8	27.6	28.3	0.44	0.44	0.44	1325	1627	1135	212	521	442	15	53	33
N_{mh}	SLS	15.2	14.1	13.5	33.9	31.0	29.2	0.46	0.44	0.45	1325	1627	1135	206	483	463	21	63	30
N_h	SLS	15.2	15.2	16.1	33.7	34.3	35.1	0.44	0.44	0.41	1325	1627	1135	185	448	414	23	89	36
N_hW_l	LS	1.2	8.4	10.0	14.0	19.8	23.2	0.09	0.42	0.43	955	1173	772	213	364	509	74	67	57
N_hW_{mh}	LS	9.9	11.7	11.8	26.7	26.2	26.7	0.37	0.45	0.44	1428	1774	1242	460	780	811	32	70	50
$N_{ml}W_{ml}$	LS	5.5	9.0	9.5	19.6	19.7	22.6	0.28	0.45	0.42	1162	1464	987	334	559	632	30	78	55
$N_{ml}W_h$	LS	10.3	8.9	10.1	23.4	20.6	25.4	0.44	0.43	0.40	1757	2098	1540	627	841	934	74	94	53

NITROGEN UPTAKE AND GRAIN YIELD PRODUCTIVITY EFFICIENCY

Plant N uptake varied from year to year (Fig. 5). The total plant N uptake in the AGB was on average 264, 225 and 198 kg N ha^{-1}. The highest values of N uptake were measured in lysimeters fertilized with 400 kg N ha^{-1} and irrigated with the highest amount of water (N_hW_h). Furthermore the lowest N uptake was achieved in lysimeters treated with the lowest inputs (N_lW_l). These results were observed every year throughout the trial.

Water inputs affected the N uptake as well (Fig. 5, Table 7). Highest values were measured in W_{mh} and W_h (Table 7). However there was little difference between the lysimeters. These results are consistent with a previous work (O'Neill et al., 2004) and illustrate the additive effect that water and N inputs have on optimizing corn productivity, by increasing the N uptake. Ki-In Kim et al., (2008) highlighted the synergistic effect of water on nitrogen. They reported that synergistic relationship occurs when supplemental water increases the N uptake. In other words, as found in our experiment, water irrigation increased the ability to use the N derived both from soil and fertilizations (Table 7). Maize, in fact, increased the ability to use the N from the fertilizations from 8 and 12% of the total amount of N applied. In particular, the increasing amount of water inputs leads to an increase of N plant uptake of -14 and +39 kg ha^{-1} in N_l and N_{ml}, respectively while at N rates of N_{mh} and N_h of +22 and +19 kg ha^{-1} (Table 7). Furthermore, the increasing amount of N rates leads to an increase of N uptake of +84 and +84 t ha^{-1} in W_l and W_{ml}, respectively while at W_{mh} inputs of W_{mh} and W_h of +115 and +100 kg ha^{-1} (Table 7).

Moreover, the initial soil water content of the four regimes were similar, these confirm that soil water inputs increased plant N uptake. These results can be viewed as results of several factors. First a large percentage of the N transported to the roots in the water transpiration stream. Second, only a portion of the inorganic N transported with the first increment of water, with additional N being transported with each additional increment of water (Ki-In Kim et al., 2008).

Table 7. Maize N plant uptake (kg ha^{-1}) averaged over the study 2006-2008 in SLS soils.

treatment	W_l	W_{ml}	W_{mh}	W_h	$\bar{x}$
N_l	210	201	212	196	**205**
N_{ml}	218	230	248	257	**238**
N_{mh}	253	264	272	275	**266**
N_h	294	285	327	313	**305**
$\bar{x}$	**244**	**245**	**265**	**260**	

In SL soils N uptake were lower than SLS soil because of the shallow soil (50 cm) that leads to a lower maize grain yield and AGB. N plant uptake over the experiment in LS soil are reported in Table 8.

Table 8. N plant uptake (kg ha^{-1}) averaged over the study (2006-2008) in LS soils.

treatment	W_l	W_{ml}	W_{mh}	W_h
N_{ml}	-	164	-	145
N_h	184	-	196	-

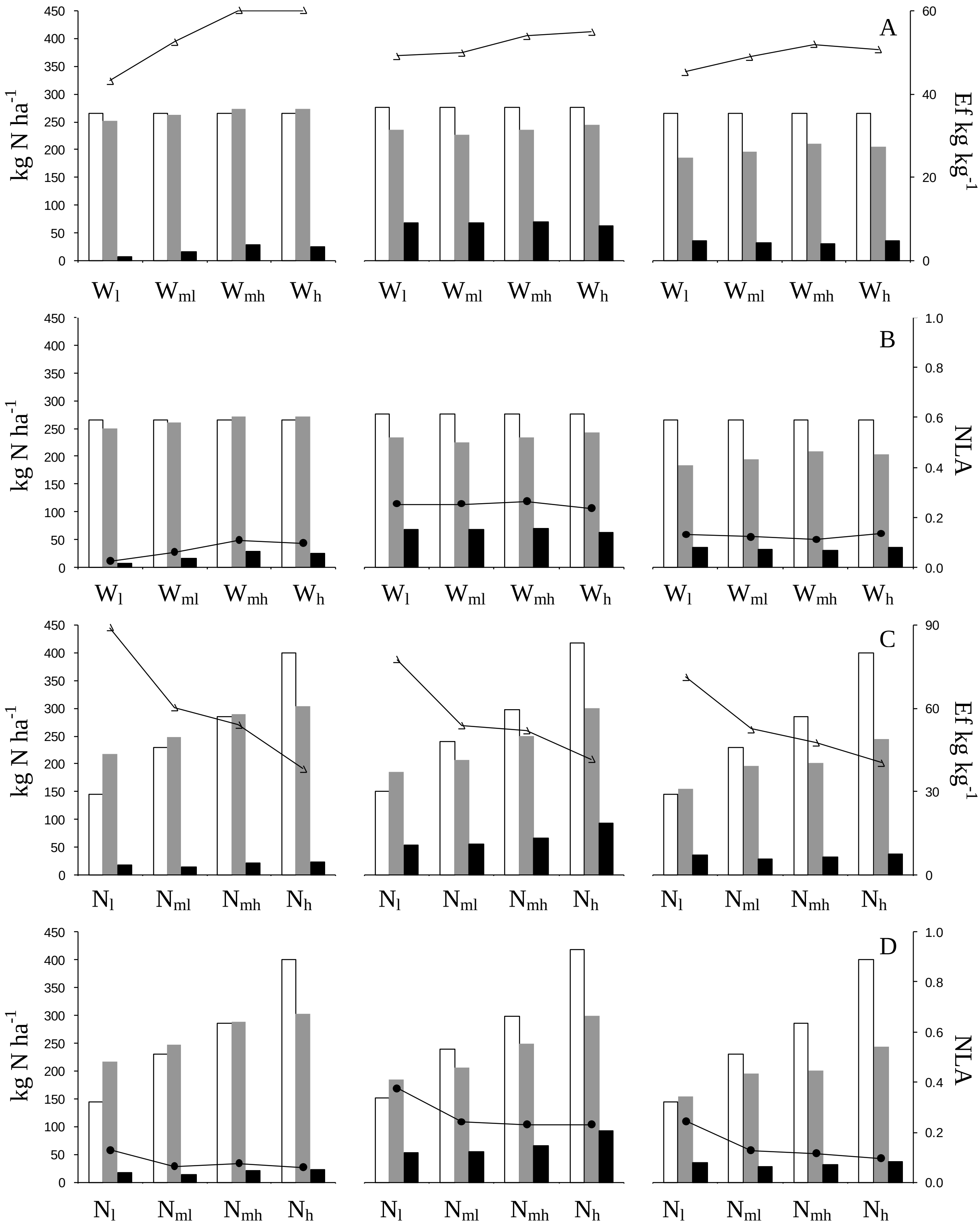

Figure 5. A, C=Ef, B, D=NLA. Mean of organic and inorganic N applied (white square), N uptake (grey square) and N leached (black square). N efficiency ($Ef = yield/N_{fert}$), nitrate leaching coefficient ($NLA = N_{leaching}/N_{applied}$), during the experiments in lysimeters treated with different rates of N and water inputs.

Yield productivity efficiency (Ef) was calculated following the methods of Daudén and Quìlez, (2004) and the results are shown in figure 5, 6. On average, the relationship between yield and N applied (Ef) was different in the W and N treatments.

The amount of grain yield produced with each kg of N fertilizer is shown in Figure 5. Yield productivity efficiency (Ef) tended to decrease with increasing N rate. Ef ranged between 78 and 40 kg of yield per kg of N applied throughout the trial. Ef varied about 78, 55, 50 and 40 kg kg^{-1} N in N_l, N_{ml}, N_{mh} and N_h, respectively. In N_l the efficiency was always higher during the 3 years, while it was lower in N_h. Despite, high rates of N fertilizer further increased the N uptake, at the highest application rates more nitrogen would be available for leaching, reducing Ef. Similar findings were observed by Dauden and Quìlez in 2004. Moreover, these results are in agreement with O'Neill et al., (2004) and Halvorson et al., (2006) who found that Ef tended to decrease with increasing of the N rates. The crop production response to N inputs shows an increasing trend to the increase of N applied.

Water inputs increased the yield productivity efficiency. On average Ef varied about 45, 50, 55 and 55 kg kg^{-1} N in W_l, W_{ml}, W_{mh} and W_h, respectively. Water inputs increased the ability of maize to use N from fertilizations however, the higher Ef values was observed in W_{mh}, (Fig. 6, Table 7). This result suggests that around 1400 mm $year^{-1}$ of water (Table 7), Ef tends to reach its optimum, after that water seems not to increase the Ef.

Ki-In Kim et al., (2008), who found similar results attributed the higher Ef in the high water regimes to two interrelated factors: i) the higher evapotranspiration in higher water regime (W_h and W_{mh}) ii) N transport to the roots increased with the water transpired. For precision, ET was higher than 19 % in W_h respect to W_l, while N transport in soil was not monitored.

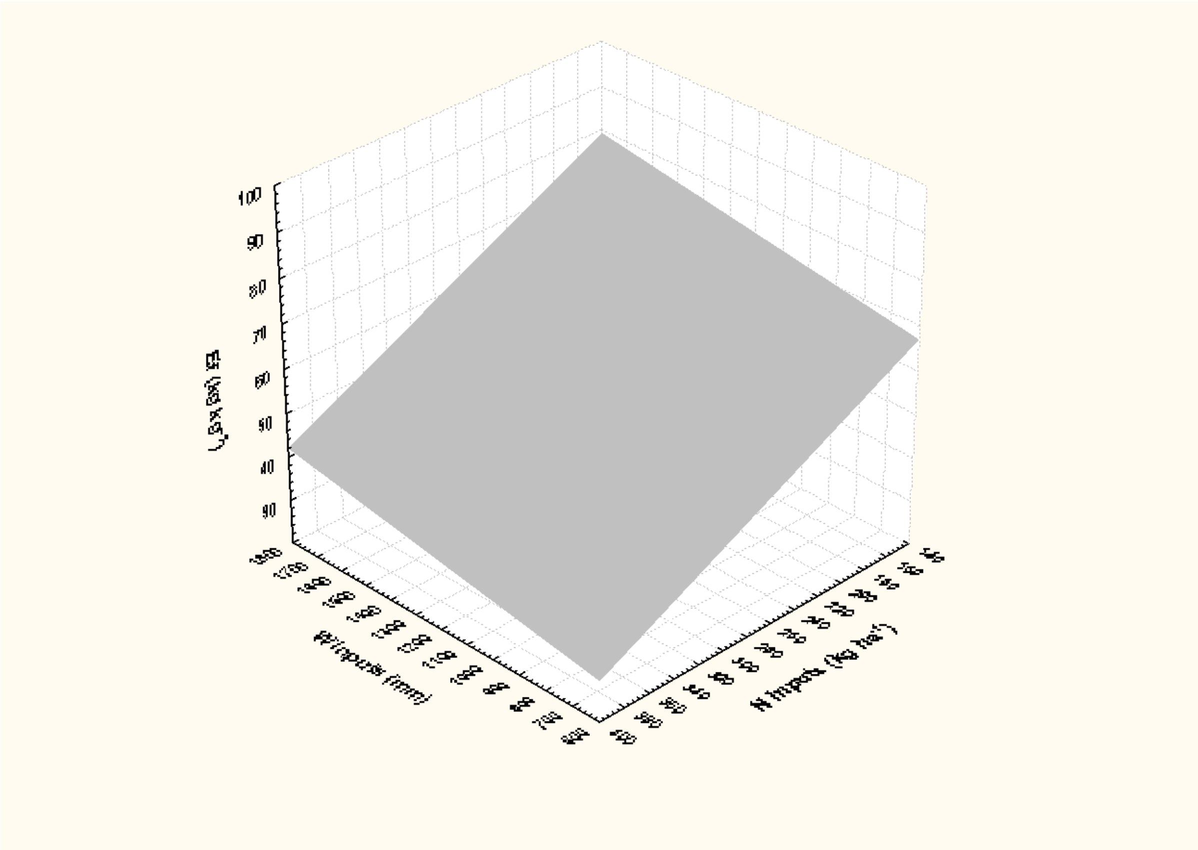

Figure 6. Ef under a combination of 4 water treatments, 4 N treatments and in SLS soil, averaged over 3 years (2006-2008) at Padova, IT.

The relationship between nitrate leaching and nitrogen applied (NLA) should increase for increased manure PPM rates. NLA varied among years. NLA was affected by the water input (Fig. 5) showing that N leaching increased by increasing the water input. However, these behaviours were more consistent in 2006 than 2007 and 2008. The higher values in 2007 are probably due to the heavy rainfall event (140 mm/day), occurred just few weeks after the harvest of the crop. This may have altered the N leaching especially in lysimeters irrigated with the lowest inputs of water. In 2007 and 2008 N losses did not differ among treatments, not leading to any differences among W treatments. On the other hand, NLA was influenced by the N application rate: higher values were detected in N_l whilst no consistent differences were observed in N_{ml}, N_{mh} and N_h.

NITRATE CONCENTRATION IN DRAINED WATER

Nitrate-N concentrations in drained water averaged over the water inputs ranged from 0.2 and 40.5 mg l^{-1} during the 2006 to 2008 period. The NO_3-N concentration in the water drainage showed differences among treatments, and these differences varied with season, apparently in response to crop and N inputs (Fig. 7).

Nitrate-N concentrations were higher in lysimeters irrigated with the lowest amount of water (35 mg l^{-1}) and this concentration was reached several times just in W_l during the study. Although, nitrate concentrations among W_l, W_{ml}, W_{mh} and W_h treatments were different throughout the trial, concentrations did not differ during a short initial phase (from May to October 2006), when maximum NO_3-N concentration values ranged between 8 to 11 mg l^{-1}. Concentrations peaked from late autumn to early spring during the study, and coincided with the maximum drainage from fallow soil.

Similar results were observed by Jaynes et al., (2001). NO_3-N concentration in drained water decreased during summer, then increased in autumn following harvest in response to increasing drainage and no transpiration by crops. During the summer the high rate of evapotranspiration prevented water drainage. Despite the high water inputs, especially in summer, we measured very low soil moisture values of 15.7, 20.9, 24.6 and 25.3% (average

0-90 cm) in W_l, W_{ml}, W_{mh} and W_h treatments, respectively. NO_3-N concentration, were very low during the 2006-2008 growing period and it only measured during the intercrop period (from December to May) when over the 80% of the annual N leached was measured (Fig. 7).

It appears that the relatively low rainfall, dry soil and warmer air temperatures, that favour rapid nitrification, increased soil NO_3-N content during the summer months and allowed it to accumulate in the soil, especially in the drier treatments W_l and W_{ml} lysimeters. This is consistent with the results of Hayakawa et al., 2009. Cordovil et al. (2005) found that PPM has a high active N fraction and a very small lignin content that are considered to be the main factors determining N mineralization rates of organic fertilizer, and Sousa et al. (2002), observed that 90% of mineralizable N was released during the first week of incubation of PPM. These results suggest that high NO_3-N concentration in groundwater results from its accumulation from mineralization during the warm dry periods followed by its subsequent leaching. These results are in agreement with those observed by Randall and Mullan (2001). After 6 years of monitoring they measured high nitrate concentrations in groundwater (twice as high as during dry years) during the first wet year after a dry period.
Lower NO_3-N concentration, measured in the heavily water lysimeters of treatments W_{mh} and W_h can be ascribed to water dilution effect and consequently an higher denitrification rates. Gradual reductions of Nitrate-N concentrations in lysimeters subjected to different inputs of water can be explained mainly by water dilution and either by denitrification or by temporary accumulation of organic N in soil (Shröder et al., 2007). Gradual changes of the amount of organic N in soil are very difficult to measure (Shröder et al., 2007). Still we do not think that accumulation is a likely explanation because on average W_l, W_{ml}, W_{mh} and

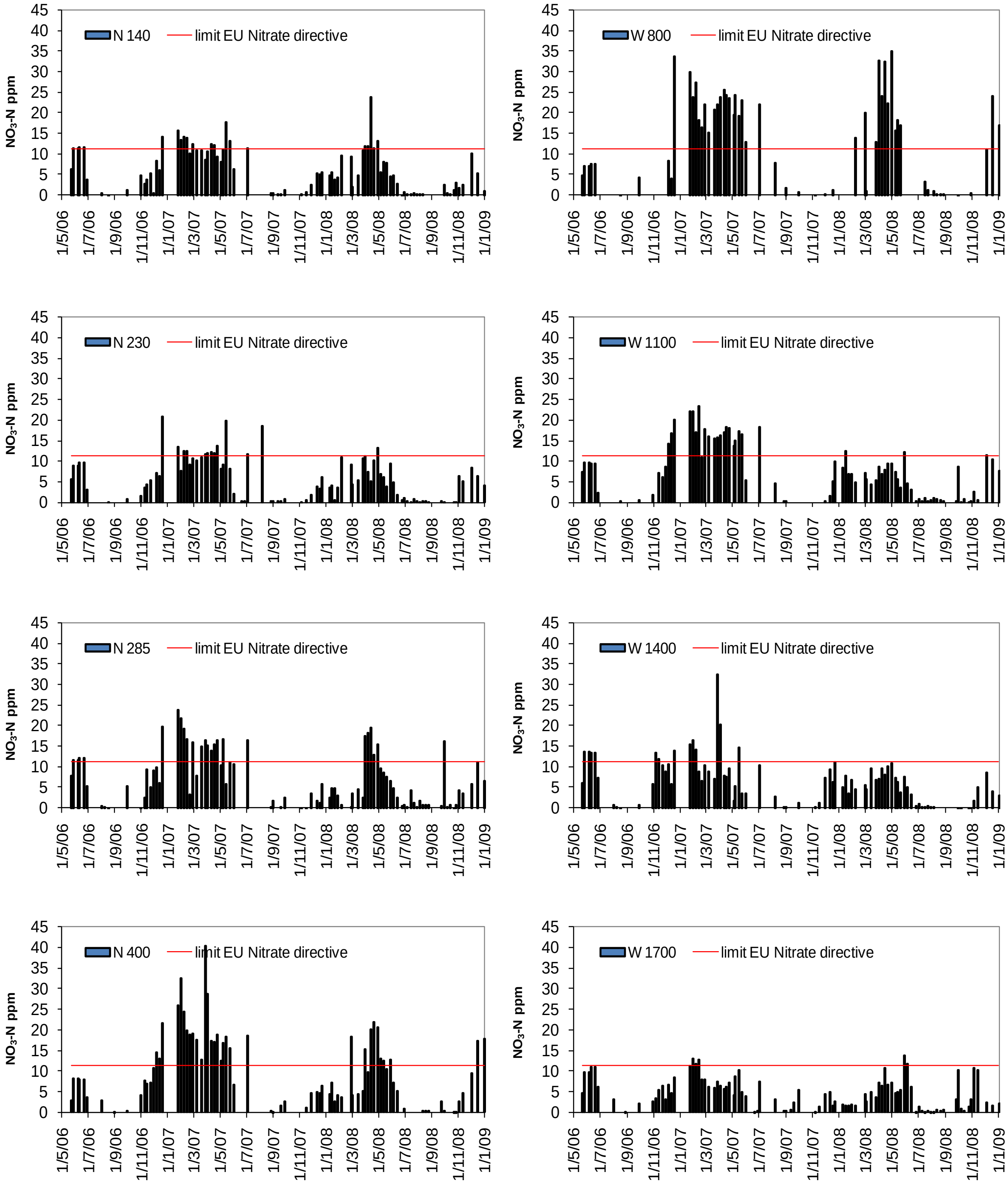

Figure 7. NO_3-N concentration from lysimeters subjected to different rates of nitrogen and water inputs, in SLS soil. N_l, N_{ml}, N_{mh}, and N_h represent the lysimeters fertilized with 145, 230, 285 and 400 kg ha^{-1}. N (PPM+urea) respectively. W_l, W_{mh}, W_{mh} and W_h the lysimeters irrigated with 800, 1100, 1400 and 1700 mm. The straight line represents the UE Nitrate Directive target of 11.3 mg l^{-1} of Nitrate-N in groundwater.

W_h lysimeters were fertilized with the same rate of N fertilizer. This leaves water dilution and denitrification the most probable explanation of this downward trend observed among these lysimeters. It is also possible that anaerobic conditions inside the pellets of manure are stimulated by moisture, and cause high N_2O fluxes by denitrification (Hayakawa et al., 2009). Martinez and Peu, (2000) found that denitrification in soil is a very important component in removing about 54% of the N mineralized. This could explain the behaviour of Nitrate-N concentration in drained water in lysimeters W_h and W_m.

Nitrate-N concentration increased with increasing rates of N application. Highest nitrate-N concentrations were measured in lysimeters fertilized with 400 kg ha^{-1} N (N_h) (Fig. 7) and the highest NO_3-N concentration was measured in the N_h treatment as well (42 mg l^{-1}). NO_3-N concentrations in drained water decreased during summer, then increased in autumn following harvest in response to greater drainage and when there was no crop. Concentrations reached their maximum in January 2007 then slowly decreased until sowing, continuing to decrease until no nitrate was detected. NO_3-N concentrations gradually increased after each October when no crops were present. The NO_3-N concentrations in the drainage showed differences among treatments, but these differences varied with season, apparently in response to crop uptake and N inputs. Although these data seem to confirm that Nitrate-N were affected by fertilization, it is very difficult to quantify the environmental impacts from fertilization practices because the nitrogen dynamics in soils and the processes that lead to leaching are very complex (Grignani and Zavattaro, 2000). However, these results are in agreement with those observed by Aronsson and Bergström, 2001, Jaynes et al. 2001, Dautén and Quìlez, 2004, Thomsen, 2005 and

Berenguer et al. 2009. In addition, as indicated by Aronsson and Bergström (2001), NO_3-N in drained water appears to be affected by a complex interaction among climate, cycle of wet and dry years, N application rates and the growing season. Our results are in agreement with those reported by Daudén and Quìlez, (2004) who measured lower nitrate in plots fertilized with the highest amount of N in a Mediterranean environment. In contrast the increased nitrogen concentrations due to additional N fertilizer were lower (0.015 mg l^{-1} of NO_3-N per unit increase of N fertilizer, Fig. 8) than those measured by Daudén et al. (2004) who reported values of 0.069 mg l^{-1} per unit of increase N fertilizer. Also, the increased water amount due to additional W inputs were 0.98 mg l^{-1} of NO_3-N per 100 mm increase of W input, (Fig. 9).

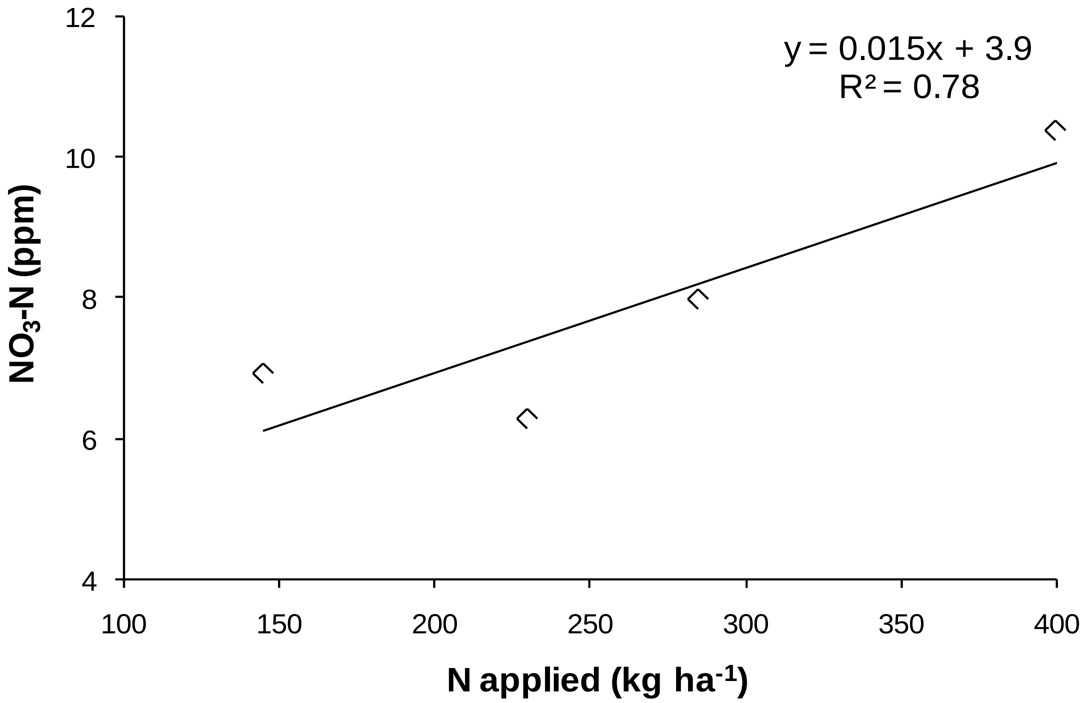

Figure 8. NO_3-N concentrations versus the rate of N fertilizer applied. Nitrogen concentration has been averaged over the period of study.

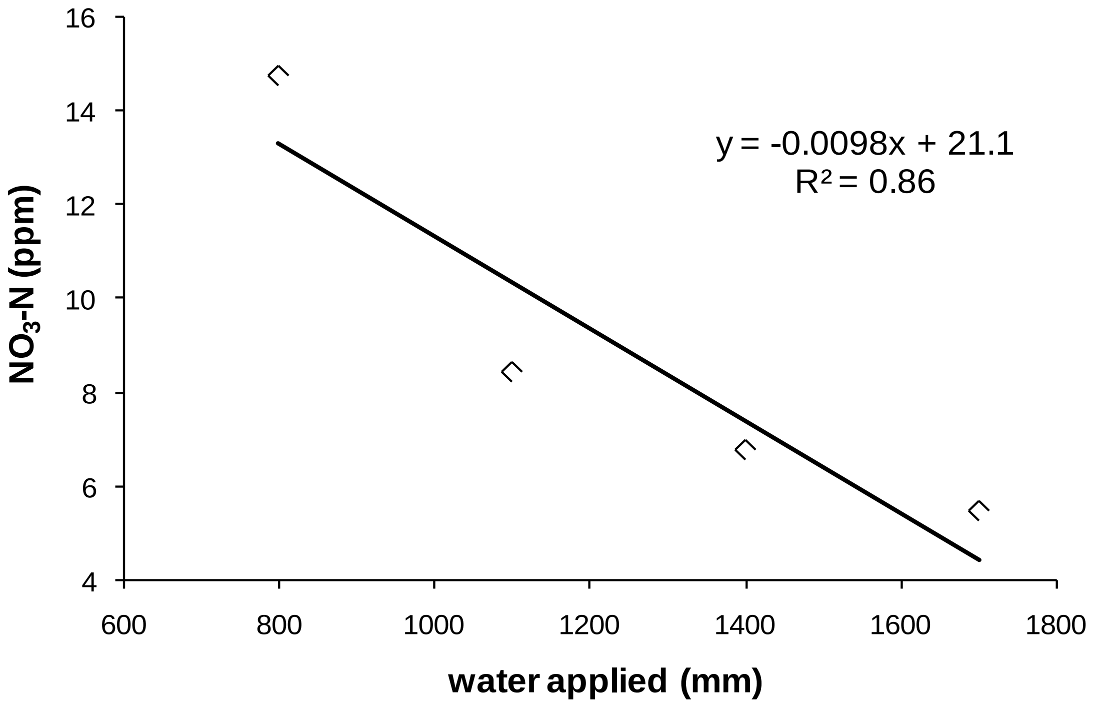

Figure 9. NO_3-N concentrations versus the amount of water applied. Nitrogen concentration has been averaged over the period of study.
Also, the decreased nitrogen concentrations due to additional W inputs were 0.98 mg l^{-1} of

N AND WATER INPUTS AND THE IMPLICATIONS OF EU NITRATE DIRECTIVE TARGETS

In view of target imposed by the EU Nitrate Directive the correct management of water and nitrogen is fundamental for meeting the objective of protecting groundwater from nitrate pollution. The high potential for nitrate pollution of groundwater from soils of the Veneto NVZ is shown by the NO_3-N concentrations in the drainage water following harvesting consistently exceeding the 11.3 mg l^{-1} for nitrate-N concentration set by the EU Nitrate Directive (Fig. 7). Nitrate concentrations exceeded the EUL even in those plots treated with the lowest rate of PPM: in 17 and 13% of the total observation during 3 years study and the highest values ranged between 24 and 21 mg l^{-1} for N_l and N_{ml}, respectively while, in N_{ml} and N_h the concentrations were higher than EUL of 22 and 29% and the highest values varied between 24 and 40 mg l^{-1} (Table 9). Except for the N_l and N_{ml} treatments where little differences in exceeding of the EUL were detected, the results clearly demonstrate that high rates of N fertilization increase the risk of exceeding the limit.

Table 9. Measured values of Nitrate-N concentration in groundwater related to the EU Nitrate Directive target of 11.3 mg l^{-1} Nitrate-N in groundwater. Table shows the percentage of NO_3-N concentration exceeded the EUL, the average it was exceeded by, and the highest values.

	N_l	N_{ml}	N_{mh}	N_h	W_l	W_{ml}	W_{mh}	W_h
% of exceeding of EU Nitrate Directive target	17	13	22	29	30	21	13	5
average exceeding EU Nitrate directive target (ppm)	14	14	17	19	22	17	16	12
max value Nitrate-N groundwater (ppm)	24	21	24	40	35	23	32	14

Our results also show that N concentrations in groundwater are not determined simply by N fertilizer inputs (both organic and inorganic) but by a combination of N fertilizer and water inputs. Water inputs played an important role in influencing the NO3-N concentration in drainage water. The nitrate in concentration ranged between 0.2 and 35 mg l^{-1}. The trends in NO_3-N concentration in lysimeters W_l and W_{ml} throughout the trial were similar. The EUL threshold was exceeded in 30 and 21% of the total observation during the 3 years of study, and the highest values ranged between 35 and 23 mg l^{-1} respectively for W_l and W_{ml}.

In W_{mh} and W_h lysimeters, water applications led to lower concentrations of Nitrate-N in drainage water. In the 13 and 5% of the analysis the concentrations were higher than UEL and the highest values varied between 35 and 14 mg l^{-1} (Table 9).

CONCLUSION

Maize grain yield and AGB were consistently increased by N (manure+urea) fertilizations and water inputs each year. Grain yields were near maximum with 1400 mm yr^{-1} of water (irrigation+precipitation). In contrast, the response of grain yield and AGB to N inputs increased up to the maximum N rate (400 kg N ha^{-1}). Highest production were obtained in theses W_hN_h. These results were attributed to a synergistic relationship between N and water. Water increased the ability of maize to use the N derived from fertilizers and so increasing yield and AGB. Crop yield efficiency (Ef) tended to decrease with increasing applied nitrogen. Water inputs slightly increased Ef, however Ef increased up to 1400 mm yr^{-1}, above that limit additional water inputs did not affect the efficiency. N uptake increased with increasing N rates used in this experiment, while little additional uptake was observed by increasing water inputs.

Nitrate in drainage water was influenced by N and water inputs. Higher concentrations were measured in N_h while no consistent differences were observed in N_l and N_{mh}. Water inputs clearly affected NO_3-N concentration in the drainage water. Higher concentrations were measured in W_l suggesting effect N accumulation in soil. Lower concentrations were found in W_h probably due to water dilution and higher N denitrification. EUL was exceeded many times in N_h and N_{mh} throughout the experiment, while it has never exceeded in W_h.

Our trial clearly shows that high nitrate concentration in drained water were measured in treatments that lost a lower amount of NO_3-N, while lower NO_3-N concentration were observed in whose lysimeters that lost high amount of nitrate-N. Our results provide interesting information that can be useful in order to improve the management of N fertilizations and maximize crop productivity, in view of complying with the European environmental policy.

APPENDIX

Figure 1.a – Experimental site with 20 lysimeters and 2 under ground sampling chamber. At the top, the automatic sliding roof.

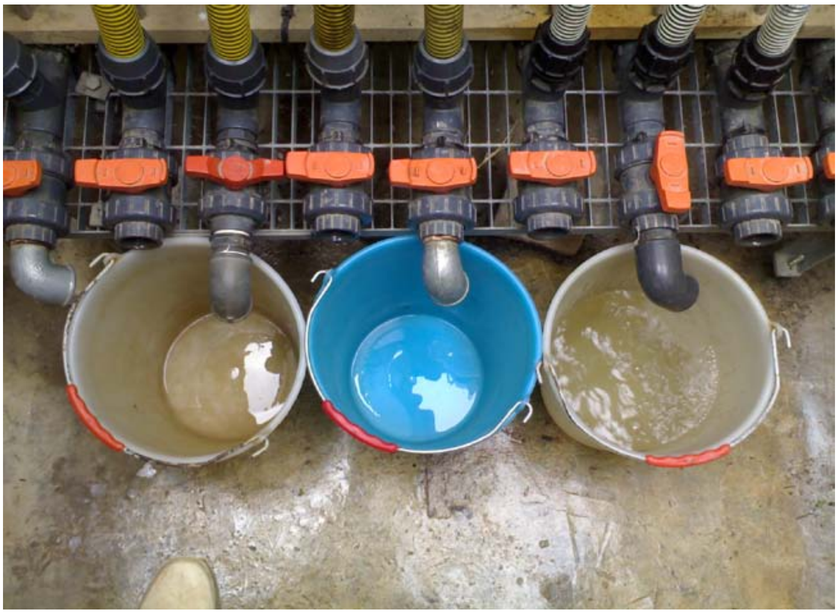

Figure 1.b – Under ground sampling chamber with the tubes that allow to collect the leachate.

Figure 1.c – particular of a lysimeters and of the irrigation system (by drippers). Picture was taken 2 weeks after sowing.

Figure 1.d – TDR (Moistuire Point®, TDR MP 917) and probes (profiling probe Moisture Point® PRB-F; Moisture Point® single diode probe SDP) to measure the moisture of soil. In this lysimeter two probes were installed: a 90 cm probe (on the left) and 30 cm probe (on the right).

Figure 1.e – maize in LS soil, 3 weeks after emergence in 2006.

Figure 1.f – maize, 1.5 months after emergence, in 2008. Differences in height are due to the different amount of N applied in each lysimeter.

ACKNOWLEDGEMENT

I would like to thank Veneto Agricoltura for supporting the project. We also extend our thanks to Vittorio Ferrari for providing soil analysis, Giovanni Albertini, Giovanni Favaron, Dr. Riccardo Polese and all the staff of the Experimental farm for their valuable assistance. We also a sincerely thank Dr. Alessandra Bonamano, Prof. Francesco Morari, Davide Cammarano, Dr. Yong Li and Dr. Ian Willett for revising the drafts and for their valuable advice. This work was founded by Veneto Agricoltura. Manuele Roitero thanks “Ing. A. Gini” Foundation for the scholarship during the period of study at the School of Land and Food Resources, the University of Melbourne.

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CHAPTER 2

DEVELOPING BEST MANAGEMENT PRACTICES FOR ACHIEVING THE EUROPEAN UNION NITRATE DIRECTIVE LIMITS FOR MAIZE CROPPING IN THE VENETO REGION, ITALY

ABSTRACT

High crop productivity with protection of water resources has become very important across Europe. Improving water use efficiency (WUE) and nitrogen use efficiency (NUE) is the best way to achieve high productivity and meet the guidelines imposed by the EU Nitrate Directive. The aim of this study was to simulate a wide range of agricultural water and N applications to develop best management practices to maximize WUE, NUE, yield and reduce N leaching in maize production on silty soil in northern Italy. The WNMM simulation model was used to understand maize productivity and N leaching under a range of N and water inputs. This study concludes that in the nitrogen vulnerable zone (NVZ) the Directive threshold of 170 kg N ha^{-1} as manure does not exceed European Water Framework targets (EWF) of 11.3 mg nitrate l^{-1}, at any level of water inputs considered. In non NVZ areas, the limit of 340 kg N ha^{-1} as manure, result in exceeding of the EWF limit only when the annual water input is less than 900 mm. At higher water inputs, N fertilizations should be reduced to between 235 and 270 kg N ha^{-1}. This, leads to increases in NUE, reductions in nitrate-N leaching and no change in grain yield. WUE tends to reach its maximum around 1200-1100 mm of water annually, but up to 1400 mm can be applied to increase yield with a negligible decrease in WUE. Reducing N applied and increasing water inputs are the best ways to achieve a high grain yield, higher NUE and WUE with a reduction in nitrate-N leaching to groundwater fop compliance with the EWF.

INTRODUCTION

Maize (*Zea Mais* L.) is a warm-season crop that is widely grown in many states of Europe. France, Italy and Romania are the leading producers contributing approximately 48% of the total European maize production. It is grown on about 4.8 million ha and has an average grain yield of approximately 9.35 t ha^{-1} (FAOSTAT, 2007). In Northern Italy the cultivation of maize currently occupies one million hectares in the Padana plain of the Veneto Region which is Italy's most important maize production area as it contributes 81.4% of the total maize production of the country, and 11.4% of that for Europe, while in Central and Southern Italy, that have a Mediterranean climate and a scarcity of water, cultivation amounts to only 130,000 ha, with an average grain yield of 9.40 and 7.40 t ha^{-1}, respectively (Di Paolo and Rinaldi, 2008).

Although water is relatively abundant across Europe problems of water scarcity are reported from many locations where there are reduced river flows, lowered lake and groundwater levels and the drying out of wetlands. As a result of over-exploitation and prolonged periods of low rainfall (Collins et al., 2009), the balance between water demand and availability has reached a critical level in many areas, particularly in southern Europe. Additionally, projections for climate change predict that water scarcity is likely to be exacerbated in the future, with predicted increases in the frequency and severity of droughts (Collins et al., 2009). Under water-limited conditions, typical of the semi-arid areas of EU such as Italy, France, Portugal and Greece (Collins et al., 2009), maize productivity is highly dependent on irrigation availability. Consequently, the limited supplies of water particularly affect this crop due to its relative large water requirements (Payero et al., 2009).

In Italy maize is grown mainly in river basins that are sensitive to nitrate pollution of groundwater (Di Paolo and Rinaldi, 2008). Significant inputs of nitrogenous fertilizers are applied to maize crops grown on these irrigated lands to maintain high productivity leading to concerns that the groundwater is being polluted by nitrate. Appropriate management of irrigation and N applications is needed in order to maintain maize yields whilst optimizing water use efficiency (WUE) and nitrogen use efficiency (NUE), whilst minimizing accessions of nitrate to groundwater.

Determining crop yield responses to irrigation in combination with N fertilization could help identify farm management practices that maximize yield and reduce groundwater pollution (Di Paolo and Rinaldi, 2008; Payero et al., 2009). Several studies have shown a significant effect of water and nitrogen on maize crop in relation to WUE (Di Paolo and Rinaldi, 2008; Ritchie and Basso 2008; Barbieri 2009, Garcia et al., 2009; Payero et al., 2009) and NUE (Dobermann, 2002; Arregui and Quemada, 2008; Di Paolo and Rinaldi, 2008; Kim et al., 2008).

Adjusting fertilizer rates and splitting of N fertilizer applications to meet the demands of the crop without excess is the key to optimizing NUE, yield and environmental protection in large-scale systems (Dobermann, 2002; Arregui and Quemada, 2008). Dobermann (2002) argued that NUE can be improved by i) increasing stress tolerance of maize hybrids, ii) improving agronomic practices such as conservation tillage, and iii) improvement of N fertilizer management. Improvements of N management include reducing N fertilizer application at sowing and splitting the application of N fertilizer during the growing season rather than by applying a large single N application (Dobermann, 2002). Low fertilizer efficiencies have been attributed to excessive N applications, especially when residual or mineralized N were ignored (Arregui and Quemada, 2008). Additionally, Kim et al., (2008) established the importance of the interaction between N and water applications and found a synergistic relationship between water and N. N fertilizer increases the water use efficiency and supplemental water increases N use efficiency.

Nitrate leaching is closely related to water movement in soils (Dai et al., 2006). A clear understanding of water use efficiency (WUE) in maize systems is therefore essential for designing efficient irrigation practice to produce high yields and limit the transport of nitrate. Increasing WUE may increase the productivity of maize, reduce N losses and consequently control the nitrate pollution of groundwater (Seckler et al., 1998). Payero et al., (2009) in Nebraska, evaluated the effect of irrigation timing in terms of water stress on maize yield and water use efficiency. They found that water stress during the critical reproductive stage resulted in lower grain yield and that water stress should be avoided early in the season and especially during the reproductive stages. Similar reductions in grain yield were also observed by Cakir (2004) who found that when the availability of irrigation water is limited it is most beneficially used when supplied at the reproductive stages (flowering and/or cob formation).

Environmental protection is one of the priorities of the new European agricultural policy (Di Paolo and Rinaldi, 2008). Growing concern about the effect of agricultural practices on the environment has led the European Union (EU) to develop new strategies to balance economic efficiency and negative effects on the environment. The EU Nitrate Directive aims to reduce water contamination caused by nitrate from diffuse agricultural sources (Anonymous, 1991). Improving the efficiency of NUE and WUE has become very important for achieving the objectives of the guidelines imposed by the new European agricultural policies. A compromise between the need to maximize profit by the use of adequate irrigation water and N fertilizer and the need to reduce the impact of maize production on the environment is required (Di Paolo and Rinaldi, 2008). In the Veneto Region, north eastern Italy, the current precautionary application thresholds imposed by the EU Nitrate Directive limit manure N applications to either 170 N ha^{-1} in nitrogen vulnerable zones (NVZ) or 340 kg N ha^{-1} in non NVZ (Fig. 1). A reduction of applied N fertilizer and better management of irrigation water appear to be the most productive ways to improve both water use efficiency and nitrogen use efficiency leading to a reduction of N losses.

The aim of this study was to identify management practices that make most effective use of limited supplies of N fertilizer and partially water applications and result in adequate grain production that comply with restrictions on nitrate accessions to groundwater. In particular we aimed to determine how farm-to-farm variability affects the regional nitrogen use efficiency, water use efficiency and nitrogen leaching. We applied the "Water and Nitrogen Management Model" (WNMM) to simulate a wide combination of N and water management scenarios typical for the Veneto Region (North-East of Italy) to analyze NUE and WUE in maize crop in a sub-continental climate. This study also evaluated nitrogen leaching in combination of different water and N inputs to propose the best agricultural practices that comply with the EU Nitrate Directive.

MATERIAL AND METHODS

SITE DESCRTIPTION

The experimental trial was located at the experimental farm of the faculty of Agronomy of the University of Padova (Veneto Region, Italy) (Fig. 1) in an area designated a NVZ, within the Padana plain (Anonymous, 2006 a) (45°20'26'' N, 11°58'0'' E, elev. 8 m).

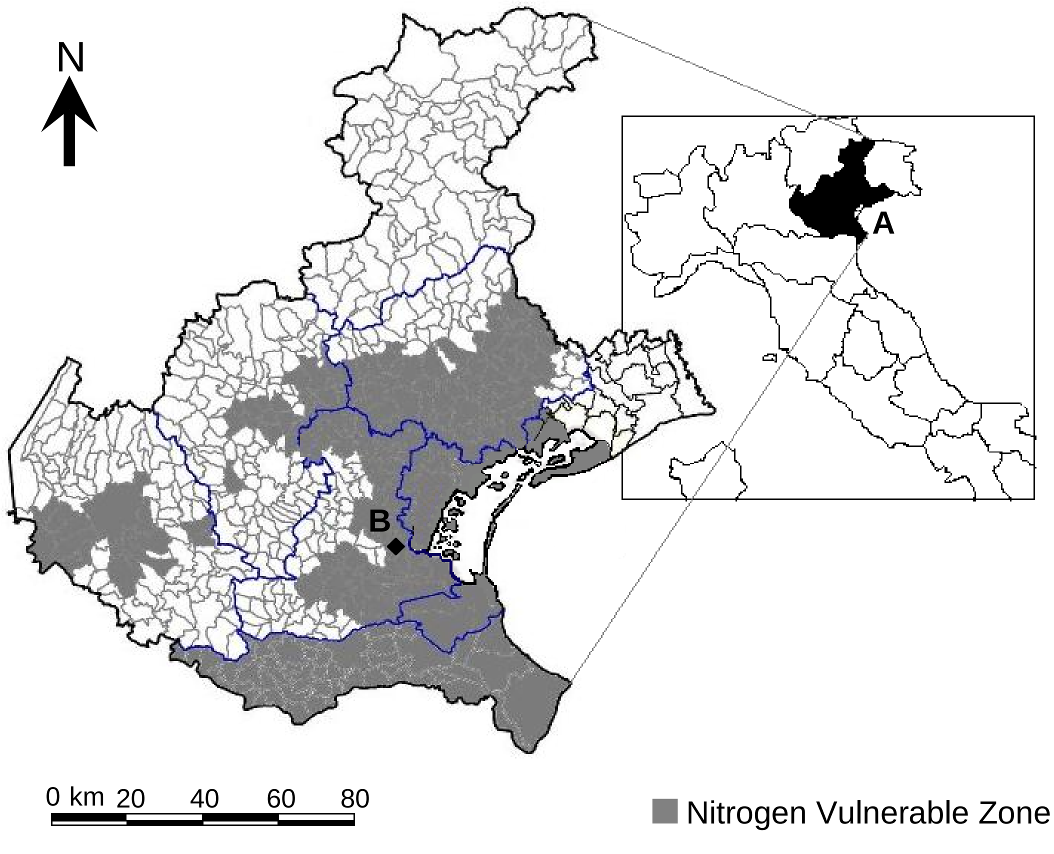

Figure 1. Veneto Region (A) with its Nitrogen Vulnerable Zone and the location of the experimental trial (B)

The Padana plain is very important area for maize growth and it contributes to 81.4% and 11.4% of the total maize production in Italy and Europe, respectively. The valley contains 3 million hectares of which 59.6% is considered to be NVZ while in the Veneto Region, 61% of the entire surface is considered non NVZ (Anonymous, 2006 b) (Fig. 1). Mean annual precipitation (1963-2007) of the area is 812 mm and averages of daily minimum and maximum air temperature during the growing season (April-September) are 13.2˚C and 23.9˚C, respectively. A description of the experimental site is explained in detail in the previous chapter. Mean annual precipitation of the area is 812 mm over a 44 year (1963-2007) and averages of daily minimum and maximum air temperature during the growing season (April-September) are 13.2˚C and 23.9˚C, respectively.

The most widely maize management practices are described below under the section "*Definition of the WNMM model AMP inputs and determination of the parameters NUE, and WUE".*

The current experiment was conducted in 2006-2008 (see chapter 1) where a lysimetrical station was established to investigate N cycling dynamics in the Veneto plain as a part of a collaboration between the Veneto Agricoltura and the Department of Environmental Agronomy and Crop Science at the University of Padova (Italy).

This trial and aimed to understand the economic and environmental impacts of the EU Nitrate Directive (91/676 CEE), and to evaluate the effectness of the precautionary thresholds of 170 and 340 kg N ha^{-1} manure in NVZ and non NVZ zones, respectively, in reducing nitrate accessions to groundwater. For the current study lysimeter data for 2006 to

2008 were used in order to reproduce the wide range of agricultural management practices (AMP) for maize production in the Veneto Region.

METHOD OVERVIEW

We investigated the effects of a wide range of agricultural management practices on maize crops in the Veneto Region in order to test whether the constraints on N fertilizations imposed by the EU Nitrate Directive are effective in controlling nitrate accessions to groundwater. In particular, we determined water use efficiency and nitrogen leaching. Simulation of maize crop growth, water dynamics in soil, and the fate of N under a range of AMPs were also carried out. The approach included: i) parameterization and testing of the Water Management and Nitrogen Model (WNMM) (Li et al., 2007) and simulation at the research/experiment level; ii) definition and testing of the inputs; and iii) simulation of individual scenarios using a wide range management practices with local soil and climate data. The simulation model was used to determine nitrogen and water management scenarios that maximize the efficiency of nitrogen and water, and reduce nitrate losses below the limits imposed by the EU Nitrate Directive. A combination of 37 rates of N fertilizer applications and 36 levels of water (irrigation+rain) regimes was used to run a total of 1368 (37 x 36) scenarios with the WNMM model. N fertilizer applications were increased by small increments over the range of 0 to 1320 kg N/ha and irrigation water inputs were increased by regular inputs of 45 mm from 600 to 2175 mm (rain+irrigation) (Table 1). Nitrogen management was simulated when it was applied as manure and urea.

Table 1. N rates and water inputs modeled with WNMM

scenarios WNMM	fertilizer N	water inputs
n°	kg ha^{-1}	mm
1	0	600
2	60	645
3	95	690
4	130	735
5	165	780
6	200	825
7	235	870
8	270	915
9	305	960
10	340	1005
11	375	1050
12	410	1095
13	445	1140
14	480	1185
15	515	1230
16	550	1275
17	585	1320
18	620	1365
19	655	1410
20	690	1455
21	725	1500
22	760	1545
23	795	1590
24	830	1635
25	865	1680
26	900	1725
27	935	1770
28	970	1815
29	1005	1860
30	1040	1905
31	1075	1950
32	1110	1995
33	1145	2040
34	1180	2085
35	1215	2130
36	1250	2175
37	1285	
38	1320	
total n° 1368	**n° 38**	**n° 36**

In accordance with local practices our simulations were run with 100% of the manure being applied at sowing, whilst urea applications were split into three events (every 30 days after sowing). During the growing season, irrigations were applied every 10-15 days, from June to early September. The combinations of AMPs were selected to represent the agricultural practices in the Veneto Region.

MODEL DESCRIPTION

WNMM simulates the key processes of water balance and N dynamics in the surface and subsurface of soils, including evapotranspiration, canopy interception, water movement and ground water fluctuations, heat transfer and solute transport, crop growth, Carbon and N cycling in the soil-crop system, and agricultural management practices (crop rotation, irrigation, fertilizer N application, harvest and tillage). The model runs on a daily time step and is driven by variables of meteorological and crop biological data (Table 2).

Table 2. variables of meteorological and crop biological data in WNMM

Parameters	Variables
Geographic information	Latitude, average air CO_2 concentration
Climate data	Average air temperature, maximum air temperature, minimum air temperature, relative humidity, solar radiation, wind speed
Crop biological parameters	Radiation use efficiency, Harvest index, Optimal temperature for crop growth, Minimum temperature for crop growth, Maximum potential leaf area index,

		Fraction of crop growing season corresponding to the 1st and 2nd point on the optimal leaf area development curve, Fraction of the maximum leaf area index corresponding to the 1st and 2nd point on the optimal leaf area development curve, Fraction of growing season when leaf area index declines, Maximum stomatal conductance, Maximum crop canopy height, Maximum crop root depth, Normal N fraction in crop yield, Lower limit of harvest index, Normal N fraction in crop at emergence/at 50% maturity/at maturity, Parameter relating vapour pressure deficit (VPD) to bio-energy ratio, Threshold VPD at 2nd point on stomatal conductance curve, Heat units required for crop maturity
Bottom boundary condition		Groundwater table depth from soil surface
Groundcover		Crop residues, Crop distribution and rotation
Soil properties	Hydraulic properties	Parameters of soil water retention curve (van Genuchten equation), Saturated soil hydraulic Conductivity
	Physical properties	Soil albedo at or close field capacity, Soil bulk density, Soil mechanic composition, Initial soil volumetric water content
	Chemical properties	Soil cation exchange capacity, Soil organic matter content, Initial soil total N content, Initial soil NO_3^--N content, Initial soil NH_4^+-N content
Agricultural practices	Tillage	Date, Mixing depth
	Fertiliser N application	Date, Method, Fertiliser N amount, Organic N fraction in fertiliser N, Mineral N fraction in fertiliser N, NH_4^+-N form fraction in mineral N, NO_3^--N form fraction in mineral N
	Irrigation	Date, Water amount
	Harvest	Date, Return rate of crop stubble

In particular, WNMM simulates all key N transformations in agricultural fields, including mineralization of fresh crop residue N and soil organic N, formation of soil organic N, immobilization in biomass, nitrification, ammonia (NH_3) volatilisation, denitrification and nitrous oxide (N_2O) emission. Detailed descriptions of the equations and parameters of the hydrological and biogeochemical processes in WNMM have been reported by Li et al. (2007).

In WNMM, vertical water flow in soil is described by the one-dimensional Richards' equation in the Kirchhoff form:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\partial U}{\partial x} - k(h)\right) - S \quad (1)$$

where h is the volumetric water content (m^3 m^{-3}), t is the time (d), x is the spatial coordinate assumed to be positive downward from the soil surface (m), $K(h)$ is unsaturated hydraulic conductivity (m d^{-1}), S is the root water uptake (m^3 m^{-3} d^{-1}), U is the Kirchhoff transform variable defined as:

$$U = \int_{-\infty}^{h} K dh \quad (2)$$

with h the pressure head (m). Equation 1 was solved numerically using a finite difference scheme with the adoption of the Newton–Raphson approach (Ross and Bristow 1990). One day is used as the time step to shorten the numerical computation to a few iterations in WNMM. If convergence of the solution is not achieved with a one-day time step, the time step is decreased by 50% until a convergence is achieved. A surface flux boundary condition (flux equals the difference between the precipitation rate and potential soil evaporation rate) and a free drainage bottom boundary condition are set up in this work. The soil profile was divided into n adjoining elements (each element is homogeneous), with the ends of the elements located at the nodal points. The outputs of water flow simulation are pressure head and water content at each node and the inter-nodal water flux at a daily time step. The average water content and water storage of each element are also summarized for output and used by other submodules in WNMM. Solute transport (nitrate only) is governed by the standard convection-dispersion equation (Eq. 3), is solved numerically by the same method as that used to calculate water flow and is subject to prescribed initial and upper/lower boundary conditions.

$$\theta \frac{\partial c}{\partial t} = \left[\theta D(\theta, q) \frac{\partial c}{\partial x} \right] \pm \Phi \quad (3)$$

where c denotes nitrate concentration in soil solution (g N m^{-3}), q is water flux (m d^{-1}) and U is a source/ sink term for nitrate transport (g N m^{-3} d^{-1}) including rates for nitrate transformations and nitrate uptake by crop roots.

$D(\theta, q)$ represents the hydrodynamic dispersion coefficient (m^2 d^{-1}) defined as:

$$D(\theta, q) = \varepsilon \frac{|q|}{\theta} + D_0 \tau \quad (4)$$

where e is the nitrate dispersivity (m), D_0 is the nitrate diffusion coefficient in pure water (m^2 d^{-1}) and s is a dimensionless tortuosity factor. The process of ammonia volatilisation is important for the N balance, nitrification and denitrification. The combined degradation rate of soil ammonium N by nitrification and volatilisation ($R_{nit+vol}$, kg ha^{-1} d^{-1}) is estimated using the first-order kinetics proposed by Reddy et al. (1979).

$$R_{nit+vo} = WHN_4 \left[1 - \exp(-k_{nit} - k_{vol})\right] \quad (5)$$

where WNH_4 is the ammonium content in the soil layer (kg N ha^{-1}) and K_{nit} and K_{vol} are the nitrification and volatilisation regulators (d^{-1}), respectively.

Nitrification is regulated by a soil temperature factor (f_{T_nit}), a soil moisture factor (f_{sw_nit}), and a soil pH factor (f_{pH_nit}) as shown in Eq. 6 (Williams 1995). Ammonia volatilization was predicted as a function of soil temperature (f_{T_nit}) and wind speed (f_{wind}) for the surface soil, and as a function of soil depth (f_{depth}), cation exchange capacity (f_{cec}), and temperature of the subsurface soil (Eq. 7; Williams 1995).

$$K_{nit} = f_{T\_nit} \cdot f_{SW\_nit} \cdot f_{pH\_nit} \quad (6)$$

$$k_{vol} = \begin{cases} f_{T\_nit} \cdot f_{wind} \\ f_{T\_nit} \cdot f_{CEC} \cdot f_{depth} \end{cases} \quad (7)$$

MODEL CALIBRATION AND EVALUATION OF ITS PERFORMANCES

Observed data used during the phases of Calibration and evaluation of performance of the model were independent to each other. For this reason, the phase of calibration was performed using measured data of 2 lysimeters (Table 3).

Table 3. List of theses used during calibration and the evaluation of the performances of WNMM. The symbol † identifies the thesis used only during the calibration (1, 16), while the symbol * the thesis used to test the performance of the model.

number	**phase**	**lysimeter ID**	**N fert (kg N ha^{-1})**	**W inputs (mm)**
1	† *	N85 W800	85	800
2	*	N170 W800	170	800
3	*	N255 W800	255	800
4	*	N340 W800	340	800
5	*	N85 W1100	85	1100
6	*	N170 W1100	170	1100
7	*	N255 W1100	255	1100
8	*	N340 W1100	340	1100
9	*	N85 W1400	85	1400
10	*	N170 W1400	170	1400
11	*	N255 W1400	255	1400
12	*	N340 W1400	340	1400
13	*	N85 W1700	85	1700
14	*	N170 W1700	170	1700
15	*	N255 W1700	255	1700
16	† *	N340 W1700	340	1700

In particular, calibration was performed by utilizing data coming from lysimeter treated with the minimum and maximum nitrogen and water inputs (lysimeter lower inputs: 145 kg N ha^{-1}+800 mm yr^{-1}; lysimeter higher inputs: 400 kg N ha^{-1}+1700 mm yr^{-1}), while measured data of 16 lysimeters (Table 3) were used to evaluate the performance of the model in simulating N and W cycle in soil-plant system. The lysimeters used during the calibration and the test of the performance of WNMM are shown in Table 3. Explanation in detail of the rates of N and W inputs used in every lysimeter is reported in chapter 1.

Before applying the WNMM model we tested it by comparing observed and simulated soil water data obtained in lysimeters over a period of three years (Fig. 2). Soil hydraulic properties of the soil of the Veneto Region required for WNMM (Table 4) were obtained using Richard's ceramic suction cups (Soil Moisture Equipment Corp., 0675 Series pressure plate cell) and measuring the soil water content when air dry, and at wilting point, field capacity and saturation, and the saturated conductivity in each soil layer. Physical and chemical soil properties, from soils of the Veneto Region used in WNMM are shown in Table 4.

Table 4. chemical and physical soil properties used in WNMM

soil properties	unit	layers (cm)			
		0-15	15-30	30-70	70-130
residual water content at dry	$cm^3\ cm^{-3}$	0.02	0.02	0.03	0.02
wilting point	$cm^3\ cm^{-3}$	0.08	0.12	0.08	0.09
field capacity	$cm^3\ cm^{-3}$	0.25	0.30	0.34	0.31
saturated water content	$cm^3\ cm^{-3}$	0.42	0.38	0.42	0.41
saturated soil hydraulic conductivity	$m\ day^{-1}$	30.96	24.84	24.74	0.04
soil bulk density	$t\ m^{-3}$	1.48	1.60	1.50	1.55
SAND	%	31	31	31	31
SILT	%	54	54	54	54
CLAY	%	15	15	15	15
soil pH		7.25	8.24	8.20	8.11
soil organic matter	%	1.14	1.00	0.50	0.42
soil total nitrogen	%	0.075	0.06	0.05	0.1
soil total NO^-_3-N	$kg\ N\ ha^{-1}$	5.1	5.0	2.0	1.0
soil total NH^+_4-N	$kg\ N\ ha^{-1}$	4.96	5.32	2.54	2.40

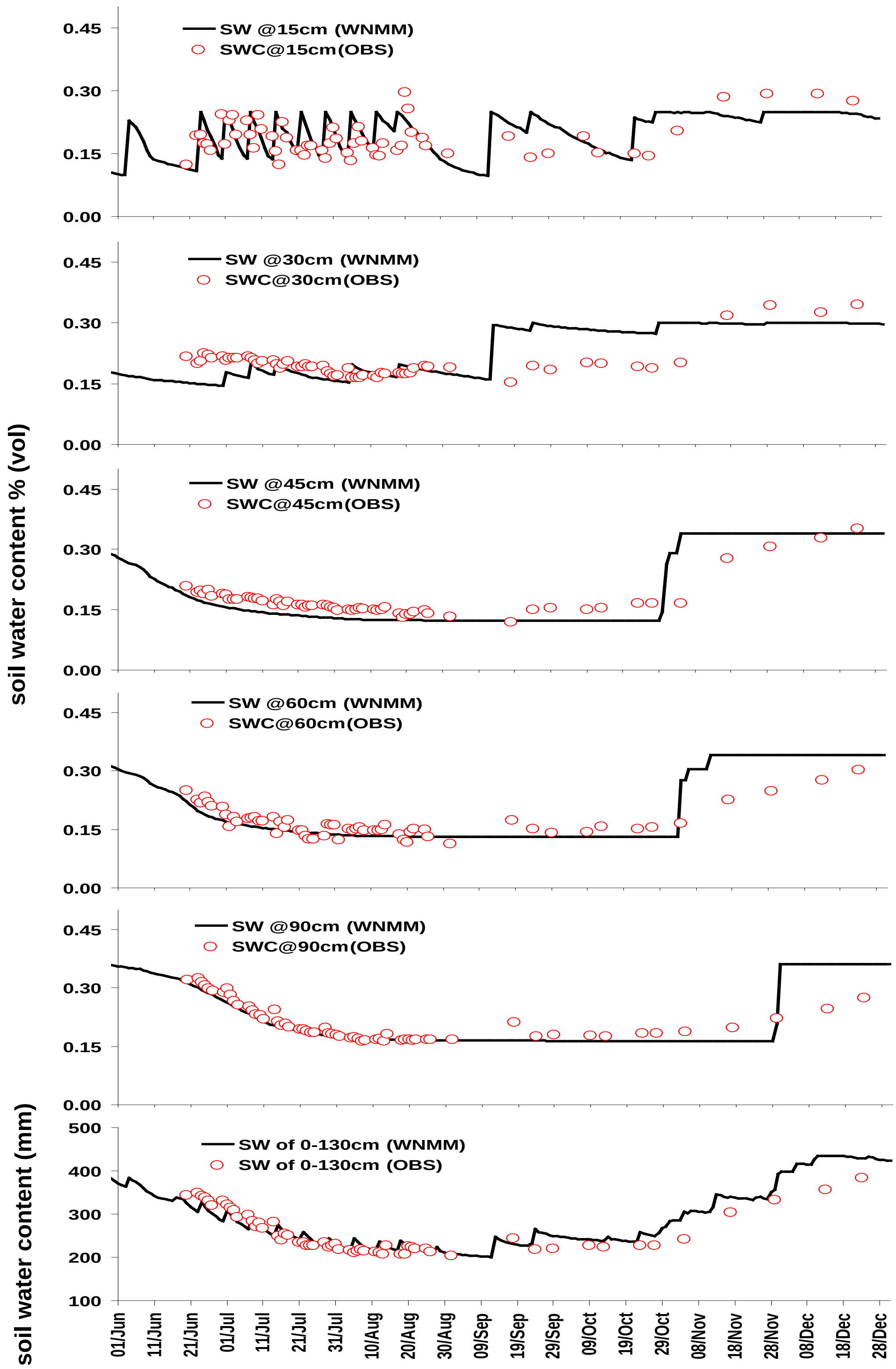

Figure 2. Observed and simulated of soil moisture data.

WNMM was calibrated using soil water at depths of 15, 30, 45, 60 and 90 cm depth measured at intervals of 7-10 days, using a the Moisture Point® MP-917 TDR system, equipped with Moisture Point® PRB-F (0-90 cm) profiling probes.

Physiological parameters used to calibrate WNMM, such as LAI, radiation use efficiency (RUE), minimum and maximum temperature of vegetation are shown in Table 5. The values of yields, water and nitrate losses simulated by WNMM at daily temporal scale were compared to the observed values (Fig 3, 4).

Table 5. Crop parameters inputs for WNMM's grow crop module

Crop Parameters	value
Radiation Use Efficiency$_{max_pot}$	45
Harvest Index$_{max_pot}$	0.48
Optimum Temperature (°C)	25
Base Temperature (°C)	8
LAI$_{pot_max}$ (m^2 m^{-2})	6
N content at harvest (%)	0.9
N content at ½ growth (%)	1.20
N content at early stages (%)	3.5

The performances of WNMM were evaluated for water dynamics, nitrate loss, yield and aboveground biomass and N plant uptake using observed data during the period from 2006 to 2008. Yearly observed values were compared with the predicted ones (Fig. 3, 4, 5, 6). Explanations in detail of the measured data were discussed in chapter 1. The yearly amount of N loss (kg N ha^{-1}) was calculated by multiplying NO_3-N concentrations (mg l^{-1}) by the total amount of water drained at weekly steps. The observed data of N losses were then compared with the predicted values. Dry yield and aboveground biomass were also compared with the predicted values. N uptake was calculated by multiplying the N concentrations of total N in grains, cobs, leaves and stalks by the dry matter of each of these yield components of maize and the observed data of N uptake compared with the predicted values. In general, the performances of the model shows a reasonable fit between simulated and observed nitrate-N losses, water drainage, yield, above ground biomass and N plant uptake on whole lysimeters (Table 6, Fig 4).

A qualitative evaluation of the model's performance was performed by a comparison of the time series graph of predicted values with that of the measured values. Objective evaluation was performed by calculating statistical parameters including: root mean square error (RMSE), modeling efficiency (EF) and relative error (E_R) (Table 6).

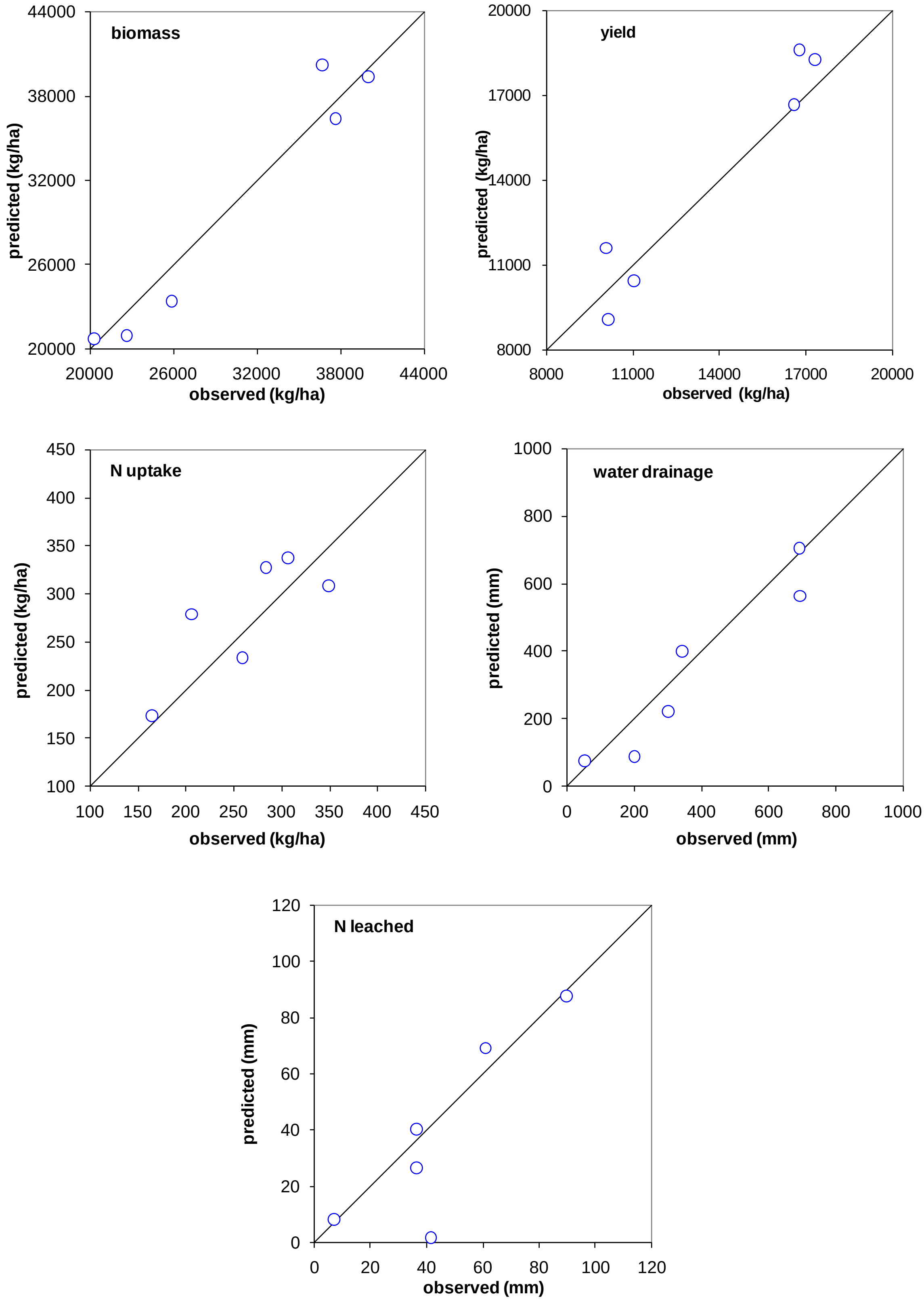

Figure 3. Calibration results for biomass, yield, N uptake, water drainage and N losses .

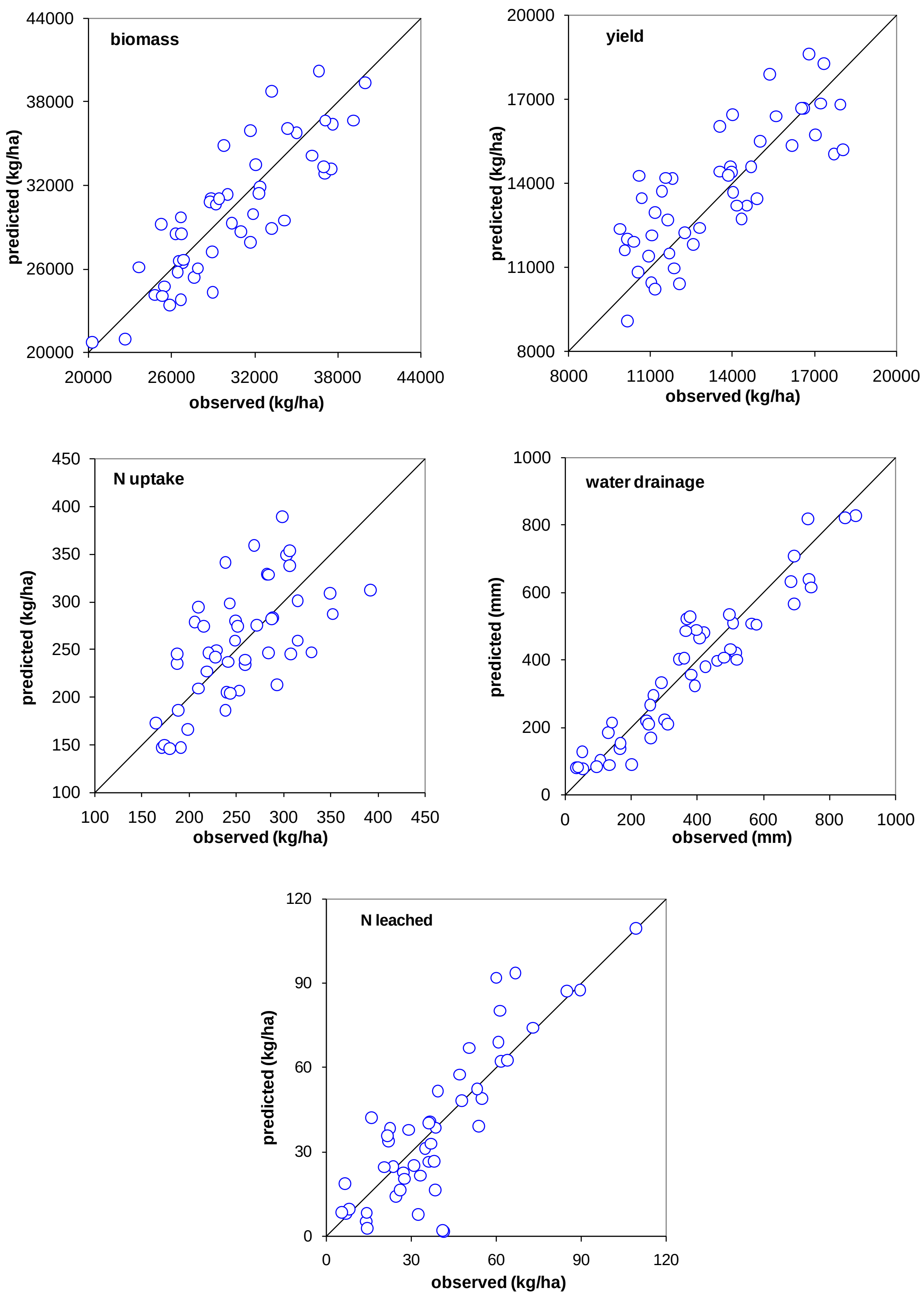

Figure 4. Evaluation of the performances of WNMM for biomass, yield, N uptake, water drainage and N losses .

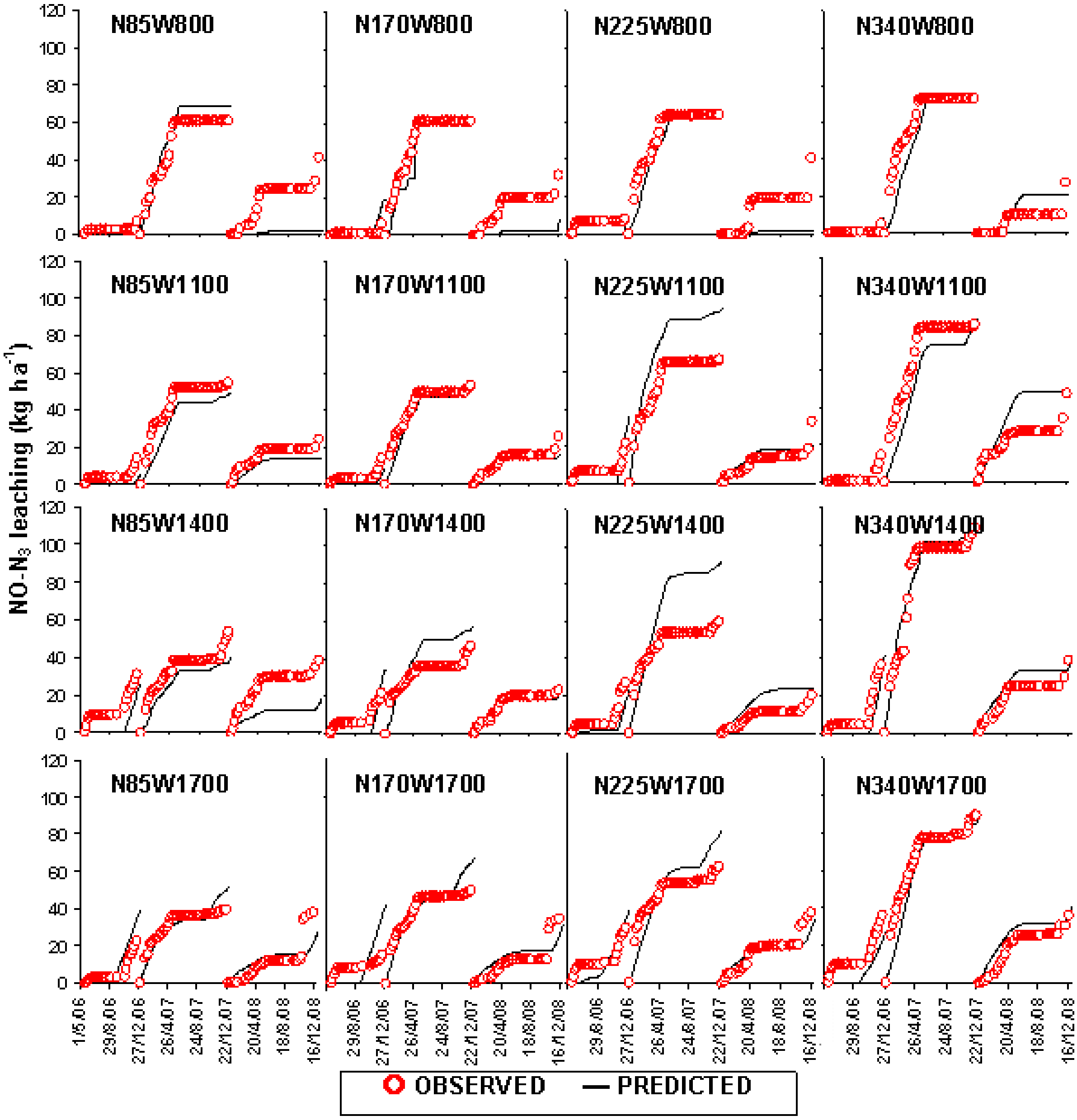

Figure 5. observed and simulated nitrate-N leaching

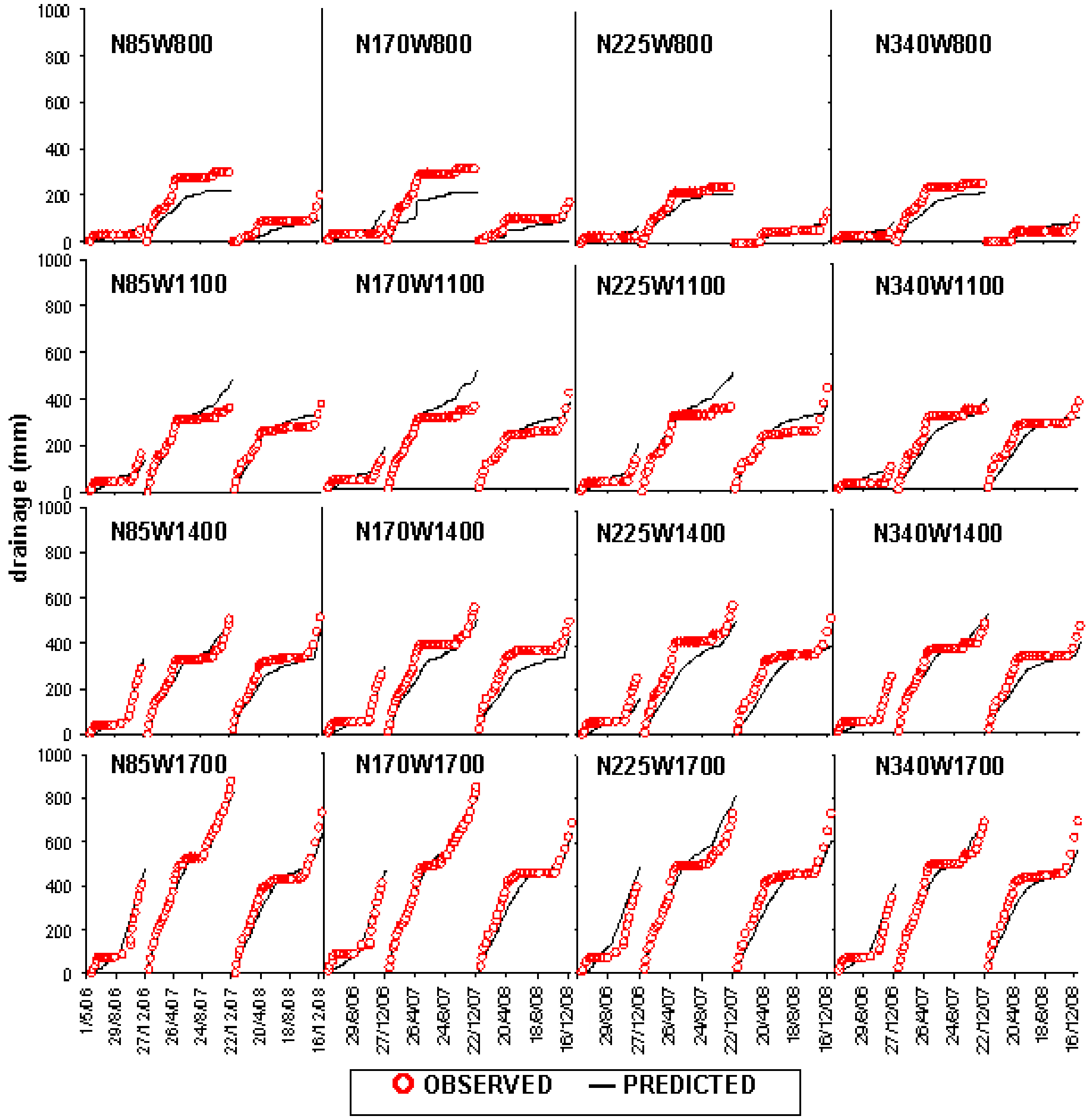

Figure 6. observed and simulated water drainage

Root mean square error measures the differences between values predicted by a model or an estimator and the values actually observed from the parameter being modelled or estimated and it is a good measure of accuracy (Smith et al., 1997)

$$RMSE = \frac{100}{\overline{O}} \frac{\sqrt{\sum_{i=1}^{n} (P_i - O_i)^2}}{n} \quad (1)$$

where P_i is the predicted values, O_i is the observed values, $\overline{O}$ is the average of the measured values and n the number of data pairs.

The accuracy of simulation was calculated by the index of modelling efficiency (EF):

$$EF = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \quad (2)$$

A modelling efficiency of 1 means a perfect fit, while a negative value indicates that the simulated values describe the data less well than the mean of the observation (Sun, et al., 2008).

The bias in the difference between the simulated and measured values was estimated by calculating the relative error (E_R);

$$E_R = \frac{100}{n} \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{O_i} \quad (3)$$

Table 6. results of statistical analysis, both during calibration and model's performances for biomass, yield, water drainage, nitrate-N leaching and N plant uptake.

parameter	statistical analysis	unit	calibration	WNMM performances
			2 treatments	16 treatments
biomass	RMSE	kg ha^{-1}	6.51	8.65
	EF		0.94	0.99
	R^2		0.95	0.72
	ER		1.73	0.93
	regression parameter			
	slope		*2555*	*3480*
yield	RMSE	kg ha^{-1}	8.61	11.7
	EF		0.87	0.99
	R^2		0.94	0.63
	ER		-2.88	-4.08
	regression parameter			
	slope		*1506*	*4012*
water drainage	RMSE	mm	21.3	19.2
	EF		0.89	1.00
	R^2		0.91	0.90
	ER		5.60	-7.51
	regression parameter			
	slope		*15.4*	*30.3*
nitrate-N loss	RMSE	kg ha^{-1}	37.9	36.3
	EF		0.54	0.99
	R^2		0.74	0.73
	ER		12.8	-3.70
	regression parameter			
	slope		*8.39*	*-2.01*
N uptake	RMSE	kg ha^{-1}	16.2	19.1
	EF		0.53	0.98
	R^2		0.62	0.41
	ER		-7.69	-1.88
	regression parameter			
	slope		*84.2*	*69.4*

DEFINITION OF THE WNMM MODEL AGRICULTURAL MANGEMENT PRACTICES INPUTS AND DETERMINATION OF NUE, AND WUE

The numerous management practices inputs used in the WNMM scenarios included N fertilization amount (both from inorganic and manure sources), timing, fertilizer type and also irrigation amount and timing. N management practice (N application rates) were collected both from the online database of the Italian Institute of Statistics (ISTAT, 2002) and from a documented survey conducted by the Department of Environmental Agronomy and Crop Science (unpublished data), from 2006 to 2007. The timing and the amount of the irrigation water was obtained by combining the information from the FAO website (AquaStat, 2001), the online databases of the Veneto Agricoltura (Veneto Agricoltura, 2000), the Italian Institute of Statistics (ISTAT, 2006), and the Land Reclamation and Irrigation Consortia National Association (ANBI, 2001). The closest meteorological station (30 m) to the experimental site was used for daily minimum, maximum and temperature, solar radiation and precipitation. All scenarios were run with the same soil inputs as the most representative soil in the Veneto Region (see chapter 1).

A series of simulations were conducted to determine the nitrogen and water use efficiency and N losses in combination over the range of rates of water and N inputs. The simulated data were used to calculate NUE and WUE.

NUE (kg kg^{-1}) is defined as the increase in crop yield per unit of applied N (Moll et al., 1982; Paponow et al, 1996):

$$NUE \quad (kg\,kg^{-1}) = \frac{(Y_f - Y_0)}{N_{rate}} \quad (4)$$

where Y_f is the yield in a fertilized crop, Y_0 is the yield in an unfertilized subplot in the same field, both expressed in kg ha^{-1}, and N_{rate} (kg N ha^{-1}) is the fertilization rate in the fertilized field. This definition has been previously used in several studies to evaluate the N management in agriculture in cereal crops in the UK, Spain, Argentina, Italy and the United States of America (Semenov et al., 2006, Arregui and Quemada, 2008, Barbieri et al., 2008, Di Paolo and Rinaldi, 2008, Kim et al., 2008).

Water use efficiency (kg m^{-3}) has been widely used and discussed previously in several studies (Vietis, 1962; Howell, 2001; Pereira et al, 2002; and Katerji et al, 2008). The following equation was used to calculate the WUE and is defined in agronomy as:

$$WUE\,(kg\,m^{-3}) = \frac{yield}{water\,consumption} \quad (5)$$

where grain yield in this equation is expressed in g m^{-2} and the water consumption (evapotranspiration) is expressed in mm. The time scale considered was the whole vegetative cycle. This definition has been discussed in several studies to evaluate the water management in agriculture in cereal crops in regions including the USA, Italy and the Mediterranean Region (Howell, 2001, Di Paolo and Rinaldi, 2008, Katerji et al., 2008, Garcia et al., 2009, Payero et al., 2009).

RESULTS AND DISCUSSIONS

MODEL PERFORMANCES

Figures 7 and 8 show the simulated nitrate concentrations in ground water over the wide ranges of rates of water and N inputs. At low water rates e.g. 735 and 825 mm, fertilizer N can be applied at large rates without exceeding EWF (Fig. 7). In these conditions, the volume of water drainage is very low and the nitrate-N concentration is below the EWF. Increasing water rate resulted in the EWF being exceeded at lower N inputs. Moreover, from 1230 to 2175 mm of water, 270 kg N ha^{-1} of N fertilizer is the maximum rate of N application that does not to exceed the EWF.

WATER AND N RATES TO COMPLY WITH THE EU ENVIRONMENTAL TARGETS

Figure 7 shows the effect of water inputs on the efficiency of fertilizer N applications. An N fertilizer rate lower than 230 kg N ha^{-1} results in nitrate-N concentrations below the EWF of 11.3 mg l^{-1} at all irrigation rates. However, EWF is exceeded at all N rates higher than 270 kg N ha^{-1} when annual water inputs are between 1095 and 1230 mm. In addition, 1095 mm seems to be the lowest amount of water that can be applied before the EWF is exceeded.

This study confirms that nitrate concentrations in leached water are determined not just by the inputs of N fertilizer (manure+urea) but rather the combination of N fertilizations and water inputs. The combination of these two inputs has an important role in meeting the threshold imposed by the European Water Framework (EWF) of 11.3 mg l^{-1} of NO_3-N.

Our simulations show that for maize grown in the Veneto Region on a loamy soil up to 340 kg N ha^{-1} can be applied annually without exceeding the concentration of 11.3 mg l^{-1} nitrate-N in the leachate at water application rates below 1100 mm yr^{-1} (Fig. 8). This is considerably more than 170 kg N ha^{-1} stipulated by the Nitrate Directive for NVZ areas.

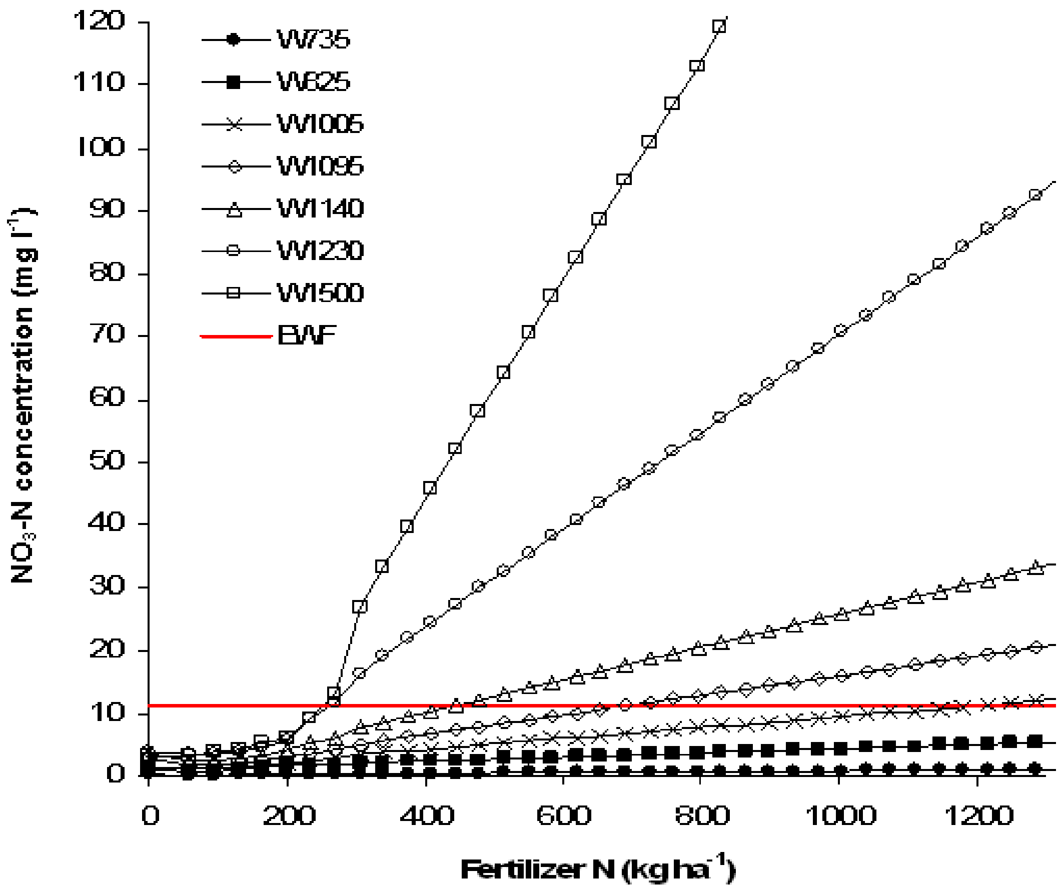

Figure 7. annual nitrate-N concentrations in water drainage under different water inputs and N fertilizer rates.

Similar conclusions were drawn by several authors such as Ten Berge et al., (2002) and Schröder et al., (2007) who found that up to 330-340 and 400 kg N ha^{-1} manure can be applied annually without exceeding the concentration of 11.3 mg l^{-1} nitrate-N, in grasslands of northern Europe. However, our simulations for maize cropping showed that 300 kg N ha^{-1} of fertilizer application did not exceed the EWF when applied water applied was less than 1110 mm (Fig. 8). However in the north of the Veneto Region the annual irrigations are usually large (average rainfall is around 1100 mm and up to 200 mm of irrigation is applied during the growing season), and therefore there is a high probability of exceeding the EWF.

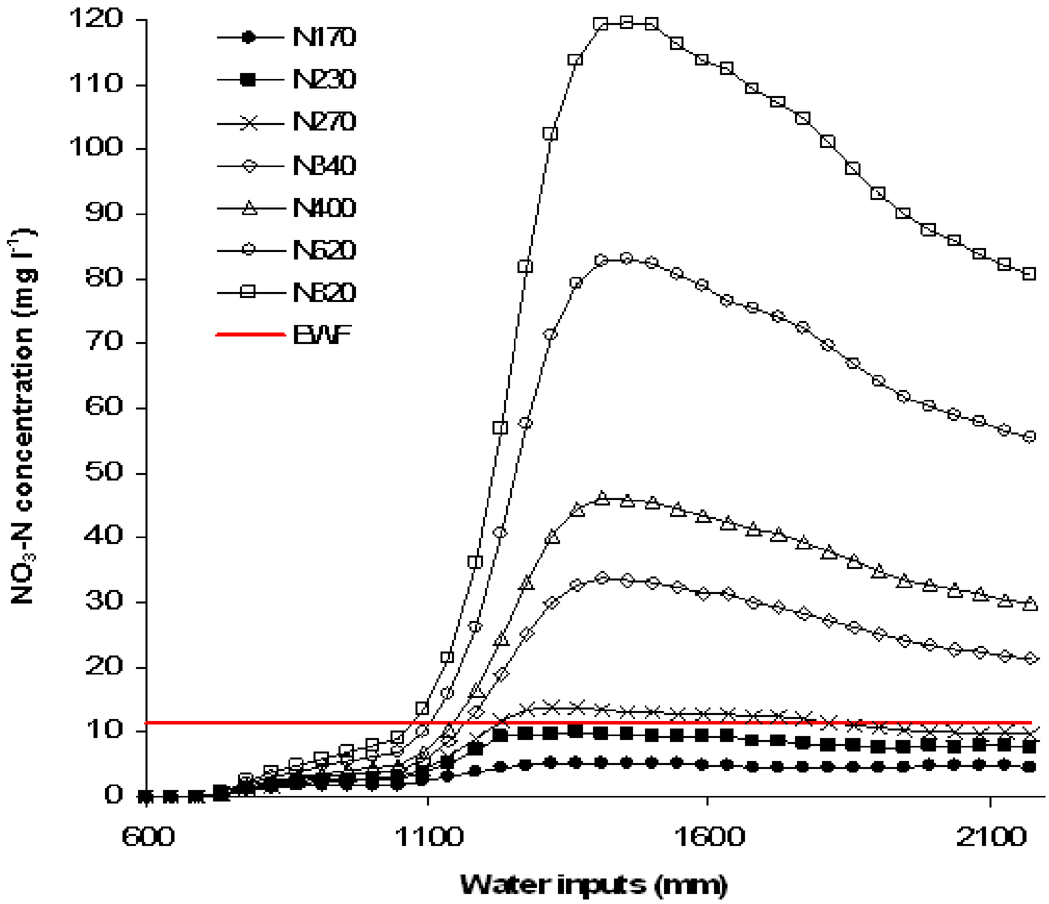

Figure 8. annual nitrate-N concentrations in water drainage under different water inputs and N fertilizer rates.

CAN THE EU NITROGEN DIRECTIVE ACHIEVE THE TARGET FOR NITRATE LEACHING IN THE VENETIAN NVZ AND NON NVZ AREAS?

Figure 9, shows the maximum N and water inputs that can be applied without exceeding the EWF limit of 11.3 mg l^{-1} nitrate-N in groundwater. The EU limit of 170 kg manure N ha^{-1} did not result in the EWF being exceeded at any of the rates of water application simulated. This confirms that the 170 kg N ha^{-1} limit for manure prevents nitrate pollution of groundwater in the Veneto Region. However, the European Directive (EU 91/676) allows farmers to use a maximum of 60 kg N ha^{-1} of inorganic fertilizer in addition to the 170 or 340 kg N ha^{-1} in NVZ and non NVZ areas respectively.

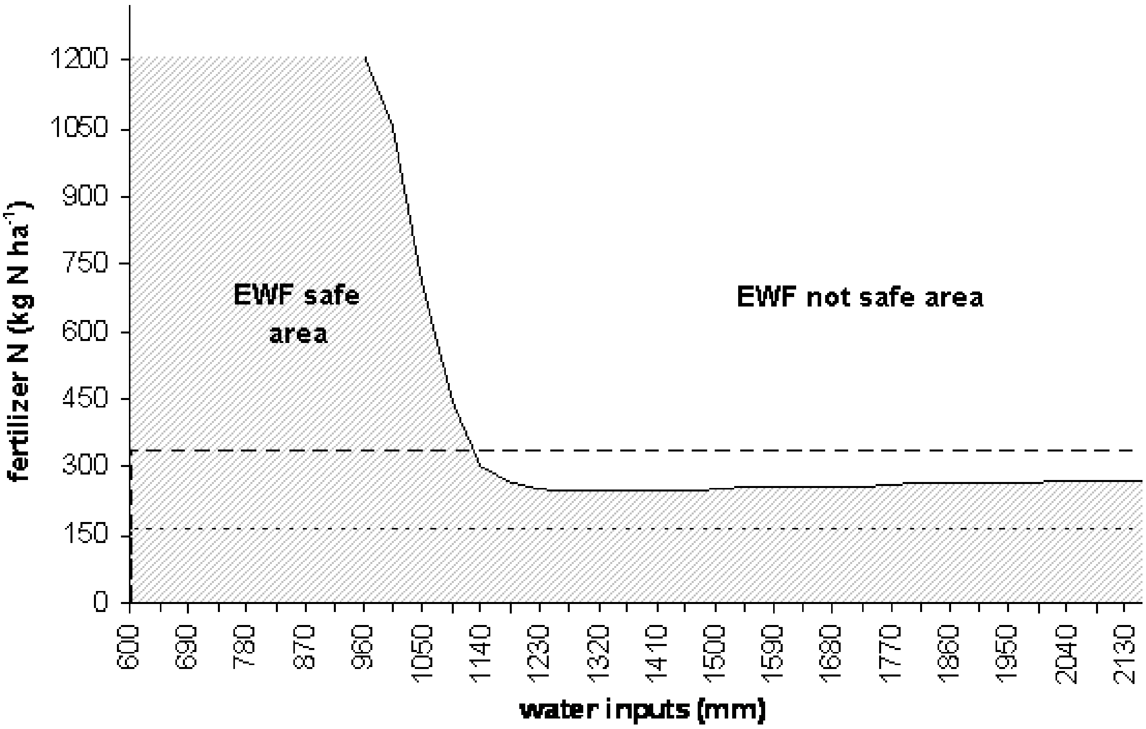

Figure 9. maximum amount of water and N fertilizer rate (EWF safe area) to comply with the EU targets. The two horizontal dotted lines identify the EU Nitrate Directive threshold of 170 and 340 kg N ha^{-1}. The gray pattern identifies the allowable combinations of water and N fertilizer (EWF safe area), while the black line the combinations beyond that EWF is exceeded (EWF not safe area).

At above 1230 mm of water annually 230 kg N ha^{-1} is very close to the maximum amount of fertilizer that can be used before exceeding the EWF (250 kg N ha^{-1}). This means that farmers should precisely determine the N content in the animal excretion present in the farm. Additionally, a correct assessment is sometimes very difficult because the N content in manures depends on the animal category present on the farm, production level and diet (Kebreab et al., 2001).

Moreover, the timing of application and the meteorological conditions also play an important role in reducing or promoting N losses. Although 230 kg N ha^{-1} of fertilizer does not cause breaching of the EWF, reducing the N application rate to 170-200 kg N ha^{-1} when the annual precipitation and irrigation is more than 1250 mm, may be a useful guide for reducing the risk of exceeding the EU target of 11.3 mg l^{-1} NO_3-N.

The threshold of 340 kg N ha^{-1} for manure deserves a special discussion. Based on our simulations, 340 kg N ha^{-1} of manure application can avoid exceeding of the EWF at up to 1110 mm of water annually, when applied to maize crops grown on loamy soil (Fig 9). However, above 1100 mm of water the amount of N applied should be limited to 250 kg N ha^{-1}. By applying this amount of N, the concentration of nitrate-N in ground water should not exceed the EWF. Moreover, at 1110 and 1275 mm, N fertilization rates of 300 and 265 kg N ha^{-1} may be applied. It has to be noted that these N rates represent the maximum amount of N that can be spread before exceeding the EWF. Extreme weather events or a year which is particularly wet could expose farmers to the risk of exceeding the EWF. In areas where the annual inputs of water ranges between 1110 and 1275 mm it can be difficult to determine rainfall and water amount. Therefore a precautionary reduction to 250 kg N ha^{-1} of N fertilizer is suggested as this would prevent the exceeding of the EWF. In addition, our simulations show that 250 kg N ha^{-1} seems to be the maximum amount of nitrogen that can be applied annually without exceeding the EWF where the annual input of water is greater than 1250 mm. However, from between 1500 and 2000 mm of water input the N applied may be gradually increased up to 270 kg N ha^{-1}. This behavior is attributed to the ability of maize to increase use of N derived from soil and fertilizations under high water inputs and consequently reduce the amount of N leached (O'Neill et al., 2004; Kim et al., 2008; also see chapter 1).

In our study we evaluated the room for manure and inorganic fertilizer to be used in view of N concentration of 11.3 mg l^{-1} nitrate-N which is in agreement with the Nitrate Directive. Our study was limited to loamy soil in the Veneto Region and considered a wide range of agricultural practices. The present study confirms that the precautionary threshold set by the EU to reduce nitrate pollution of ground water can prevent the risk of exceeding the European Water Framework target of 11.3 mg l^{-1} nitrate-N in NVZ areas, while it can partially prevent it in non NVZ areas only if water inputs are kept below 1100 mm yr^{-1}.

MAXIMIZING YIELD IN RELATION TO NUE, WUE AND N LEACHING

Although it appears that the maximum N fertilization rates can comply with limits set by the European Nitrate Directive, it does not necessarily help farmers to make the agronomical decisions to maximize crop yield and reduce nitrate leaching. Fertilizer and water are the main important factors farmers can manipulated to maximize crop production.

Consequently, if excessively used they can cause pollution of superficial and ground water as well as reduction of profits. We discuss the optimum rate of N fertilization by considering the interaction of nitrogen use efficiency, nitrate-N leaching and maize yield.

The Figure 10 shows the behavior of NUE, NO_3-N and yield under different inputs of water and nitrogen. At 800 mm water annually, nitrate-N leaching did not exceed the EWF at any N rate (Fig 10). However, the results show that 130 kg N ha^{-1} is the best N rate because it leads to an increase of NUE, decreases of nitrate leaching, and virtually no change in grain yield (Table 7). The highest crop production, under 1110 mm, is achieved at 170 kg N ha^{-1}. This implies that inside NVZ, 170 kg N ha^{-1} is the optimal rate of N fertilizer because it results in a high NUE (22.5 kg kg^{-1}) and maximum yield, without exceeding the EWF.

Applications of 340 kg N ha^{-1} of fertilizer do not cause the exceeding of the EWF at below 1110 mm of water inputs. However, considering that the highest yield is reached at 170-200 kg N ha^{-1} our results suggest that N inputs should be reduced to 200 kg N ha^{-1}. This leads to an increase in NUE (from 9.14 to 18.72 kg kg^{-1}) and decreases in NO_3-N concentrations (from 6.8 to 3.1 mg l^{-1}) with only a slight reduction in grain yield (Table 7, Fig 10). At 1275 mm, the NO_3-N leaching exceed EWF at 255 kg N ha^{-1} while, the highest yield is reached at 235-240 kg N ha^{-1}. This means that 170 kg N ha^{-1} of fertilizer can be applied without exceeding EWF and consequently achieving a high value of NUE (26.8 kg kg^{-1}), but with virtually no reduction in grain yield (Table, 7).

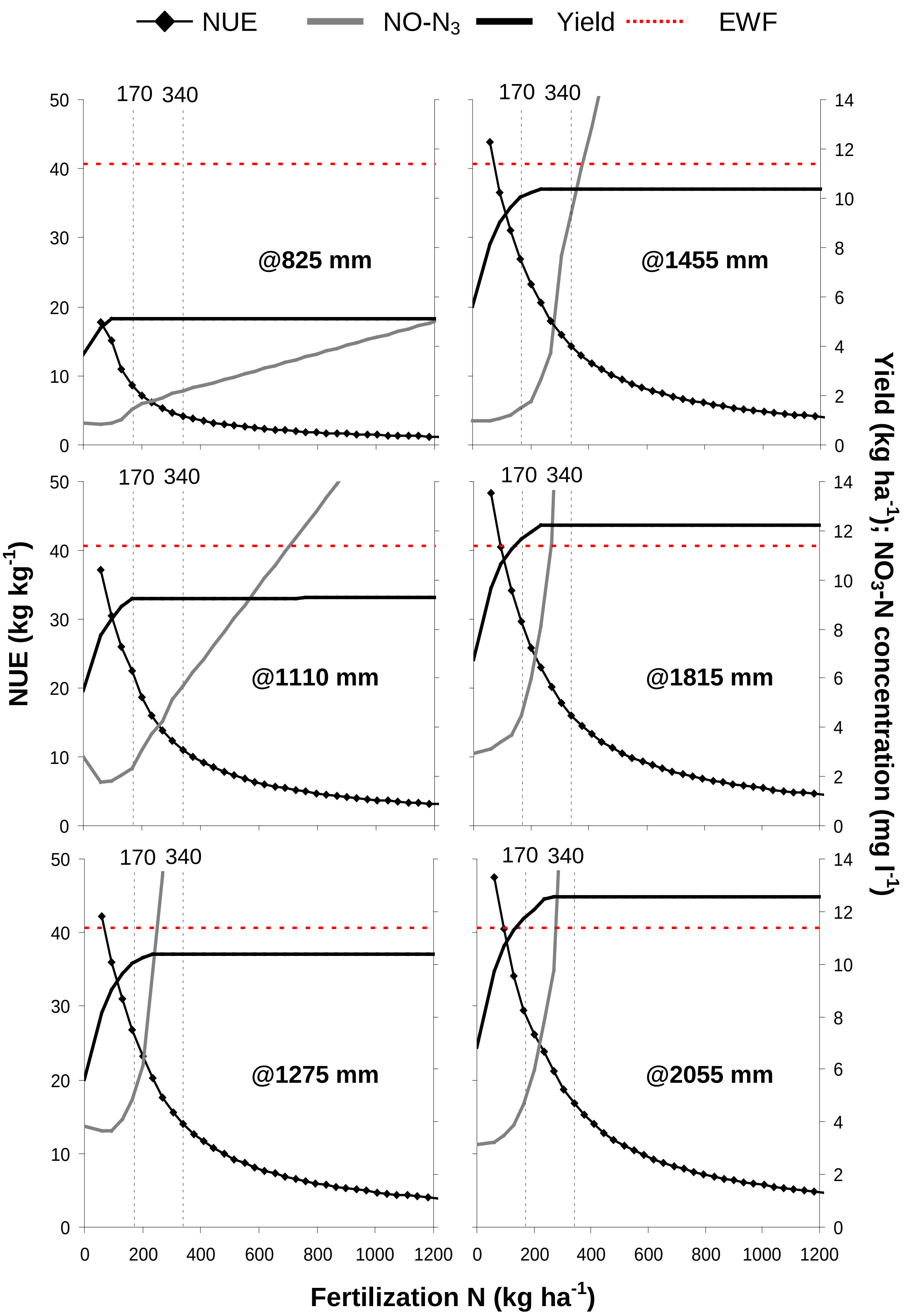

Figure 10. effect of different N fertilization rates on yield, NUE and nitrate-N leaching, in diverse scenarios with different water inputs amount. The two vertical dotted lines identify the EU thresholds of 170 and 340 kg N ha^{-1} of N fertilizer.

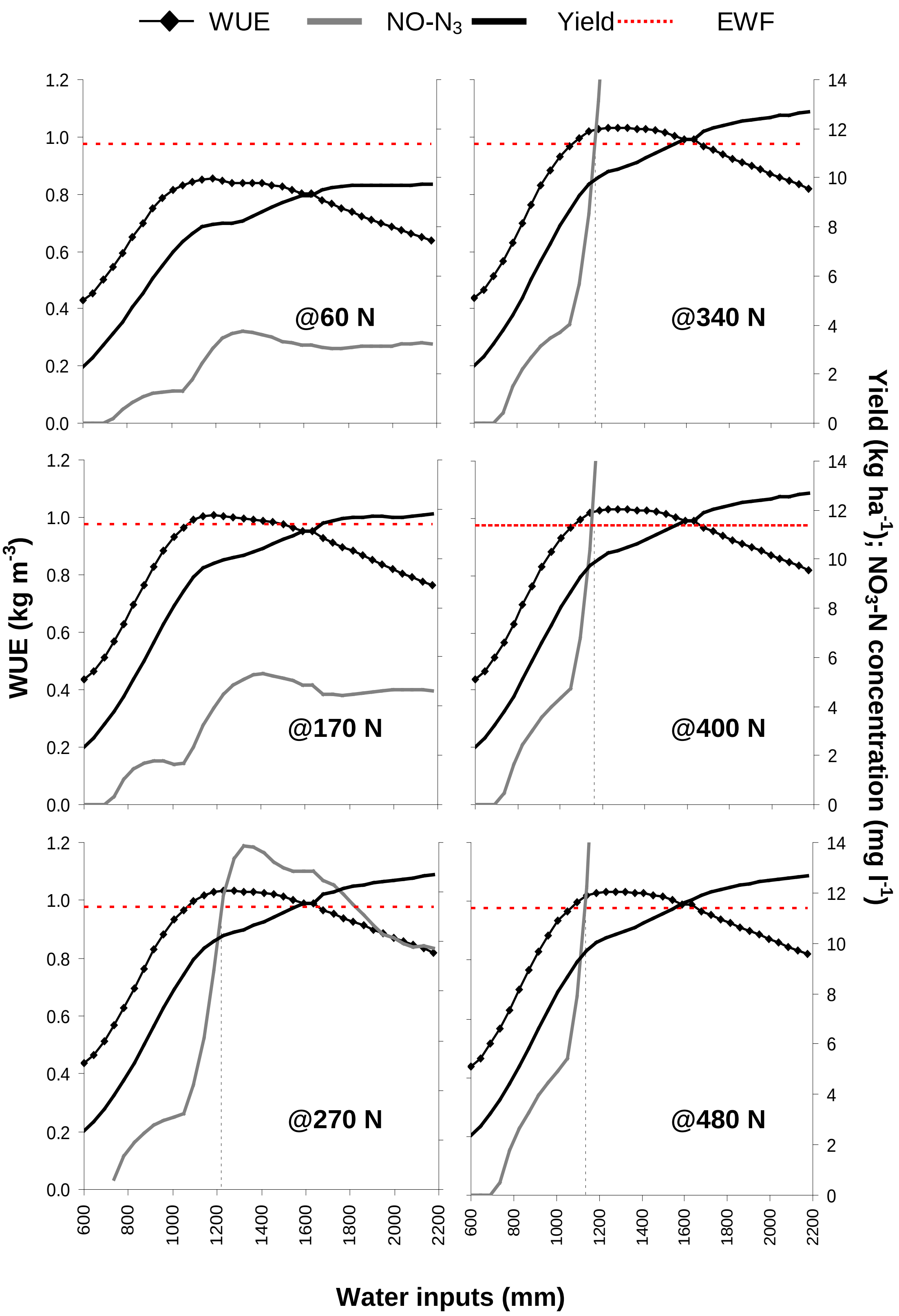

Figure 11. effect of different water inputs on yield, WUE and nitrate-N leaching, in diverse scenarios with different N fertilization rates. The vertical dotted line identifies the water amount beyond that EWF is exceeded.

Moreover, our simulations show that 340 kg N ha^{-1} in non NVZ areas , may exceed 11.3 mg l^{-1} of nitrate-N in ground water when annual water inputs are higher than 1200 mm. This implies that the EU Nitrate Directive 91/676 threshold of 340 kg N ha^{-1} may not respect the targets imposed by the EWF.

Our findings, in fact, suggest that farmers should apply a maximum of 235-240 kg N ha^{-1} in the non NVZ in order to not exceed EWF. Moreover, 235 kg N ha^{-1} corresponds to the N inputs which allow the highest maize yield with the lower N rate to be reached. Therefore, by reducing the N inputs up to 235-240 kg N ha^{-1}, farmers can increase NUE (from 11.82 to 20.58 kg kg^{-1}) virtually with no reduction in grain yield (Table 7, Fig 10).

From 1455 up 2175 mm of water inputs, 170 kg N ha^{-1} do not exceed EWF. Moreover, 170 kg N ha^{-1} leads to the increasing of NUE and the decreasing of nitrate-N leaching, even though with a reduction in grain yield (Table 7, Fig 10). The highest crop yield peaks at 235, 245 and 270 kg N ha^{-1} of fertilizer, under 1455, 1815 and 2085 mm of water, respectively (Fig 10).

Thus, our results suggest that The European Union Nitrate Directive of 170 kg N ha^{-1}, is a good threshold that allows the reduction of nitrate-N in ground water and abide by the guidelines imposed by the EWF targets. Alternatively, 340 kg N ha^{-1} exceed EWF in all scenarios run using the WNMM, especially when annual water inputs exceed 1275 mm. Consequently, it is important to reduce the rate of fertilizer applied to maize. In particular, we suggest to decrease the N fertilization up to 235, 240 and 275 kg N ha^{-1} when the annual water input is 1455, 1815 and 2085 mm, respectively. These rates of fertilization lead to an increase in the NUE, a reduction in nitrate-N leaching and allow the highest crop yield with the minimum N inputs to be achieved (Table 7, Fig 10).

Table 7. Parameters are expressed as follow, N $fert_{170}$ and N $fert_{340}$ (kg N ha^{-1}), yield (kg ha^{-1}), NUE (kg kg^{-1}) and NO_3-N leaching (mg l^{-1}). N $fert_{EWF}$ indicates the maximum amount of N in order to achieve the highest production of maize grain yield, without exceeding EWF. Bold values identify the concentration of NO_3-N that exceeded 11.3 mg l^{-1}.

EU policy	evaluated parameters	water inputs (mm)					
		W825	W1095	W1275	W1455	W1815	W2085
EU 170 N	N $fert_{170}$	170	170	170	170	170	170
	yield	5.10	9.23	10.0	10.5	11.6	11.7
	NUE	8.68	22.5	26.8	26.8	29.5	29.4
	NO_3-N leaching	1.45	2.31	4.83	5.24	4.48	4.68
EU 340 N	N $fert_{340}$	340	340	340	340	340	340
	yield	5.10	9.25	10.3	11.0	12.2	12.5
	NUE	3.50	9.14	11.6	11.8	13.2	13.9
	NO_3-N leaching	2.42	6.78	**33.2**	**46.0**	**37.9**	**31.2**
EWF	N $fert_{EWF}$	130	200	235	235	235	270
	yield	5.10	9.25	10.3	10.9	12.2	12.5
	NUE	11.0	18.7	20.2	20.5	23.0	12.1
	NO_3-N leaching	1.03	3.08	9.70	9.54	8.18	9.78

Our results show that 60 and 170 kg N ha^{-1} do not exceed EWF at any water inputs tested in our scenarios. This means that farmers can reach a higher crop yield by applying more water. However, water use efficiency must be considered, in view of an efficient use of water in agriculture. Our simulations demonstrate that the highest WUE is achieved at 1140 and 1185 mm for water and at 60 and 170 kg N ha^{-1} for the N applications respectively (Fig. 11). However, up to 1400 mm of water may be applied to maize because WUE tends to not decrease until 1400-1450 mm of water (Fig. 11).

From 270 kg N ha^{-1}, water applied becomes the limiting factor in order to comply with the EWF. NO_3-N concentration in ground water exceed 11.3 mg l^{-1}, after 1220, 1170, 1160 and 1135 mm, at 270, 340, 400 and 480 kg N ha^{-1}, respectively. These results suggest farmers should limit water inputs up to 1200-1100 mm. However, this management could lead to a worst results as Figure 11 illustrates, 1100-1200 mm do not allow farmers to reach high crop productions, even though the EWF target is achieved. Our results, show that, reducing the N inputs and consequently applying medium-high irrigations (e.g. 1300-1400 mm) is the best agronomic practice for high crop production whilst at the same time complying with the EU Nitrate Directive for reducing nitrate-N in ground water.

HOW TO AVOID INCORRECT MODEL SIMULATIONS?

The applicability of this calculation to the general practice strongly relies on a precise determination of all relevant inputs such as N and water inputs. Output levels are determined by assumptions concerning the extent to which inputs are properly utilized by crops and net production potentials are exploited as much as possible. We ran our simulations through a wide range of optimized agricultural crop managements in the Veneto Region, under optimal conditions. Optimal agricultural management practices and conditions may pertain to many aspects such as incorrect timing of tillage, manuring, establishment or destruction of swards and harvests (Schröder et al., 2007). Proper attention should be paid to all these factors, in particular timing and strategies of irrigation and fertilization as well as the evolution of the climate throughout the year, to avoid incorrect estimates of output.

Often, if these best practices are not enforced by incentives or fees, farmer's objective are to reach a high crop products by applying high amount of N inputs. High N rate, however, can cause N environmental pollution of the groundwater. In addition the ecological targets, to be defined in accordance with the water framework directive may required a lower N concentration than 11.3 mg l^{-1} nitrate-N (Camargo and Alonso, 2006). Therefore our conclusions will not necessary mean that nitrate leaching will comply with the Nitrate Directive when fully implemented. However, this study provides the valuable information on the effect of N fertilizer and water on the NO_3-N leaching, in the climate of the Veneto Region. Our results can be a good starting point for several studies in areas with unique characteristics (texture, shallow ground water, annual precipitation etc.) and AMP, in the Veneto Region.

CONCLUSIONS

The purpose of this study was to analyze the interactions of nitrate-N leaching, NUE and WUE in a high-inputs agricultural region in relation to compliance with the EU Nitrate Directive. Water and nitrogen played an important role in controlling nitrate-N leaching in groundwater. Maize on loamy soil in the north of Italy can utilize fertilizer N up to 340 kg ha^{-1} without exceeding a target value of 11.3 mg l^{-1} in the groundwater. However, the water input should not exceed 1100 mm annually. The EU Nitrate Directive threshold of 170 kg N ha^{-1} did not exceed the EWF at any water inputs considered in our scenarios. Moreover, this N rate allows farmers to maximize NUE and reduce nitrate-N leaching in groundwater even though this does not correspond with maximum yield. Yield, however, could be increased by applying more water to crops. WUE tends to reach its maximum around 1200-1100 mm of water annually, and up to 1400 mm can be applied in order to increase yield with negligible decreases in WUE.

In non NVZ areas, the threshold of 340 kg N ha^{-1} of N, prevents the limit of 11.3 mg l^{-1} of NO_3-N being exceeded in groundwater when the annual water input is less than 900 mm. At higher water inputs, in order to reach the EWF targets a reduction of applied N is needed. In particular, our results suggest fertilizations should be reduced to between 235 and 270 depending on the amount of water inputs. Furthermore, this leads to increases in NUE, reductions in nitrate-N leaching, and with a virtually no change in grain yield.

Our results show that reducing N applied and increasing water inputs are the best way to achieve a higher grain yield, higher NUE and WUE and a reduction in nitrate-N leaching in groundwater, whilst complying with the European Water Framework. Nonetheless our results provide scientific basis and references for governments' decision-making from the view of complying with the EU Nitrate Directive. Also, it must be clarify that we calibrated and tested the performances of WNMM using physical and chemical properties of most representative soil in the area of Padova Province. Therefore, this results can be extended only to those areas of the Veneto Region with similar soil characteristic to those used in this experiment.

ACKNOWLEDGEMENT

I wish to thank Prof. Ian Willet for his helpful comments and insight. Dr Yong Li and Prof. Deli Chen for their precious advices during the analysis of the data and throughout the writing of this chapter. Again, many thanks to Dr. Yong Li, for his patience and passion in teaching me how to use and run simulations with WNMM. Also, I thanks Fondazione Gini for supporting the period of study at the University of Melbourne and the Faculty of Land and Food Resources, the University of Melbourne.

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CHAPTER 3

CLIMATE CHANGE PRESENTS NEW CHALLENGES FOR MAIZE NITROGEN MANAGEMENT AND THE EU NITRATE DIRECTIVE. AN ITALIAN CASE OF STUDY

ABSTRACT

Corn productivity and N cycle may be influenced by climatic and environmental condition. An higher temperature, a shift in the distribution of rainfall and thus soil moisture, could alter the productivity of crops, soil N dynamics, consequently increase rates of N mineralization and N losses. Climatic projection are fundamental for better understand the future impact of N into the environment. Determining the interaction of climate change with the N cycle could help to identify the promising recommended farm management practices that maximize yield and reduce groundwater pollution in the long term. The aim of this study was to better understand the evolution of crop yield, N leaching and nitrogen use efficiency during the next years. We projected the simulations from 2010 to 2100 hypothesizing different nitrogen and water management practices in a silty-loamy soils, on maize, in northern Italy. For this, we used climate data from global climate models (ECHAM5-r3) forced by the emission scenario A1B. The results clearly indicate that grain yield would decrease approximately by up to 6.8% from 2010 to 2100. This reduction could be more exacerbated at N rates higher than 280 kg N ha^{-1}, (-7.9 and -16.8 kg ha^{-1}, at rates of 170 and 280 kg N ha^{-1}). In contrast, higher temperature and lower precipitation increased NO_3-N losses. EU Nitrate Directive limit of 170 kg N was the most promising N rate for preventing exceeding of EU target of 11.3 ppm. In contrast, N rates of 170+60 kg N was a good option in preventing N loss only during an initial period (2010-2030), but less efficient at the end of simulation. N rates higher than 340 kg N exceed always 11.3 ppm. Also, when water inputs (irrigations) are lower than 300-400 mm yr^{-1} there is a higher probability of exceeding 11.3 ppm. This study shows that future climatic condition could affect maize crop development and soil N cycle under maize crop in the Veneto Region in

the future. This may lead governments to face new environmental challenges in order to achieve the EU Nitrate Directive.

INTRODUCTION

The latest report of the intergovernmental panel of climate change (IPCC) states that the most of the observe increase in the global change temperature since mid-century is very likely due to an increase in anthropogenic greenhouse gas conditions (Alcamo et al., 2007; Meza et al., 2008). Moreover, it is predicted that future emissions of greenhouse will continue to rise, leading to climatic change (Meza et al., 2008). Although, there are some differences among countries, the majority of the locations will face an increase in temperature, particularly minimum temperature, changes in precipitation, and higher concentration of carbon dioxide in the atmosphere (Alcamo et al., 2007).

Although the global climate change is expected to affect the productivity of farming systems in Europe, the magnitude and direction will likely depend on the area of Europe. The yearly maximum temperature is expected to increase much more in southern of Europe (Alcamo et al., 2007) (Mainly Spain, Italy and Greece) shows that, in summer, the warming of central and southern Europe may more closely connected on higher temperature on warm days than to general warming. In north of Italy, global warming is particularly evident for minimum and maximum temperature and evapotranspiration: in particular, temperatures show a significant increase (respectively +1.5 and + 0.9 °C) for yearly averages of maximum and minimum temperatures throughout the season and particularly evident in spring, summer and winter, for maximum temperatures, and in summer for the minimum ones (Chiaudani, 2008).

Intensity of daily precipitation in expected to increase as well (Giorgi et al, 2004; Chiaudani, 2008). Many authors found a substantial increase in the intensity of daily precipitation connected by a decreasing trend in yearly availability of rainfall over the Mediterranean region (Giorgi et al., 2004; Kjellström et al., 2007; Chiaudani, 2008). Despite the impact in the Mediterranean region during summer is not clear (Alcamo et al., 2007), Chiaudani 2008, reported that in the North-East of Italy time series show a substantial stationary of seasonal precipitation with the only exception of winter, which show a significant decrease (in average -78 mm as regards to the previous phase). In addition, he has found an increase of extreme precipitation events driven by a reduction of the duration of the precipitation especially in summer and winter.

The combined effects of warmer temperature and reduced mean summer precipitation would enhanced the occurrence of heatwaves and droughts across Europe (Alcamo et al., 2007) concluding that Europe, particularly the Mediterranean region, would experience a pronounce increase in year-to-year variability and thus a higher heatwaves and droughts (Beninston et al., 2007). The Mediterranean region may experience an increase in dry period, despite yearly rainfall may slightly reduce, by the late of 21th century (Alcamo et al., 2007). Under these condition an assessment of the risks that can affect environment but mainly agriculture deserve and important role in facing global warming.

Quantifying the potential costs and benefit of these climatic changes requires assessment of the exposure of a suite of climatically sensitive natural and human systems. Exposure of agro-ecosystems to climatic changes is an important case in point. Several Authors who studied the effect of climate changes on crop and environment concluded that while there are expected to be some positive impacts of climate change upon agriculture, they will likely offset by other negative consequences (Mo et al., 2009). Generally, it is projected that C3 crops will increase their productivity and water use efficiency due to the atmospheric CO_2 enrichment, however the vulnerability of these crops will be exacerbated (Mo et al, 2009). On the other hand, C4 plants have a low growth response to elevated CO_2 concentration, due to their complex mechanisms in the photosynthetic path (Mo et al, 2009). In addition, with an increase in mean annual temperature of 2°C and the CO_2 concentration, cereal yield are expected to increase, because of the additive effect of warmer temperature and CO_2 fertilization (Lavalle et al., 2009). However, crop yield are also at risk from more intensive precipitation and prolonged periods of drought (Lavalle et al., 2009) especially in the Mediterranean areas, where the effects of climate change will be higher than other areas (Smith et al., 2007).

According to the results from general circulation models (GCM) at the end of the century, Italy will be characterized by a temperature increase between 2 and 5°C, and a very likely shift in the seasonal distribution of rainfall and thus in soil moisture (Dueri et al., 2007; Alcamo et al., 2007). This shift in climatic condition could alter the productivity of crops by influencing soil N dynamics. Increase rates of N mineralization driven by climate change may increase plant N availability and N losses affect relative N losses (higher availability of NO_3^- through increase of mineralization) (Rustad et al., 2001; Dueri et al., 2007; Turner and Hugh, 2010). For instance, Turner and Henry, (2010) showed that changes to soil N dynamics caused by warmer season increase ecosystem N losses despite plants have the capacity of take up excess of N. Their results suggest that warming over the season (especially during winter) may amplify soil N losses under condition of N saturation and heavy rain events. N cycle is sensitive to gradually increase of air/soil temperature and decreasing of precipitation. In addition, in system more heavily relying on crop production (such as Padana Plain) global warming causes an increasing of fraction N lost to the environment mainly in the form of NO_3^- and N_2O (Dueri et al, 2007).

Determining crop yield responses to irrigation in combination with N fertilization could help identify farm management practices that maximize yield and reduce groundwater pollution especially in view of a change of the climatic conditions (Di Paolo and Rinaldi, 2008; Payero et al., 2009). Environmental protection is one of the priorities of the new European agricultural policy (Di Paolo and Rinaldi, 2008). The European Union (EU) Nitrate directive aims to develop new strategies to balance economic efficiency and negative effects on the environment by reducing water contamination caused by nitrate from diffuse agricultural sources (Anonymous, 1991). In the Veneto Region, north eastern Italy, the current precautionary application thresholds imposed by the EU Nitrate Directive limit manure N applications to either 170 N ha^{-1} in nitrogen vulnerable zones (NVZ) or 340 kg N ha^{-1} in non NVZ (Fig 1).

The use of models developed to simulate dynamic soil water movement and soil-crop C/N provide and excellent opportunity to quantify how N fertilizer distribution may change as climate continue to change in order to meet the goals imposed by the EU Nitrate Directive. Because N losses (NO_3^-) are highly related to crops growth, critical temperature and precipitation (Alcamo et al., 2007; Smith et al., 2007) a long term evaluation of N cycling in soil-plant system in response of climate change is required to evaluate the net impact of climate change on the EU Nitrate Directive.

In this study Water and Nitrogen Management Model (WNMM) was used to investigate the effects of climate change on N losses and crop development in maize in north of Italy on a loamy soil. In particular, we evaluated if the environmental goals imposed by the EU Nitrate Directive, are meet while climatic conditions (rainfall, temperature, ect.) are expected to change throughout the century.

MATERIALS AND METHODS

SITE DESCRIPTION

Legnaro, (north-east of Italy, 45° 21' N; 11° 58' E, 8 m elevation) was selected to perform this study (Fig. 1). The climate of the area is subhumid (FAO-UNEP, 1977) with highest temperatures during July and August with a total annual precipitation of 800 mm, mainly concentrated in spring and winter. The Mean minimum temperature in winter is -0.8°C (average from 1963-2007) while in summer is 16.2°C. Mean maximum temperature in winter is 6.1°C while in summer is 27.2°C.

Figure 1. Italy and the location of the site (source, Google Earth 2009)

Maize is one of the most important and diffuse crop in this area and it is grown under irrigated condition. In the Veneto Region, irrigation plays an important role, allowing farmers to reach high yields, both in cereal than in other crops. Due to the insufficient precipitation in the growing season, the spring-summer crops (maize) need supplemental irrigation to obtain favorite production. This site was chosen to analyze the impact of climate change on maize yield and the dynamics of N in the plant-soil system under irrigated conditions, inside the Veneto Region over the period 2010-2100.

Table 1. chemical and physical soil properties used in WNMM

soil properties	unit	layers (cm)			
		0-15	15-30	30-70	70-130
residual water content at dry	$cm^3\ cm^{-3}$	0.02	0.02	0.03	0.02
wilting point	$cm^3\ cm^{-3}$	0.08	0.12	0.08	0.09
field capacity	$cm^3\ cm^{-3}$	0.25	0.30	0.34	0.31
saturated water content	$cm^3\ cm^{-3}$	0.42	0.38	0.42	0.41
saturated soil hydraulic conductivity	$m\ day^{-1}$	30.96	24.84	24.74	0.04
soil bulk density	$t\ m^{-3}$	1.48	1.60	1.50	1.55
SAND	%	31	31	31	31
SILT	%	54	54	54	54
CLAY	%	15	15	15	15
soil pH		7.25	8.24	8.20	8.11
soil organic matter	%	1.14	1.00	0.50	0.42
soil total nitrogen	%	0.075	0.06	0.05	0.1
soil total NO_3^--N	$kg\ N\ ha^{-1}$	5.1	5.0	2.0	1.0
soil total NH_4^+-N	$kg\ N\ ha^{-1}$	4.96	5.32	2.54	2.40

Two soil was chosen to represent the predominant textures found within the Veneto NVZ. The soil correspond to a typical silty-loam soil from the Venetian Plain NVZ area, with 1.3 m depth, bulk density of 1.4-1.5 t m^{-3} and in good conditions. This soil is the most representative of the cultivated area that surround the site. Chemical and physical property are shown in Table 1.

The current experiment is based on the results of a previous experiment conducted in the same area in 2006-2008 (see chapter 1) where a lysimetrical station was established to investigate N cycling and dynamics in the Veneto plain as a part of a collaboration between the Veneto Agricoltura and the Department of Environmental Agronomy and Crop Science at the University of Padova (Italy).

The current paper aimed to understand the environmental impacts of climate change on the EU Nitrate Directive (Anonymous, 1991), and to evaluate the affectless of the precautionary thresholds of 170 and 340 kg N ha^{-1} manure in NVZ and non NVZ zones, respectively, in reducing nitrate accessions to groundwater, over the period 2010-2100. For the current study a wide range of agricultural management practices (AMP) were used to simulate the behavior of maize production and N leaching in the Veneto Region.

MODEL DESCRIPTION

The Water and Nitrogen Management Model (WNMM) (Li et al., 2007) is a spatially referenced GIS-coupled biophysical model developed to simulate dynamic soil water movement and soil-crop C/N cycling for the purpose of identifying optimal strategies for managing water and fertilizer N under intensive cropping systems (mainly wheat and maize) from single point to regional scales (Figure 2). WNMM simulates the key processes of the water and C/N dynamics in the surface and subsurface of soils including; evapotranspiration, canopy interception, water movement, groundwater fluctuations, soil temperature, solute transport, crop growth, N cycling in soil-crop system and agricultural management practices (crop rotation, irrigation, fertilizer application, harvest, and tillage).

WNMM runs at a daily time step with a range of spatial scales. Data required by WNMM are categorized as GIS layer information (soil type, land cover, and village administrative boundary); database-formatted source data (soil physical and chemical properties, land use types, and agricultural management survey based on village units); referenced data (climatic reference data and crop biological data); and control data (starting date, period of simulation, initial land surface and soil conditions, agricultural management scenarios). The first two data categories are needed to convert to ARC GRID (ESRI, 1996) ASCII format from other formats and sources in the GIS environment.

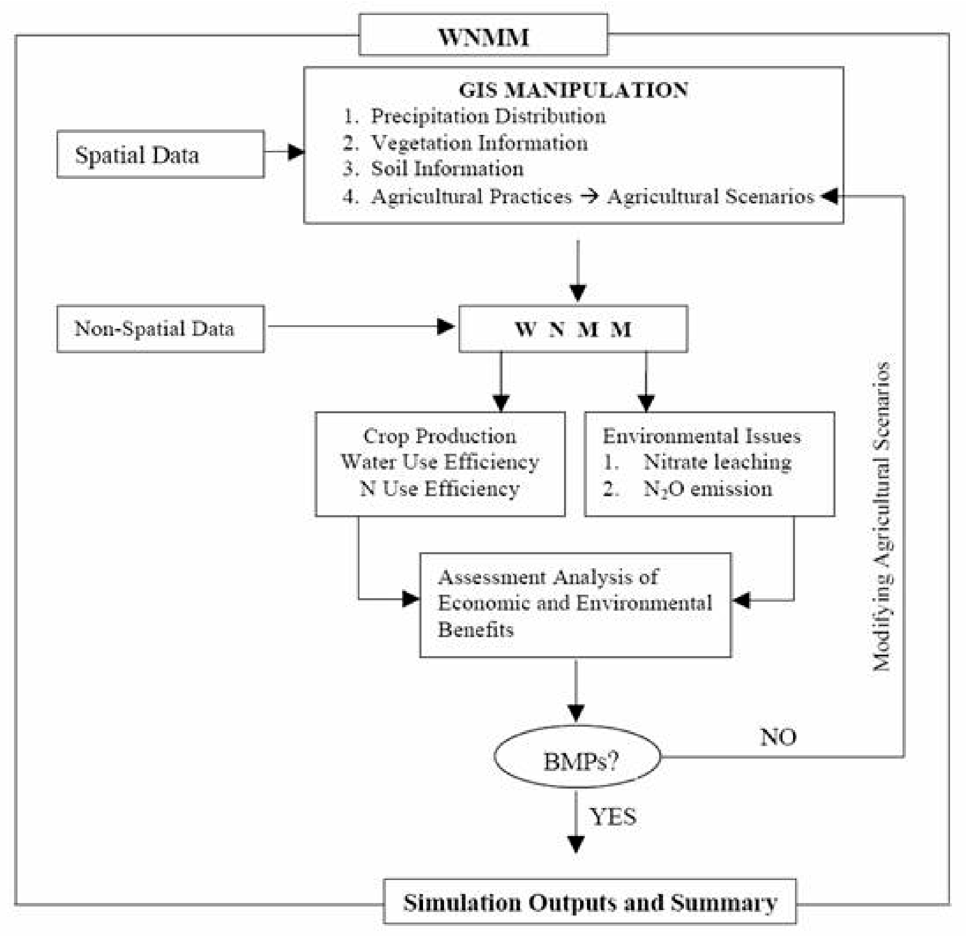


Figure 2. the schematics of modeling structure in WNMM

Soil evaporation and plant transpiration are predicted separately by considering ground cover, leaf area index and crop root density distribution in the soil profile. Dynamic soil water content and flux are calculated by two options: one is governed by the one-dimensional Richards' equation in the Kirchhoff form, and solved numerically by using finite difference with the adoption of a Newton-Raphson approach, and the other is a simple water balance module adopted from the approaches used in PERFECT (Littleboy et al., 1989) and EPIC (Williams, 1995). A sink term regarding crop root water uptake is considered in both approaches. Nitrate transport is governed by the convection-diffusion equation and solved numerically by the same scheme used in the water flow, or an empirical solute transport equation. Ammonium transport in the soil is simulated using an empirical equation adopted from EPIC only when there is a significant water flux in the soil profile. Soil temperatures at depth are estimated using the approach applied in EPIC and SWAT.

The crop growth module is a simplification of the EPIC crop model, which applies the concepts of phenological crop development based on daily accumulated heat units, harvest index for partitioning grain yield, Monteith's approach for potential biomass, and stress adjustments for water, temperature and nitrogen availability in the root zone of the soil profile. Total crop dry matter, leaf area index, root depth and density distribution, harvest index, crop yield, and N uptake are predicted. The crop N utilization is estimated using a supply and demand approach. The actual crop uptake is composed of uptake due to convection (mass flow of N to the roots) and uptake as a result of N movement to roots by diffusion. WNMM simulates the transformations of several N species in agricultural fields, including mineralization of fresh crop residue N and soil organic N, formation of soil organic N, immobilization in biomass, nitrification, ammonia volatilisation, denitrification, and N_2O emission. It divides soil C into three main pools: fresh residue C, microbial biomass C (living and dead), and humus C (active and passive for mineralization). The flows between the different pools are calculated as first-order processes in terms of C, the corresponding N flows depending on the C/N ratio of the receiving pools. The C/N ratios of the various pools are assumed to be constant in the simulation. Mineralization or immobilization was determined as the balance between the release of N during organic C decomposition and immobilization during microbial synthesis and humification. All the rate constants of first-order reactions for C/N transformations in soil are modified by factors involving soil pH, temperature, and water content in soil layers.

The N_2O emission from the nitrification process is estimated as a function of nitrification rate and soil water filled pore space. As one of the microbial processes, denitrification simulated in WNMM, is a function of soil temperature, soil water content and soil organic carbon content, and its main products are N_2O and N_2. Currently, two options of threshold of the fraction of soil pore space filled with water for initiating denitrification are used: constant 0.80 and the ratio of water content at field capacity to water content at saturation. In addition, the denitrification process was limited to occur in the upper 20 cm of topsoil. N_2O emission from denitrification was estimated using the approach of Xu et al. (1998) under saturated and unsaturated conditions, respectively. The ratio of N_2O to N_2 produced was fully controlled by soil saturation status. Gas diffusion between soil layers was not simulated, but the fraction of gases that diffused from given layers to the soil surface was predicted using the DNDC method by considering clay content, soil air-filled pore space and soil temperature. In the latest version of WNMM, N_2O emissions from soils can be predicted using either its own N gas module or the DNDC dynamic microbial growth approach or DAYCENT empirical approach.

MODEL CALIBRATION AND EVALUATION OF ITS PERFORMANCES

No calibration and validation was performed. It was assumed that WNMM was properly calibrated and validated in all the variables and conditions which can affect model results. For this reason, we used the same parameters (chemical, physical soil properties, crop ect.) used in a previous study carried out in the same area (see chapter 2). Results of calibration and validation are shown in the paragraph “*MODEL CALIBRATION AND EVALUATION OF ITS PERFORMANCES*”, chapter 2. Based on results obtained in chapter 2, in the same area of study, WNMM can generally simulate crop yield, drainage and N leaching reasonably well in most of the year

DATA

CLIMATE DATA: CLIMATE CHANGE SCENARIO

The climate change projection from the runs of the global circulation model (CGM) ECHAM5-r3, model DMI-HIRHAM5 (0.22 degree, 25 km grid resolution) (Fig. 3), archived by the European project ESEMBLES (http://ensemblesrt3.dmi.dk/), for A1B emission scenario developed by the Intergovernal Panel of Climate Change (IPCC) IPCC-SRES, were used to simulate the response of maize grain yield and N in soil to climate change in the 21st century for the Veneto Region.

The A1B scenario, that is part of A1, describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A1B scenarios distinguished by the other ones (A1FI and A1T) for the technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (http://www.ipcc.ch/ipccreports//tar/wg1/029.htm).

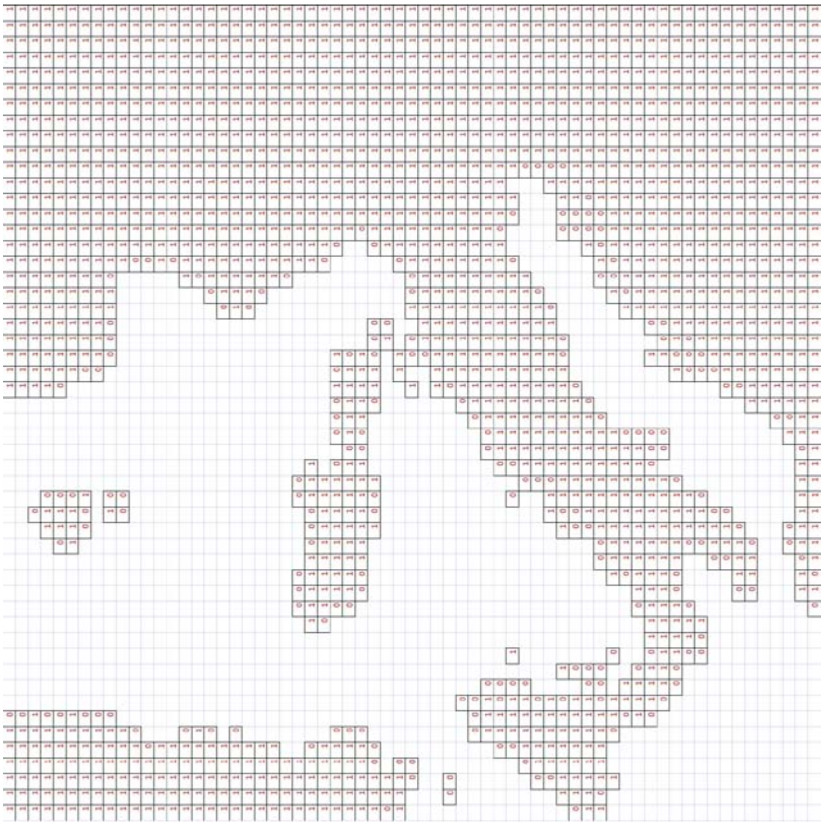


Figure 3. Italy, ENSEMBLES project RCM minimum area, 0.22 degree (25 km) grid mesh

It has to be note that, based on the goals achieved with Kyoto protocol and the last environmental aims stipulated at Copenhagen 2010, there is a common opinion that the world congress on climate change, (Copenhagen) did not achieve any effective action to face the effects of climate change. Even though, deep cuts in global emissions are required according to science, and also as documented by the IPCC Fourth Assessment Report with a view to reduce global emissions, the decision made by at Copenhagen that admitted an increase in global temperature below 2 °C, seems not enough to take action to meet the objective consistent with the science and on the basis of equality. Although the Intergovernal Panel of Climate Change (IPCC), proposed 4 projections of climate change, for this, we decided to projected the simulations using climate data from global climate models (ECHAM5-r3) forced by the emission scenario A1B. Therefore, we wanted to evaluate the response of N leaching and crop development under the worst emission scenarios.

ECHAM5-r3 model was chosen because it generally performs reasonably well reproducing the seasonality variation of rainfall and precipitation at daily steps. The data for the scenario A1B includes maximum and minimum temperature (°C), wind speed (m s^{-1}), relative humidity (%) and daily precipitation (mm) over the period 2010-2100. Solar radiation data was generated performing RADEST (Donatelli et al., 2003) by using the model OF Donatelli and Bellocchi, 2001 that accounts the effect of the seasonal variation of the clear sky trasmissivity using a trigonometric function. According to the projections, for instance, in 2100s, maximum and minimum yearly mean air temperature will respectively increase of +20.9% (+2.82°C), +11.0% (+2.84°C) while solar radiation +13% while precipitation decreases of -6.8%. Climatic features of the period 2010-2100 used to performed the simulations are shown in Figure 4, 5.

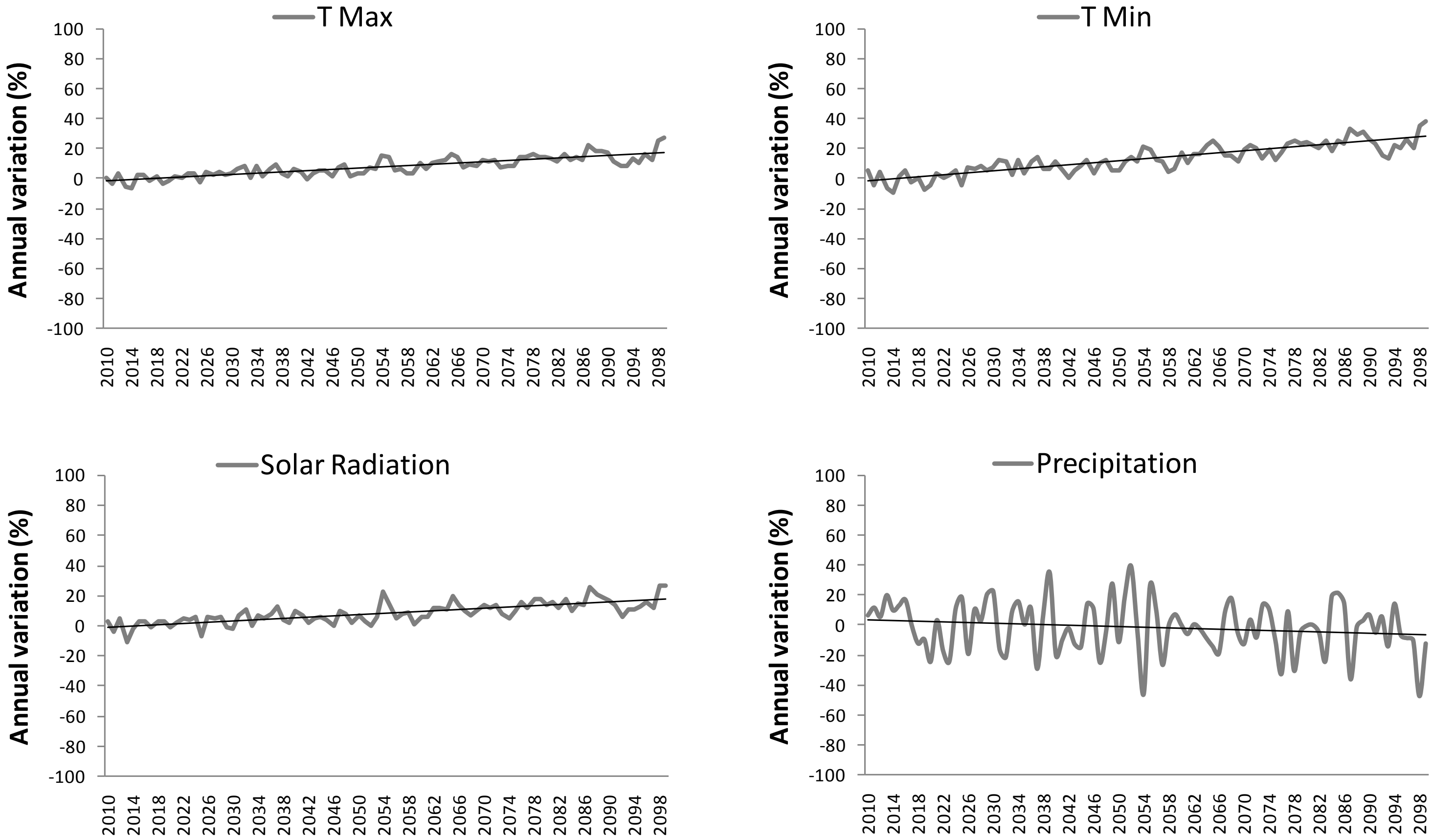


Figure 4. Annual variation in percentage: minimum and maximum temperature, solar radiation and precipitation from 2010 to 2100

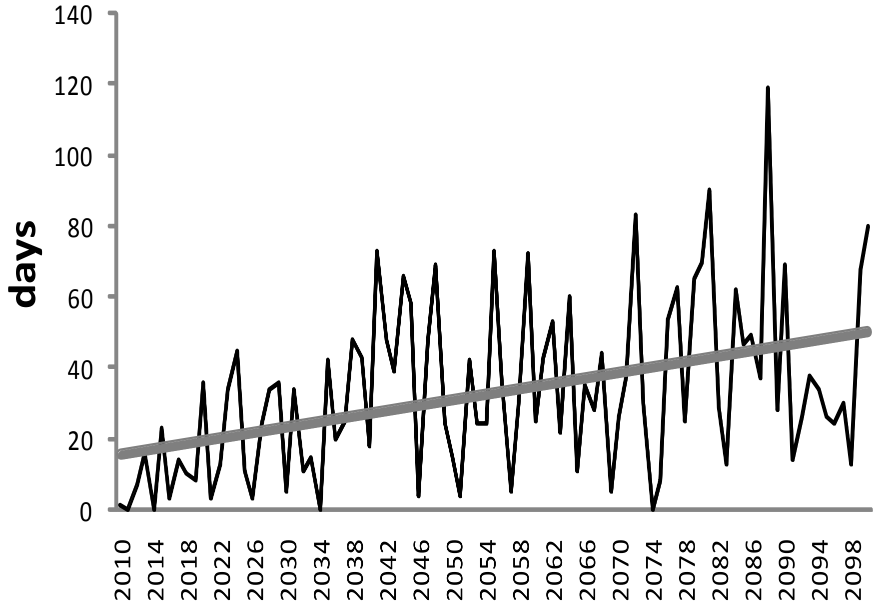


Figure 5. number of consecutive days of drought (at least 30 days without rainfall)

AGRICULTURAL DATA

To test management strategies of fertilizer and maize and identify the possibilities of adaptation we evaluated a wide range of treatments The data of N fertilization amount (both from inorganic and manure sources), timing, fertilizer type and also irrigation amount and timing. Irrigations and N fertilization amount were decided based on the results of reported in chapter 2 so, 30 different nitrogen levels and 30 different irrigation rates were chosen to better represent the wide variability of agricultural management practices (AMP) (30x30=900 scenarios) (Table 2).

N fertilizer and water irrigation inputs used to run WNMM scenarios N management practice (N application rates) were collected both from the online database of the Italian Institute of Statistics (ISTAT, 2002) and from a documented survey conducted by the Department of Environmental Agronomy and Crop Science (unpublished data), from 2006 to 2007.

The timing and the amount of the irrigation water was obtained by combining the information from the FAO website (AquaStat, 2001), the online databases of the Veneto Agricoltura (Veneto Agricoltura, 2000), the Italian Institute of Statistics (ISTAT, 2006), and the Land Reclamation and Irrigation Consortia National Association (ANBI, 2001). All scenarios were run with the same soil inputs as the most representative soil in the Veneto Region (see chapter 1).

Table 2. N fertilizer and water irrigation inputs used to run WNMM scenarios.

Number	**N_{man}**	**N_{urea}**	**W_{app}**
1	0	0	0
2	30	10	35
3	30	30	70
4	30	60	105
5	45	60	140
6	60	60	175
7	75	60	210
8	90	60	245
9	105	60	280
10	120	60	315
11	135	60	350
12	150	60	385
13	165	60	420
14	180	60	455
15	195	60	490
16	210	60	525
17	225	60	560
18	240	60	595
19	255	60	630
20	270	60	665
21	285	60	700
22	300	60	735
23	315	60	770
24	330	60	805
25	345	60	840
26	360	60	875
27	375	60	910
28	390	60	945
29	405	60	980
30	420	60	1015

Maize, in the area of Vicenza-Padova, is usually sown between the last week of March and second week of April (average of the years 2006-2009). Based on the knowledge of planting system from local areas, in our simulations maize was sown on first week of April.

Physiological parameters such as LAI, radiation use efficiency (RUE), minimum and maximum temperature of vegetation are shown in Table 3.

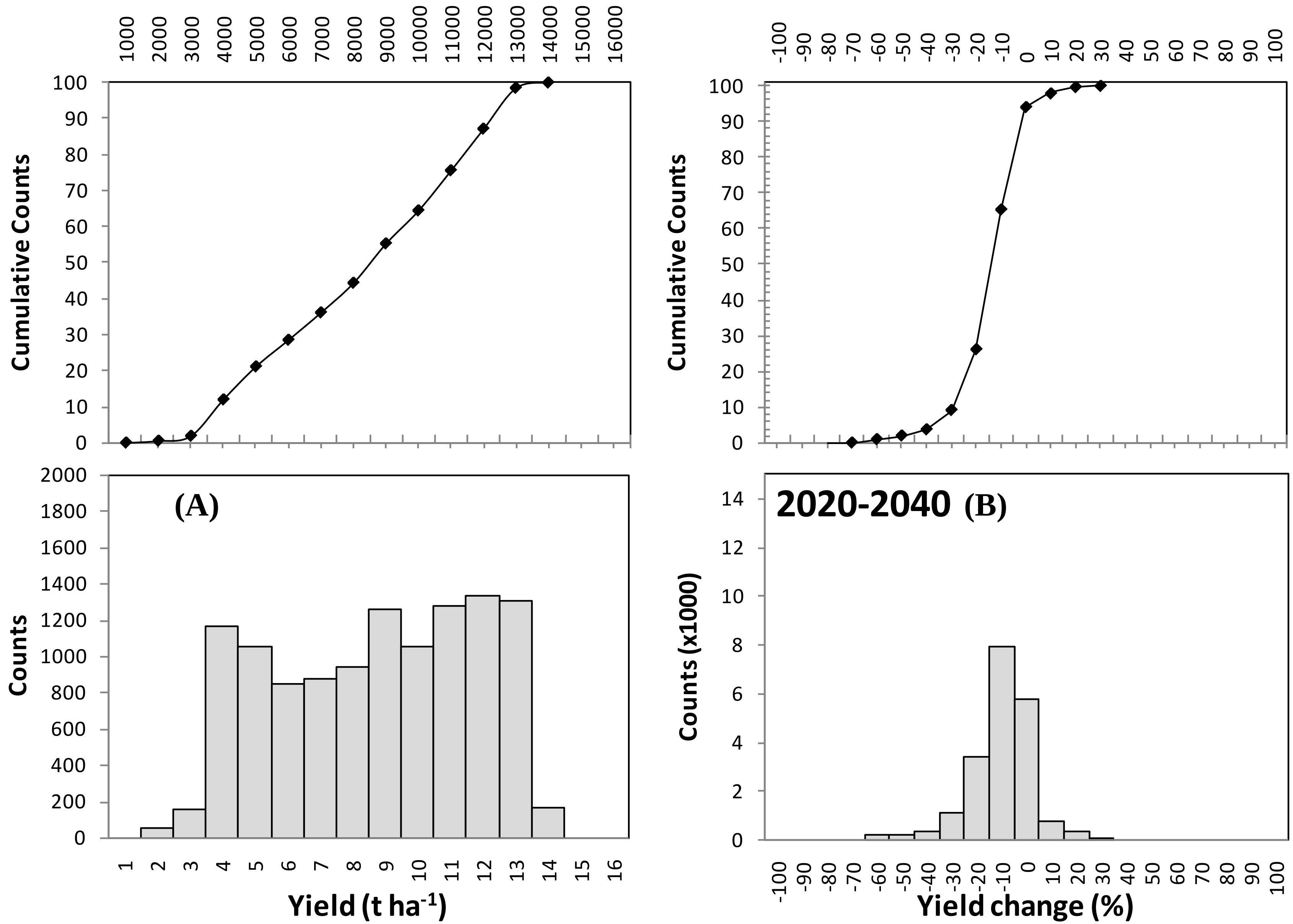
Table 3. Crop parameters inputs for WNMM's grow crop module

Crop Parameters	value
Radiation Use Efficiency$_{max_pot}$	45
Harvest Index$_{max_pot}$	0.48
Optimum Temperature (°C)	25
Base Temperature (°C)	8
LAI$_{pot_max}$ (m^2 m^{-2})	6
N content at harvest (%)	0.9
N content at ½ growth (%)	1.20
N content at early stages (%)	3.5

RESULTS AND DISCUSSIONS

MAIZE YIELD AND CROP DEVELOPMENT IN RESPONSE TO CLIMATE CHANGE

The resulting of cumulative distribution functions (CDF) of maize yield changes during 2030s, 2050, and 2080s, relative to the period 2010-2020, are represented in figure 4. Each of CDF is based on the projected yield change from 20 (2030s) or 29 years (2050, 2080s) x 60 scenarios = 18000 and 26100. For all maize throughout the periods of simulation, the histogram of and CDM of maize yield changes, show that 66, 69 and 84% of probability


(A)
2020-2040 (B)
Cumulative Counts
Counts
Counts (x1000)
Yield (t ha-1)
Yield change (%)

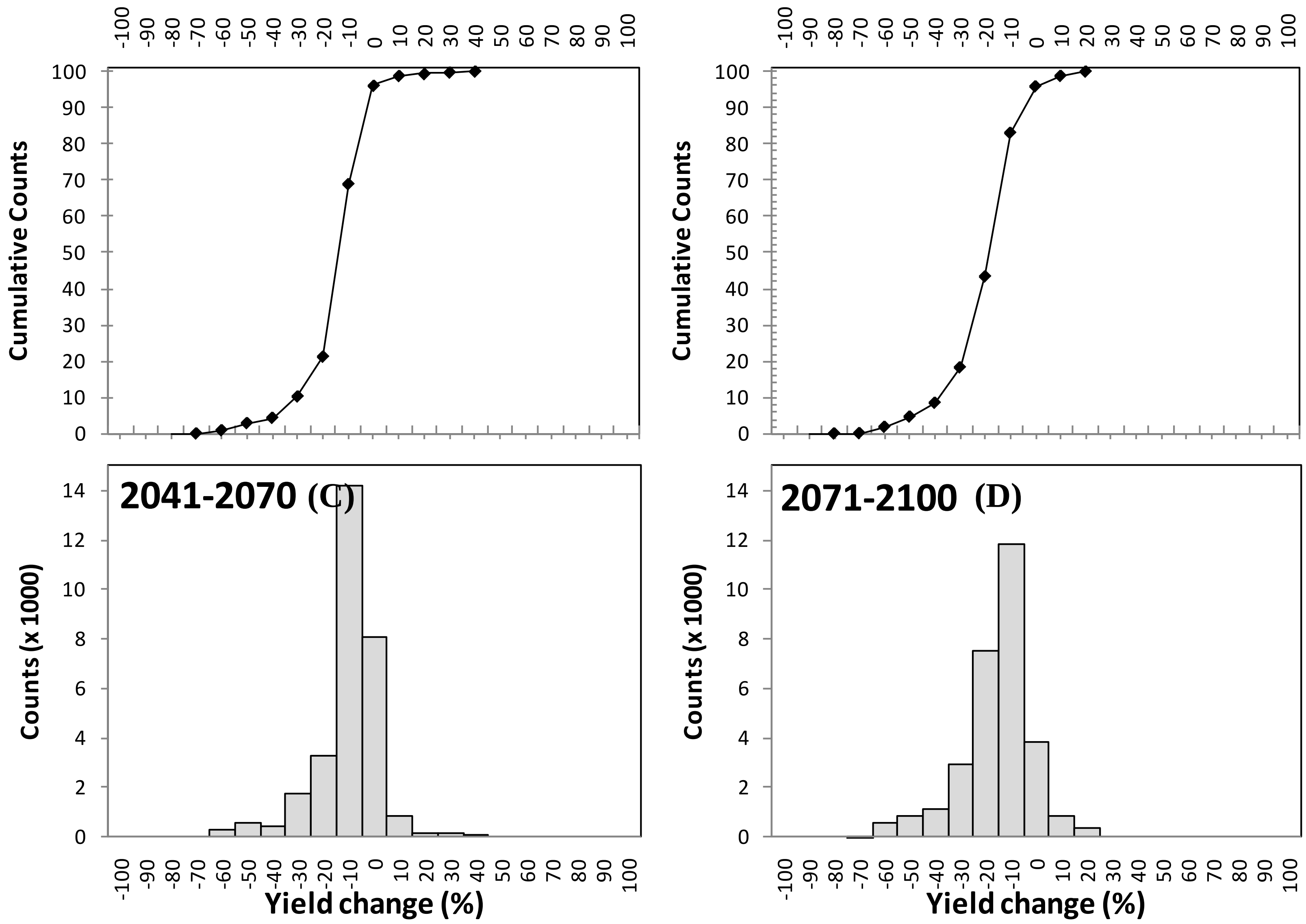


Figure 6. Cumulative probability and histograms of grain yield during 2010-2020 (a), and its changes during 2030s (b), 2050 (c) and 2080s (d)

maize yield could decrease of 10% (Fig 6b, 6c, 6d) during 2030s, 2050s, and 2080s, respectively, relative to 2010-2020 yield (Fig 6a) (Table 4). Maize could decrease averagely by 4.9% with S.D. 12.2, 5.1% with S.D. 12.3 and 10.4% with S.D. 13.7 during 2020s, 2050s, and 2080s, with 95% probably intervals of (-27.0, +11.6), (-28.4, +8.8) and (-38.8, +8.4).

Table 4. statistic analysis of the yield changes in maize cultivation for 2030s, 2050s, and 2080s, relative to 2010-2020.

Periods	Samples	Mean (%)	P5 (%)	P50 (%)	P95 (%)	S.D. (%)	S.E. (%)
2030s	18000	-4.9	-27.8	-3.0	11.6	12.2	0.086
2050s	26100	-5.1	-28.4	-3.3	8.8	12.3	0.071
2080s	26100	-10.4	-38.8	-8.4	8.4	13.7	0.079

These results show that the reduction in maize grain yield is one of the most important reason for crop yield decrease under the climate change. Same findings were obtained by Lugato and Berti, 2008 (Veneto Region), who found that in the scenario A1F, the increase temperature and the precipitation led to a strong decrease in crop yield, especially from 2040 when climate change began to be more evident. Same findings were find by Meza et al., 2008; Reidsma et al., 2009; Tao et al., 2009, in Chile, Illinois, Europe, and China, respectively. Our findings show that, depending of the severity of the climate change, reduction of grain yield will represent -8.5% of the current crop productivity. Higher temperature and lower precipitation accentuated summer drought, which could halve the maize yield.

However, as shown in Figure 7 the reduction of maize yield could be different in relation to N fertilization rate applied. The resulting of the maize yield trend over the period 2010-2100, demonstrate that this reduction will be likely influenced by a combination between global warming and N fertilizer applied (Fig. 7). This reduction could be more exacerbated when N fertilization rate is higher than 280 kg N ha^{-1}, with a reduction of -7.9 and -16.8 kg year^{-1} of grain yield, at rates of 170 and ≥ 340 kg N ha^{-1}, respectively (Fig. 7).

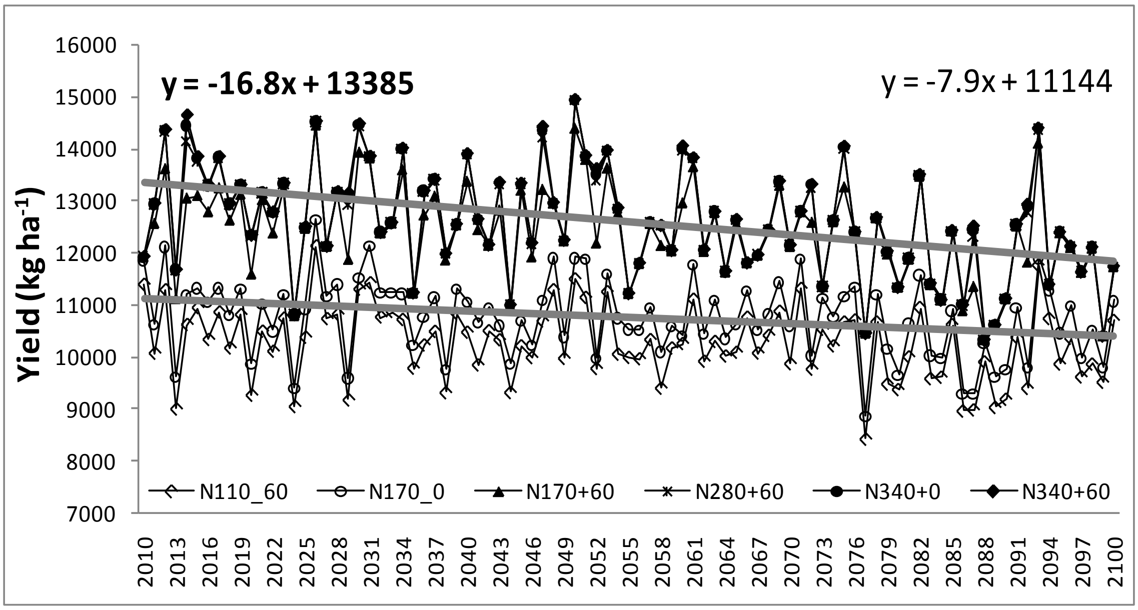


Figure 7. Maize grain yield trend for maize treated with 110+60 (110 N manure+60 N urea), 170+0 (170 N manure + 0 N urea), 170+60 (170 N manure + 60 N urea), 280+60 (280 N manure + 60 N urea), 340+0 (340 N manure + 0 N urea), 340+60 (340 N manure + 60 N urea)

Besides, our results suggest that no significant differences ($p>0.05$) were observed between the scenarios N110+60 and N 170+60. Though, The EU Nitrogen Directive allows farmers to apply up to 170 N manure plus 60 N urea kg ha^{-1}. This findings suggest that inside NVZ farmer could apply up to 170+60 kg N ha^{-1} in order to reach an higher productivity, however, besides crop yield productivity, N leaching should strongly considered before making any decision of the N rate. N rates ≥ 340 kg N ha^{-1} do not lead to an increase of crop productivity ($p<0.05$). Additionally, no significant differences ($p<0.05$) in maize productivity were observed when fertilizations ≥ 340 kg N ha^{-1} (Table 5).

In view of complying with the EU Nitrate Directive, our results strongly suggest that farmers should not exceed 340 kg N ha^{-1} both to prevent N losses by leaching and because no additional increase of productivity can be achieved. Results in Table 5 show that no significant differences of crop productivity occur between 340+0 and 280+60 kg N ha^{-1}. This implies that manure can be a source of N during the growing season. However, we suggest to combine N manure + N urea in order to reduce the risk of N accumulation in soil and so likely an higher probability of N losses especially during heavy rainfall.

Table 5. Statistic analysis of maize yield changes for 2030s, 2050s, and 2080s, relative to 2010-2020. (p=0.05).

YIELD	**N110+60**	**N170+0**	**N170+60**	**N280+60**	**N340+0**	**N340+60**
N110+60	***1.000***	***0.878***	0.000	0.000	0.000	0.000
N170+0	***0.878***	***1.000***	0.000	0.000	0.000	0.000
N170+60	0.000	0.000	***1.000***	0.000	0.000	0.000
N280+60	0.000	0.000	0.000	***1.000***	***0.930***	***0.872***
N340+0	0.000	0.000	0.000	***0.930***	***1.000***	***0.942***
N340+60	0.000	0.000	0.000	***0.872***	***0.942***	***1.000***

NITRATE-N LEACHING THROUGHOUT THE PERIOD 2010-2100

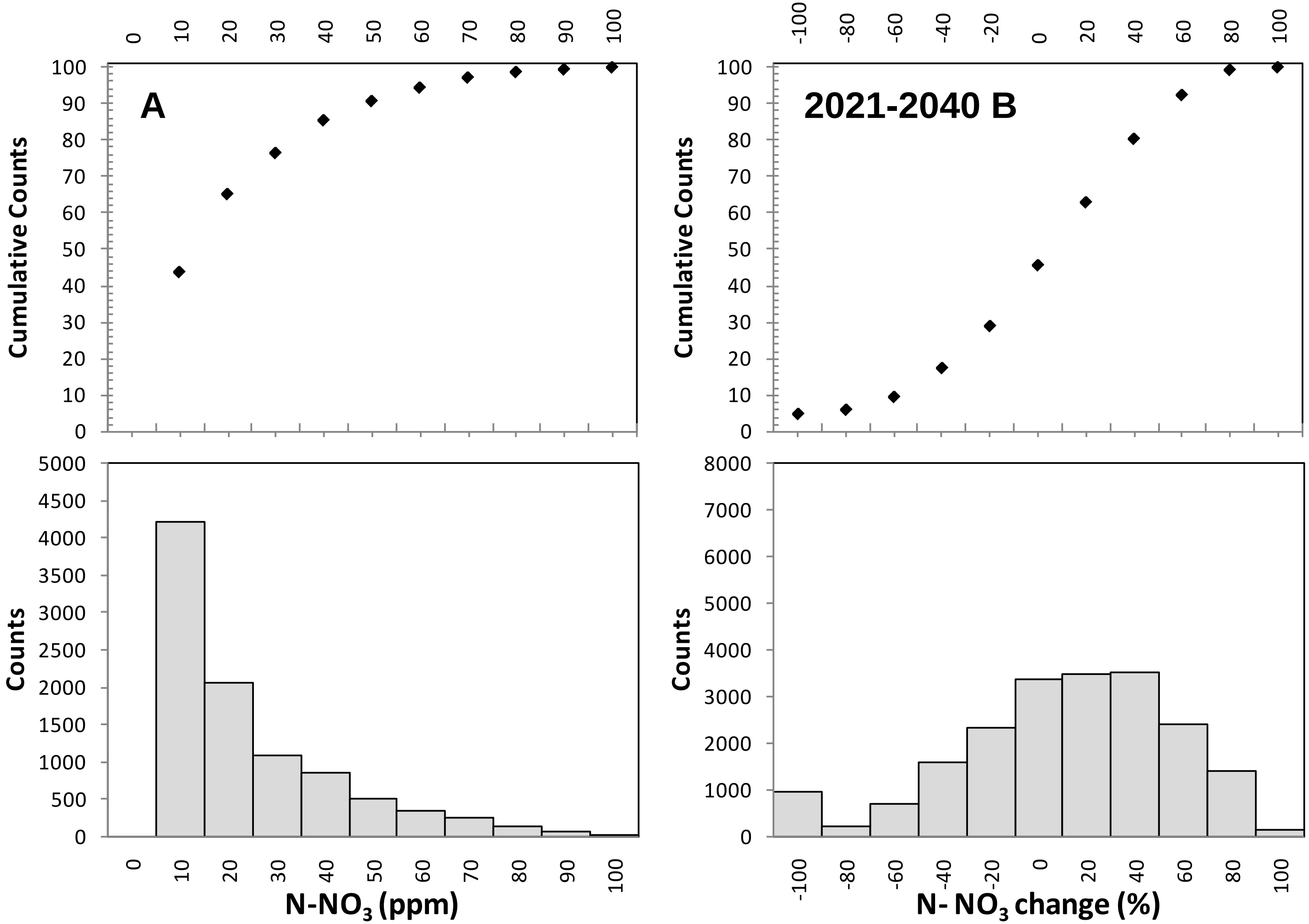
The resulting of cumulative distribution functions (CDF) of concentration of nitrate-N leaching changes during 2030s, 2050, and 2080s, relative to the period 2010-2020, are represented in figure 6. Each of CDF is based on the projected N leaching change from 20 (2030s) or 29 years (2050, 2080s) x 60 scenarios =18000 and 26100. For all theses throughout the periods of simulation, the histogram of and CDM of N leaching changes, show that 64, 76 and 70% of probability N-NO_3 leaching could increase of 40% (Fig 8b, 8c, 8d) during 2030s, 2050s, and 2080s, respectively, relative to 2010-2020 yield (Fig 8a) (Table

6). N leaching could increase averagely by 1.8% with S.D. 43.8, 10.0% with S.D. 38.8 and 11.3% with S.D. 44.0 during 2020s, 2050s, and 2080s, with 95% probably intervals of (-95.0, +66.0), (-57.0, +65.0) and (-88.0, +69.0).

Table 6. Statistic analysis of NO3-N leaching for 2030s, 2050s, and 2080s, relative to 2010-2020. (p=0.05)

Periods	Samples	Mean	P5 (%)	P50 (%)	P95 (%)	S.D. (%)	S.E. (%)
2030s	18000	1.8	-95	6	66	43.8	0.31
2050s	26100	10.0	-57	14	65	38.8	0.23
2080s	26100	11.3	-88	20	69	44.0	0.26

The change of N leaching throughout the years of simulation could be explained either by a change in precipitation and a change in the rate of mineralization of N in soil. However, as shown in figure 2, precipitation does not change considerably, while temperature and days of drought may increase. As reported by many authors, global warming could affect the N cycle in soil by affecting N mineralization in soil. Dueri et al., (2006) argues that *"The shift in climatic conditions could affect relative N-loss by, for instance, influencing the availability of soil* NO_3^- *through increased rates of mineralization resulting in higher losses via denitrification and leaching, or through effects on crop growth and related plant uptake of N. As a result, climate change could have a negative impact on N losses from farms, i.e., higher N loss relative to N export in products, which in turn would call for adjustments in N management"*. Also, Turner and Henry, (2010) highlighted the importance of the unusual (higher) temperature events in influencing annual N dynamics. In particular, they reported that winter warming had important carryover effects on N dynamics, especially by affecting N mineralization in soil.


A
2021-2040 B
Cumulative Counts
Cumulative Counts
Counts
Counts
N-NO3 (ppm)
N- NO3 change (%)

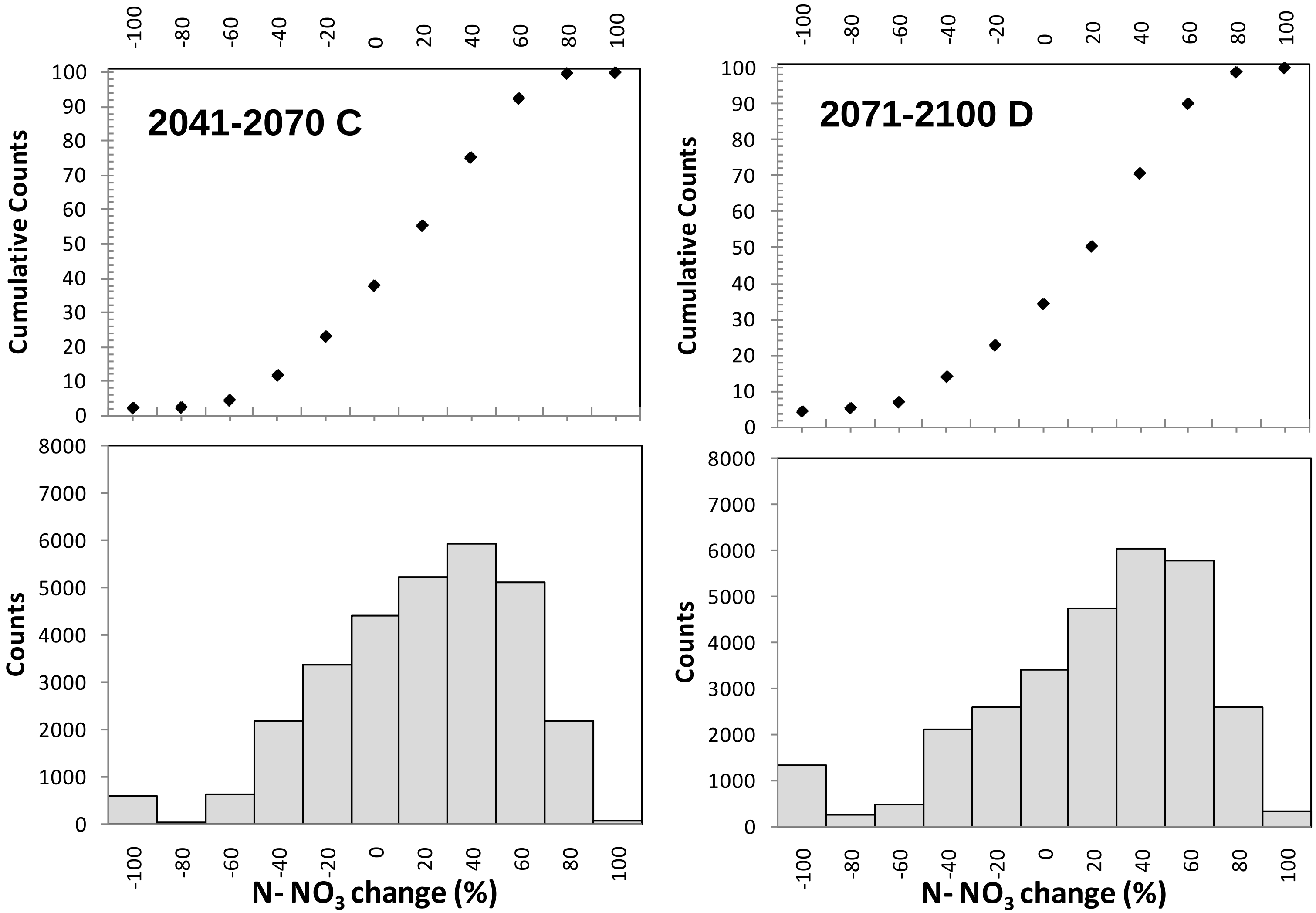


Figure 8 a, b c, d. Cumulative probability and histograms of NO_3-N leaching during 2010-2020 (a), and its changes during 2030s (b), 2050 (c) and 2080s (d)

Our results are in agreement with whose reported above by these authors. Based on this evidences, climate change could increase soil N availability over the season by increasing soil N mineralization (especially in winter when plant roots are largely inactive), and so, this may increase soil N leaching losses (Dueri et al., 2006; Turner and Henry, 2010).

Figures 9 (A-L) show the evolution of NO_3-N concentration over the period 2010-2100. Due to the high number of N and W combinations studied in this study, we decided to describe the behavior of nitrate-N concentration only at the N rates allowed by the UE Nitrate Directive. In particular: 170+0 (170 manure + 0 urea), 110+60 (110 manure + 60 urea), 170+60 (170 manure + 60 urea), 340+0 (340 manure + 0 urea), 280+60 (280 manure + 60 urea), and 340+60 (340 manure + 60 urea) kg N ha^{-1}. Four irrigation inputs were considered: 315, 630, 805 and, 1015 mm $year^{-1}$.

The N rates of 170+0 and 110+60 kg manure N ha^{-1} did not result in the EWF being exceeded at any of the rates of water application simulated (Fig. 9 A-D). This results show that for maize grown in the Veneto Region on a loamy soil 110+60 and 170+0 kg N ha^{-1} may be applied annually without exceeding the concentration of 11.3 mg l^{-1} nitrate-N in the leachate at water application rates below, during the future period of 2010-2100. The similar trend in nitrate-N leaching between these two N fertilizations ($p>0.05$; Table 7), shows that reducing the amount of manure from 170 to 110 kg N ha^{-1} and, applying 60 kg N ha^{-1} of urea (in 3 dates, 20 kg N ha^{-1} each) after emergence, do not affect the NO_3-N leaching in drained water.

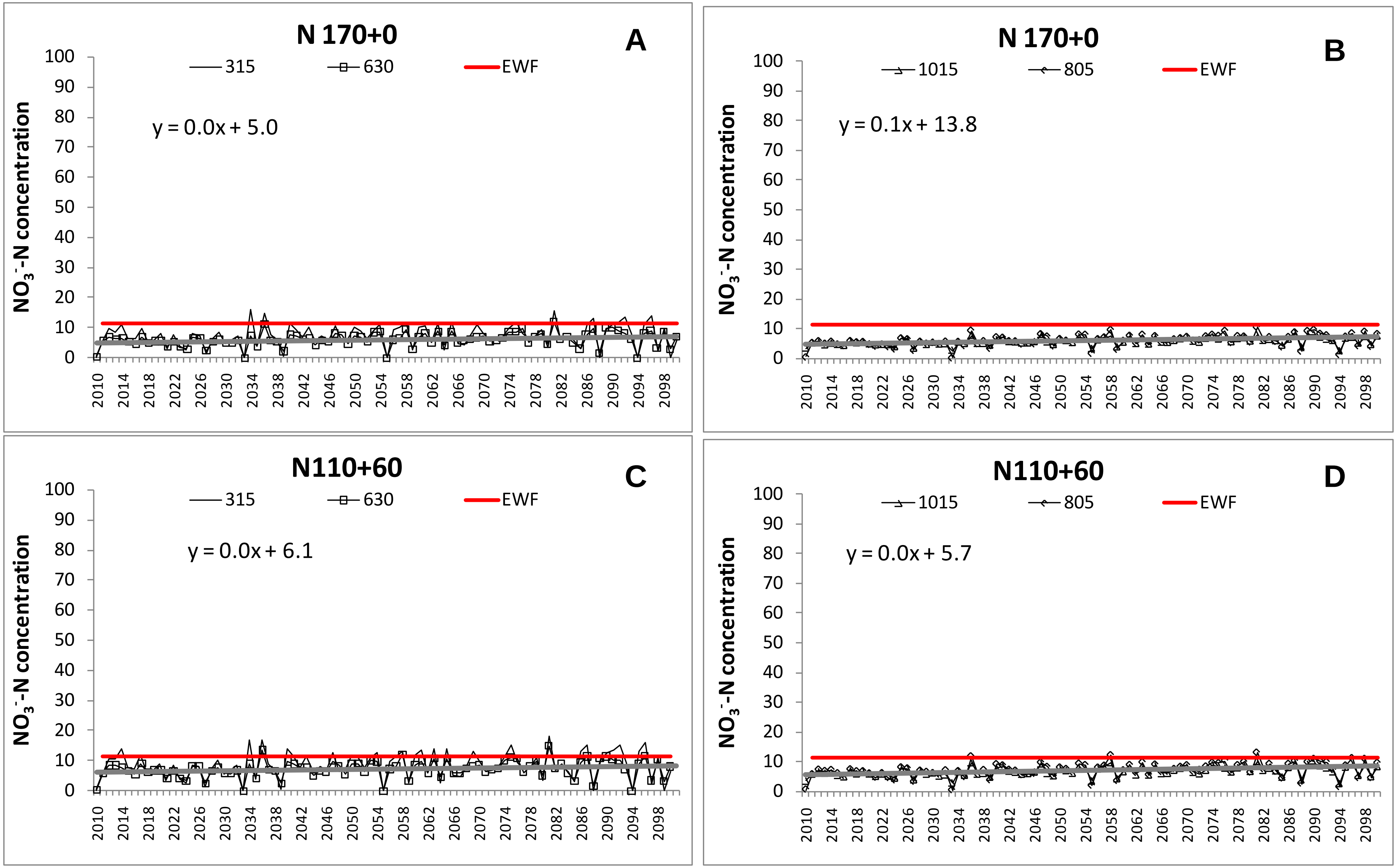
The N rates of 170+60 kg manure N ha^{-1} resulted in exceeding EWF (Fig. 9 E, F). However, the behavior of nitrate-N leaching in drained water were affected by the amount of water applied with irrigation (Fig. 9 E, F). At 315 mm $year^{-1}$ EWF was exceeded in the 59% of the years, while 31, 20 and, 10% under 630, 805 and, 1015 mm year^{-1}. This results can be explained either by a water dilution effects and, an higher N losses via denitrification (Dueri et al., 2006). This results show that for maize grown in the Veneto Region on a loamy soil 170+60 kg N ha^{-1} may exceed the concentration of 11.3 mg l^{-1} nitrate-N in the leachate at water application of 315 and 630 mm during the period 2010-2100, although high N concentration were observed after 2035. During the initial phase (2010-2039), EWF were exceeded just in the 33, 7, 3 and, 3% of years.

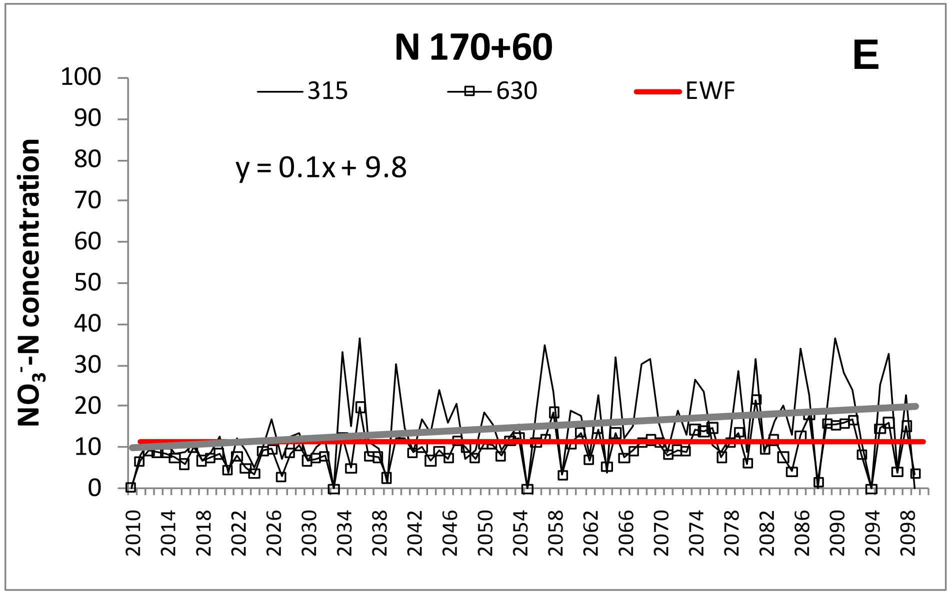
Table 7. Statistic analysis of NO_3-N concentration in drained water changes for 2030s, 2050s, and 2080s, relative to 2010-2020. (p=0.05).

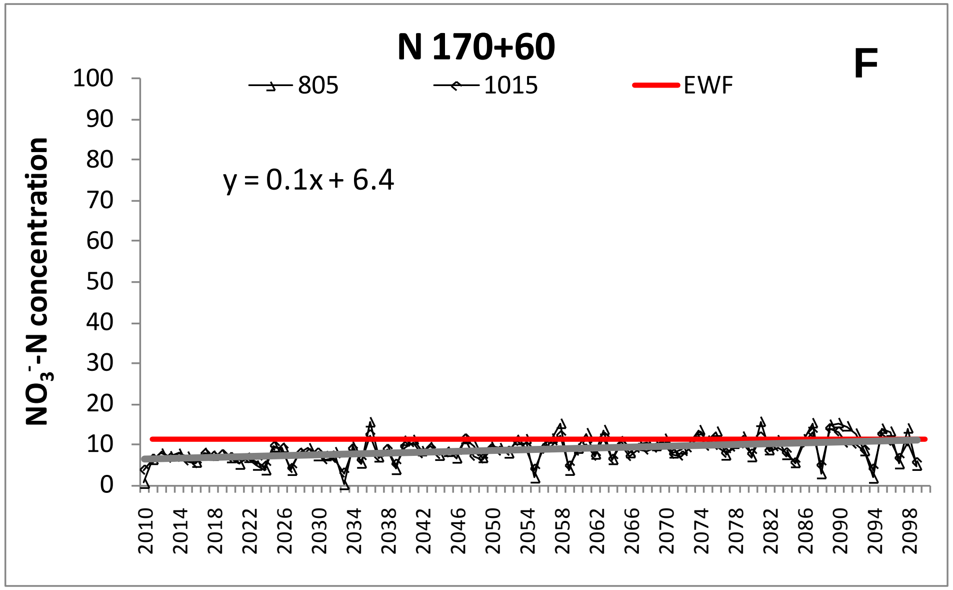
	N110_60	N170_0	N170+60	N280+60	N340+0	N340+60
N110+60	***1.000***	**0.218**	0.000	0.000	0.000	0.000
N170+0	**0.218**	***1.000***	0.000	0.000	0.000	0.000
N170+60	0.000	0.000	***1.000***	0.000	0.000	0.000
N280+60	0.000	0.000	0.000	***1.000***	**0.497**	0.004
N340+0	0.000	0.000	0.000	**0.497**	***1.000***	0.025
N340+60	0.000	0.000	0.000	0.004	0.025	***1.000***

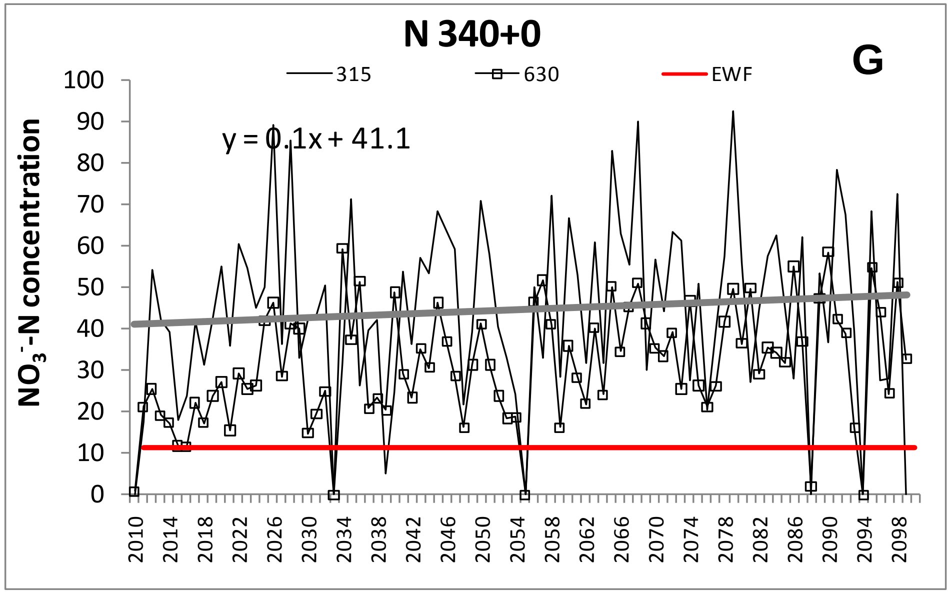
N fertilizations with 340 kg N ha^{-1} may exceed EWF (Fig. 9 G, L). Higher nitrate-N concentration were observed in scenarios irrigated with less water (<300-400 mm yr^{-1}). No significant differences were detected between 340+0 and 280+60 (p>0.05) (Table 7).

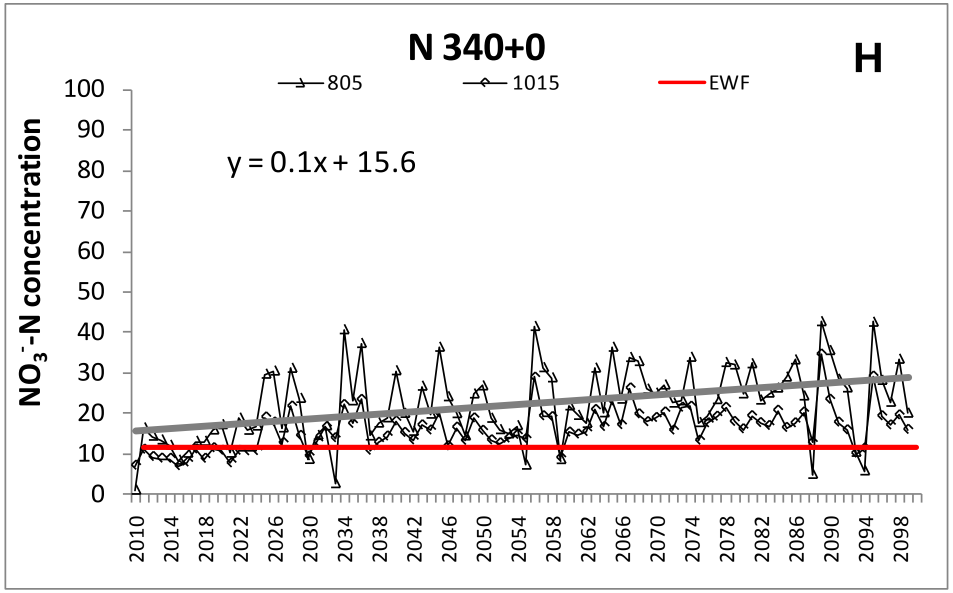
This study shows that global warming may play an important role in affecting and increasing the concentration of NO_3-N. In particular, N concentration may increase of 0.1 ppm year^{-1} (Fig. 9 E, F). Based on our simulations, nitrate-N loss should not increase its trend during an initial phase (from 2010 to 2035), while after 2040, probably under a stronger effects of climate change, nitrate-N concentration should increase about 0.1 ppm $year^{-1}$ (Fig. 9 E, F). It has to be noted that the year 2040 is indicated as the year of temperature breakpoint. After that minimum and maximum temperature should increase quicker than before. This could explain the results we obtained in our simulations.


N 170+0
A
315
630
EWF
y = 0.0x + 5.0
N 170+0
B
1015
805
EWF
y = 0.1x + 13.8
N110+60
C
315
630
EWF
y = 0.0x + 6.1
N110+60
D
1015
805
EWF
y = 0.0x + 5.7
NO3-N concentration


N 170+60
E
315
630
EWF
y = 0.1x + 9.8
NO3-N concentration


N 170+60
F
805
1015
EWF
y = 0.1x + 6.4
NO3-N concentration


N 340+0
G
315
630
EWF
y = 0.1x + 41.1
NO3-N concentration


N 340+0
H
805
1015
EWF
y = 0.1x + 15.6
NO3-N concentration

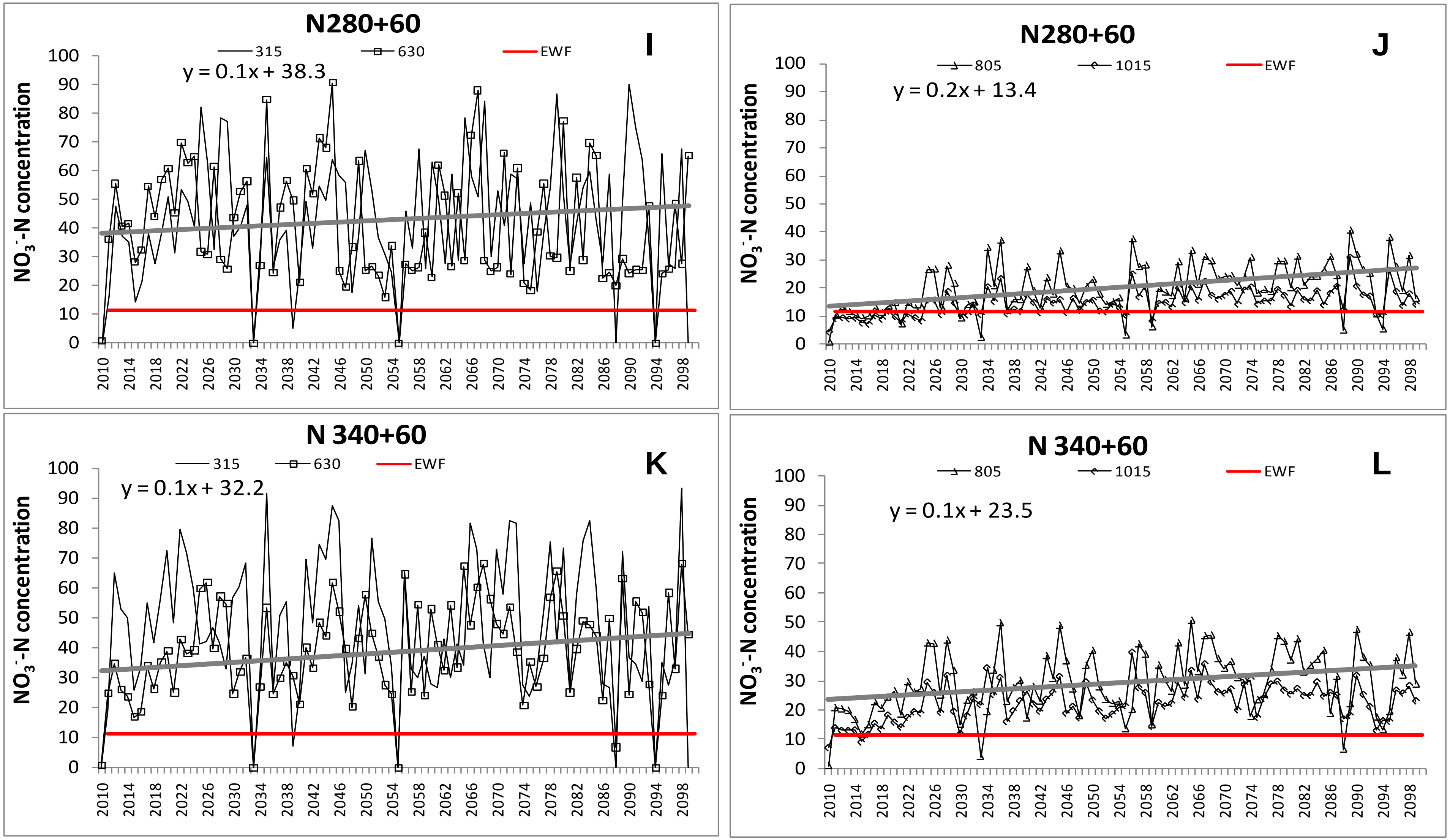


Figure 9 A-L. Concentration of NO_3-N leaching during the period 2010-2100 for scenarios fertilized with 170+0 (170 manure+0 urea), 110+60 (110 manure+60 urea), 170+60 (170 manure+60 urea), 340+0 (340 manure+0 urea), 280+60 (280 manure+60 urea) and 340+60 (340 manure+60 urea).

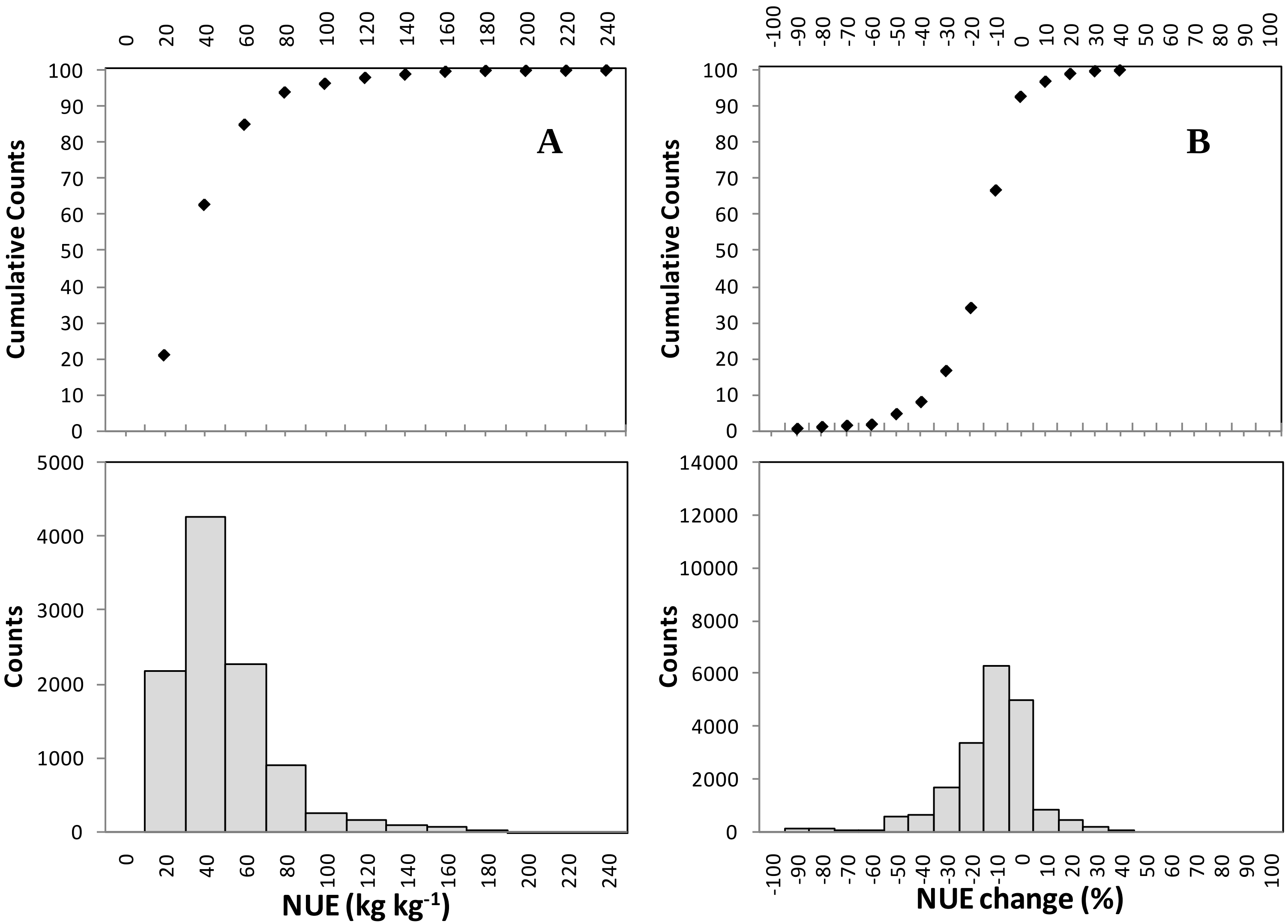
THE EFFECT OF CLIMATE CHANGE ON NITROGEN USE EFFICIENCY

The resulting of cumulative distribution functions (CDF) of NUE changes during 2030s, 2050, and 2080s, relative to the period 2010-2020, are represented in figure 10 (a, b, c, d). Each of CDF is based on the projected NUE change from 20 (2030s) or 29 years (2050, 2080s) x 60 scenarios =18000 and 26100. For all theses throughout the periods of simulation, the histogram of and CDM of N leaching changes, show that 66.7, 74.5 and 84.0% of probability NUE could decrease of 10% (Fig 10b, 10c, 10d) during 2030s, 2050s, and 2080s, respectively, relative to 2010-2020 yield (Fig 10a). NUE could decrease averagely by 7.4% with S.D. 17.0, 6.3% with S.D. 12.6and 11.3% with S.D. 13.9 during 2020s, 2050s, and 2080s, with 95% probably intervals of (-39.5, +13.9), (-30.6, +9.0) and, (-37.5, +7.9) (Table 8).

Table 8. Statistic analysis of NUE for 2030s, 2050s, and 2080s, relative to 2010-2020. (p=0.05)

Periods	Samples	Mean (%)	P 5	P 50	P 95	S.D.	S.E.
2030s	18000	-7.3	-39.5	-4.3	13.9	17.0	0.123
2050s	26100	-6.3	-30.6	-5.0	9.0	12.6	0.074
2080s	26100	-11.3	-37.5	-9.4	7.9	13.9	0.082

As discussed above NUE changes throughout the simulation period (2010-2100). Figure 11 shows that NUE may decrease about 5.9 kg kg^{-1} in 90 years (-0.059 kg kg^{-1} yr^{-1}). The results indicate that the decrease of the N-efficiency is due to a decreasing of productivity and increasing N losses. Although more productive farm systems tend to have lower relative N losses, and so higher N efficiency (Dueri et al., 2007), in contrast, our simulations demonstrate that higher farm production intensity increased N surplus (N losses) and lowered N efficiency. Same results were obtained by Olsen et al., 2006 who studied the Climate change affects farm nitrogen loss, in Switzerland.


A
B
Cumulative Counts
Counts
NUE (kg kg-1)
NUE change (%)

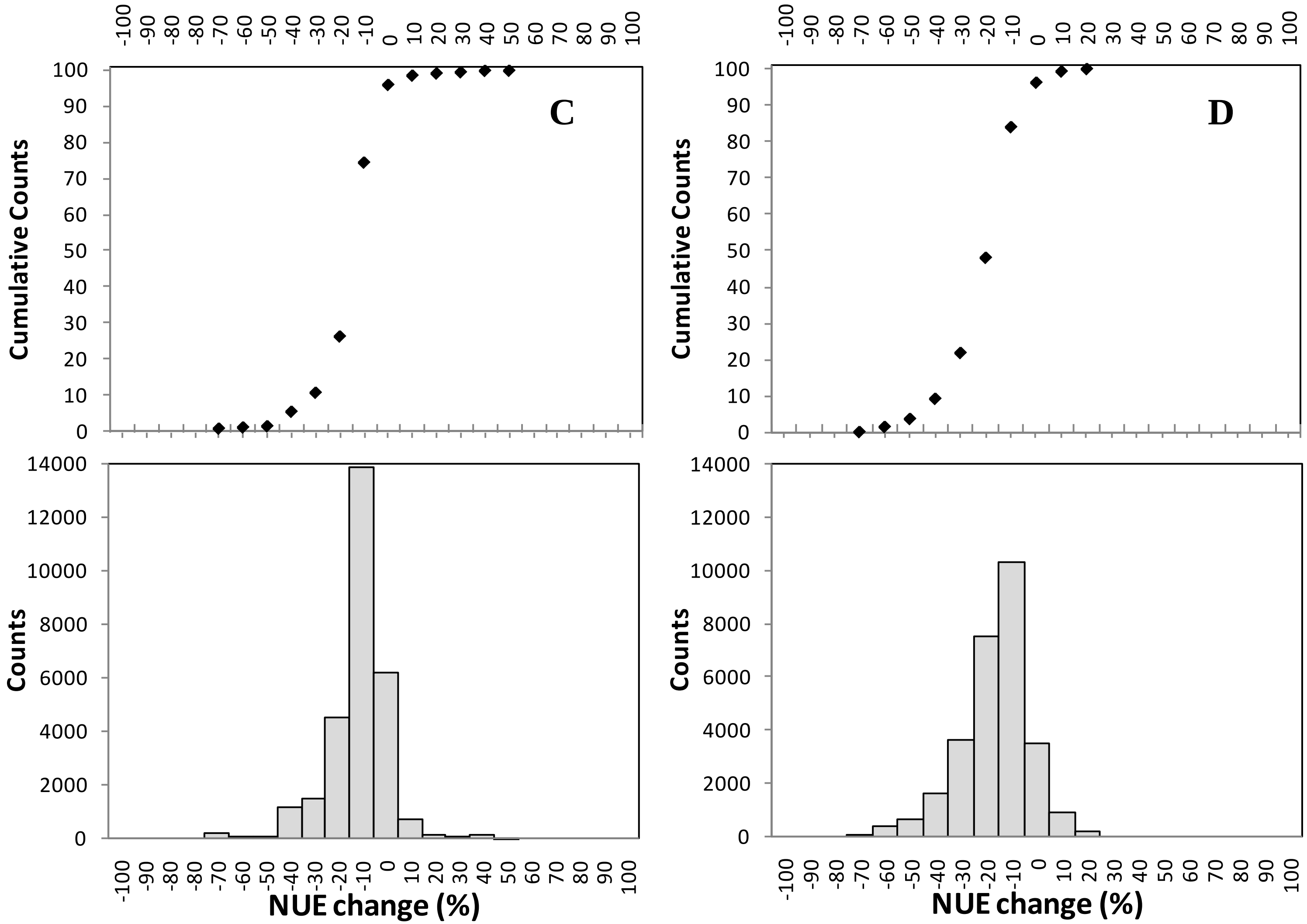


Figure 10 a, b c, d. Cumulative probability and histograms of NUE 2010-2020 (a), and its changes during 2030s (b), 2050 (c) and 2080s (d).

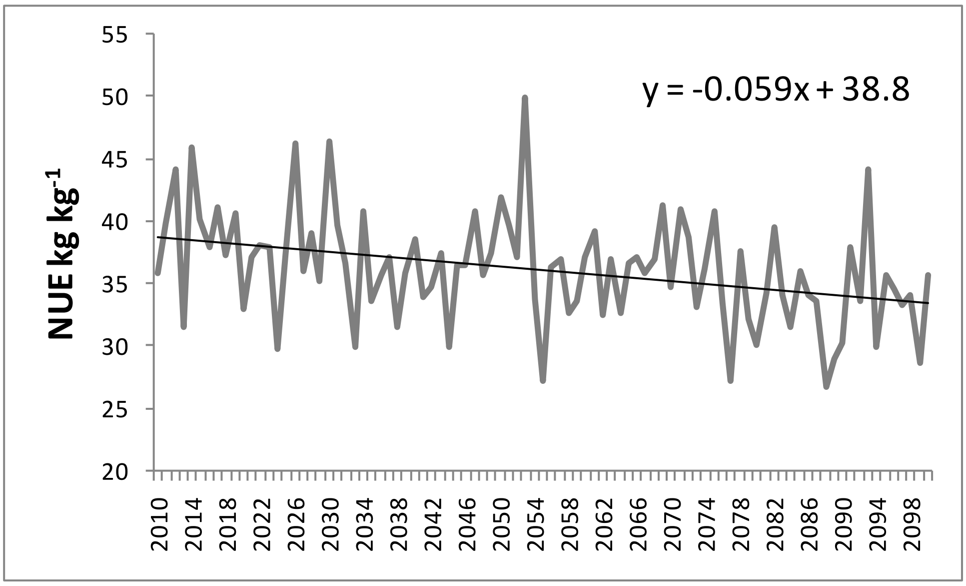


Figure 11. Trend of NUE over the period 2010-2100

CONCLUSION

Crop models are a good basis to simulate the impacts of climate variability and climate change on crop yields and N cycle. In this study we identified factors that explain variation of the future trend of grain yield, N loss and NUE throughout the period 2010-2100 under maize crop in northern Italy (Veneto Region). Simulations revealed that N-cycle and crop grain yield may be sensitive to gradually increasing temperature and decreasing precipitation.

Grain maize yield in the Veneto Region, relative to 2010–2020, maize yield would decrease approximately by up to 4.9%, 5.1% and 10.4% during 2020s, 2050s, and 2080s, respectively. N rate of 170+60 kg N ha^{-1} and 280+60 kg N ha^{-1} maximize grain yield in NVZ, and non NVZ, respectively. Crop grain yield may be more affected by global warming when N fertilization ≥ 280+60 kg N ha^{-1}.

In contrast, N leaching may increase during the next 90 years, under the pressure of global warming. Temperature and water availability could play major roles in increasing NO_3-N in future in the Veneto Region. Our results show that temperature and precipitation could affect N-loss, probably by influencing the availability of soil NO_3^- through increased rates of mineralization resulting in higher losses via leaching.

The EU Nitrate Directive of 170 kg N ha^{-1} do not exceed EWF under 4 mount of water applied with irrigation, throughout the simulation period. In contrast, 170+60 may exceed EWF especially when i) water inputs are lower than 300-400 mm yr^{-1} and ii) during the 2080s when the effects of climate change may affect the N cycle in soil. N fertilization $\geq$ 340 kg N ha^{-1} may exceed EWF under all water scenarios simulated from 2010 to 2100. In NVZ farmers should limit N fertilization up to 170 (170+0 manure only or 110+60 manure + urea) in order to achieve the EWF targets. In non NVZ, N rate of 280+60 kg N ha^{-1} should be combined with a water input $\geq$ 400 -500 mm yr^{-1} in order to reduce the environmental effect of N leaching on groundwater. N rate of 340+60 should be strongly avoided by farmers either because it may promote N leaching and not increases maize grain yield. NUE could decrease, on average, of 6.0%. The results indicate that the decrease of the NUE is due to a decreasing of maize productivity and increasing of N loss.

This study shows that future climatic condition could affect maize crop development and soil N cycle under maize crop in the Veneto Region in the future. This may lead farmers and governments to face new environmental challenges in order to achieve the EU Nitrate Directive. Nonetheless our results provide scientific basis and references for governments' decision-making from the view of regional climate change response.

ACKNOLEDGEMENT

I wish to thank Prof. Ian Willet for his helpful comments and insight. Dr Yong Li and Prof Deli Chen for their precious advices during the analysis of the data and throughout the writing of this chapter. Also, I thank Fondazione Gini for supporting the period of study at the University of Melbourne and the Faculty of Land and Food Resources, the University of Melbourne.

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