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Research Paper

Environmental and economic evaluation of N fertilizer rates in a maize crop in Italy: A spatial and temporal analysis using crop models

Bruno Basso[a,b,c,*], Luigi Sartori[d], Davide Cammarano[e], Costanza Fiorentino[a], Peter R. Grace[c], Spyros Fountas[f], Claus A. Sorensen[g]

[a] Dept. Crop Systems, Forestry and Environ. Sciences, University of Basilicata, Via Ateneo Lucano, 10, 85100 Potenza, Italy
[b] W.K. Kellogg Biological Station, Michigan State University, 3700 Gull Lake Dr. Hickory Corner, MI, USA
[c] Institute of Sustainable Resources, Queensland University of Technology, Brisbane, Australia
[d] University of Padua, Landscape and Agroforestry Systems, Agripolis, Legnaro, PD, Italy
[e] Dept. Agr. and Biosystem Engineering, University of Florida, Gainesville, FL, USA
[f] University of Thessaly, School of Agricultural Sciences, Fytoko Str., 38446 Volos, Greece
[g] Århus University, Faculty of Science and Technology, Department of Engineering, Research Centre Foulum, Blichers Alle 20, 8830 Tjele, Denmark

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Crop simulation models have the potential to assess the risk associated with the selection of a specific N fertilizer rate, by integrating the effects of soil-crop interactions on crop growth under different pedo-climatic and management conditions. The objective of this study was to simulate the environmental and economic impact (nitrate leaching and N_2O emissions) of a spatially variable N fertilizer application in an irrigated maize field in Italy. The validated SALUS model was run with 5 nitrogen rates scenarios, 50, 100, 150, 200, and 250 kg N ha^{-1}, with the latter being the N fertilization adopted by the farmer. The long-term (25 years) simulations were performed on two previously identified spatially and temporally stable zones, a high yielding and low yielding zone. The simulation results showed that N fertilizer rate can be reduced without affecting yield and net return. The marginal net return was on average higher for the high yield zone, with values ranging from 1550 to 2650 € ha^{-1} for the 200 N and 1485 to 2875 € ha^{-1} for the 250 N. N leaching varied between 16.4 and 19.3 kg N ha^{-1} for the 200 N and the 250 N in the high yield zone. In the low yield zone, the 250 N had a significantly higher N leaching. N_2O emissions varied between 0.28 kg N_2O ha^{-1} for the 50 kg N ha^{-1} rate to a maximum of 1.41 kg N_2O ha^{-1} for the 250 kg N ha^{-1} rate.

* *Corresponding author*. Dept. Crop Systems, Forestry and Environ. Sciences, University of Basilicata, Via Ateneo Lucano, 10, 85100 Potenza, Italy. Tel.: +39 3204371042.
E-mail address: bruno.basso@unibas.it (B. Basso).
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1. Introduction

Increasing maize yield has been one of the main challenges for agronomists and researchers worldwide for the last 50 years (e.g. Egli, 2008; Hafner, 2003). In areas where Nitrogen (N) fertilizer is affordable or subsidized, there is an increased probability that farmers will apply in large quantities, potentially imposing a high environmental impact, including nitrate leaching (Basso & Ritchie, 2005; Giola, Basso, Pruneddu, Giunta, & Jones, 2012; Martin, Tanksley, Slack, & Basso, 2006, Syswerda, Basso, Hamilton, Tausig, & Robertson, 2012), ammonia volatilization, nitrous oxide (N_2O) emissions and soil acidification (Chen, Li, Grace, & Mosier, 2008; Grace et al., 2011; Spiertz, 2010). The environmental impact that agriculture exerts is gaining more attention from society. For example, the European Union (EU) Nitrates Directive (91/676/EEC) aims to preserve the quality of groundwater through promotion of good farming practises to increase N use efficiency through a reduction in direct the application of N.

Determining the optimum amount of N fertilizer to meet plant needs while simultaneously minimizing environmental impacts is not an easy task (Robertson & Vitousek, 2009). The optimum N fertilizer rate varies within the same field with each growing season as a result of the heterogeneity of soil properties (which in turn affects soil water content) and inter- and intra-annual weather patterns (Basso, Bertocco, Sartori, & Martin, 2007). In most cases, farmers apply N fertilizer without considering the within field variation of soil properties. The concept of 'precision farming' was introduced in the early 1990s, with yield monitors being the most important technological tool for a successful application of precision farming (Pierce & Sadler, 1997). Since then, much research has been conducted in the search for site-specific and optimized application rates for several input resources, such as fertilizers and pesticides.

Some research has examined and found reasonable consistency between variable rate N fertilizer applications and the factors affecting nitrogen variability. These factors that have shown to have high influence are elevation, apparent electrical conductivity (ECa), and soil texture (Fraisse, Sudduth, & Kitchen, 2001; Godwin & Miller, 2003; Kyveryga, Blackmer, & Caragea, 2011; Ruffo, Bollero, Bullock, & Bullock, 2005; Welsh et al., 2003). Walter, Bausch, and Brodahl (2012) recommended using ECa maps as a method of obtaining reference strip normalizing values in fields with spatially variable sandy soils.

Delin, Linden, and Berglund (2005) reported that the potential for improvement of yield or nitrogen efficiency by site-specific nitrogen fertilization is only relevant if the causes of within-field variation are predictable before fertilization. Approaches to derive uniform management zones have been described by Mulla (1991), Schepers et al. (2004), Chang et al. (2004), Miao et al. (2006); Basso et al. (2007), and Basso, Ritchie, Cammarano, and Sartori (2011). Specific studies by Lawes and Roberston (2011) found that information needed for precision fertilizer management may neither be feasible nor easy to interpret. However, the complete decision making process on the application of N at the farm level must consider the specifics of information necessary to aid in decision making, including the cost–benefit of acquiring this information. The decision making process on N-application therefore becomes an integral and sustained element of the farm management information system as demonstrated by numerous studies (Basso, Sartori, Bertocco, & Olivero, 2003; Doole, Bathgate, & Robertson, 2009; Fountas, Wulfsohn, Blackmore, Jacobsen, & Pedersen, 2006; Janssen & van Ittersum, 2007; Lawes & Roberston, 2011; Sørensen et al., 2010). An improved understanding of the factors affecting the determination of the optimal N-application in terms of both external influences (e.g. cost of fertilizers, chemicals, fuels, etc.) as well as the on-farm and in-field influences will assist farmers in achieving higher yields at lower costs.

The complexity of decision making is illustrated by the fact that even if farmers have a spatial map of soil properties, the decision about the amount of N fertilizer to apply on the field is taken without any prior knowledge of future weather conditions. A feasible approach to cope with such uncertain future information is to quantify the uncertainty under different scenarios as part of a predictive decision support system (Basso, Ritchie, et al., 2011; Fountas et al., 2006).

Crop simulation models can quantify the interaction between multiple stresses and crop growth under different environmental and management conditions (Basso, Ritchie, Pierce, Jones, & Braga, 2001; Basso, Sartori, Bertocco, Cammarano, & Grace, 2011; Batchelor, Basso, & Paz, 2002; Schnebelen et al., 2004). Using long-term historical weather data, the models can be used to develop alternative management strategies for optimizing productivity and maximizing profit as well as capturing the diversity of environments that can be encountered at a given farm. Crop simulation models are rarely used in precision farming because of the costs of obtaining detailed site-specific field attributes, as inputs are prohibitive, except in few case (Basso et al., 2001; Basso, Sartori, et al., 2011; Basso, Fiorentino, Cammarano, Cafiero, & Dardanelli, 2012; Batchelor et al., 2002; Booltink et al., 2001; Cora, Pierce, Basso, & Ritchie, 1999; Link, Batchelor, Graeff, & Claupein, 2008; Miao et al., 2006; Wong & Asseng, 2006). Models can help farmers in a strategic way assessing the probability that a certain outcome will occur for those measured pedo-climatic condition and management practises. Models have also being shown to be useful in a tactical management of N fertilizer rate associated with more easily observed variables (i.e. water availability based on rainfall amounts). Basso, Ritchie, et al. (2011) demonstrated that N fertilizer amount needs to be different over space and time depending on the amount of water stored in the soil profile. In the past, best management of N fertilizer and irrigation recommendations have mainly aimed at increasing crop yield giving the environmental impact (potential for NO_3 leaching and N_2O emissions) a lower priority. In order to obtain information on nitrate leaching data over a long period of time, long-term experiments need to be implemented. This kind of information is normally not available due to the prohibitive cost of the long-term experiment and nitrate leaching collection protocol. A much more practical way of obtaining these data is through the use of crop simulation models. Several models are able to predict nitrate leaching potential under different fertilization strategies. Asseng et al. (1998) used the

APSIM model to predict the leaching potential under different initial soil water and inorganic soil N showing that the soil water and the soil inorganic N content at the beginning of each season had no effect on grain yield, implying that pre-seed soil NO_3 was mainly lost from the soil by leaching.

The objective of this study was to simulate the environmental and economic impact (nitrate leaching and N_2O emissions) of spatially variable N fertilizer applications in an irrigated maize field in Italy using a validated crop model. The research aims at demonstrating the importance of using crop models for selecting best N management strategies from the economic and environmental perspective over space and time and in places where previous knowledge or long-term experiments are not present to reduce the risks the farmers face when selection N fertilizer strategies.

2. Material and methods

2.1. Site description

The study was carried out on an 8-ha field with a near zero slope, located close to Rovigo (44° 4′ 12″ N, 11° 47′ 22″ E, 6 m.a.s.l.) NE Italy grown with continuous maize for 5 years (1998–2002). The soil type was clay according to the USDA particle-size distribution limits, defined as FAO Ombric and Thionic Histosols. The climate of the area was characterized by an average annual rainfall of 700 mm (in years 1997–2008), distributed mostly in autumn and spring. The annual average temperature, for the same time period, was 13.3 °C, with a monthly maximum of 23.5 °C in July and a minimum of 3.2 °C in January.

2.2. Agronomic management

The agronomic practises applied to the maize crop (*Zea mays*, L.) consisted of minimum tillage and integrated weed control strategies. The N fertilizer rate applied by the farmer was 250 kg N ha^{-1} in two split applications (30% at planting and 70% at V6 stage, which is the vegetative stage of a maize plant with 6 leaves). The hybrid *Pregia* was sown with a planter (0.75 m rows) using a seeding rate of 28.4 kg ha^{-1} resulting in 8.1 plants m^{-2}.

2.3. Management scenarios

The farmer current N fertilizer management (250 kg N ha^{-1}) was simulated and compared with four nitrogen rates, 50, 100, 150, and 200 kg N ha^{-1} split in two applications (30% at planting and 70% at side dressing). The simulations were performed on two spatially and temporally stable zones (yield changes mainly occurred over space). The identification of homogeneous management zones was carried out by considering the level of yield obtained from the field and the degree of stability over the years (Blackmore, 2000). In particular, the spatial variability of yield was analysed by calculating the relative percentage difference of yield crop from the average yield level obtained within the field at each point mapped. The final map of the zones with different yields was created by overlaying the single map of the relative percentage difference of yield. Different zones were then classified in relation to a relative percentage difference threshold of 100%: the zones for which this value was greater were classified as the zone with high yield, while the zones for which this value was lower were defined as the zone with low yield. The temporal variability of yield patterns, expressed as degree of stability, was calculated as temporal variance (yield value recorded at each point mapped minus the field mean) according to the method proposed by Blackmore, Godwin, and Fountas (2003). Details about the delineation of these two zones are outlined in Basso et al. (2007).

The optimal N fertilizer rate for each of two zones was based on the yield response to N, amount of N leached, amount of greenhouse gas emitted, and marginal net return (MNR). The MNR was calculated using the following equation:

$$MNR_z = (Y_z * G_p) - (N_z - N_p) - \text{Fixed Costs} \quad [1]$$

where MNR_z is the marginal net return for the management zone z (€ ha^{-1}), Y_z is the grain yield for the management zone z (kg ha^{-1}), G_p is the grain price (€ kg^{-1}), N_z is the N application rate for the management zone z (kg N ha^{-1}), N_p is the price of N (€ kg^{-1}), and Fixed Costs are the costs associated with the input associated with N application (€ ha^{-1}).

2.4. Crop model

The crop model used in this study was the SALUS (System Approach to Land Use Sustainability; Basso, Rtichie, Grace, & Sartori, 2006; Basso, Cammarano, Troccoli, Chen, & Ritchie, 2010; Senthilkumar, Basso, Kravchenko, & Robertson, 2009) model. SALUS simulates crop yield, soil water and nutrient balance under different management strategies for multiple years. The model accounts for effects of rotations, planting details, fertilizer, irrigation and tillage practises on the final yield and environmental impact. The model simulates plant growth and soil conditions on a daily time-step. Different management strategies can be evaluated simultaneously. SALUS requires input on soil properties (e.g., physical and chemical properties, soil water contents and N concentrations), weather (minimum, maximum temperature, precipitation and solar radiation) and agronomic management details (tillage operation and residues management, planting, fertilization, irrigation and harvest). The model provides output information on crop yield, crop developmental stages, N uptake, nitrate leaching, soil water balance (soil evaporation, transpiration, drainage, runoff), and soil organic C and N levels. SALUS model can be downloaded from www.salusmodel.net.

In the case of an 8-ha maize field mentioned above, a 25-year weather record (1983–2008) was used to simulate the N rates. The model was validated with the observed yield data for the years 1999–2007 using the root mean square error (RMSE). SALUS has been validated for nitrate leaching measurements in different environments and ecosystems (Giola et al., 2012; Syswerda et al., 2012) but nitrate leaching measurements in this study were not carried out to validate the model.

The model was run in two spatially and temporally stable zones only for the 200 and 250 N rate characterized by higher yields and higher MNRs as compared with the other N scenarios. The two designated zones, called high stable (HS) and low stable (LS) were previously defined by Basso et al. (2007). The model's output used for this study was maize yield and N leaching.

2.5. Nitrous oxide (N_2O) emission estimation

The N_2O production was estimated using the site-specific emission factors, which in this case resulted in a 0.5643% of N fertilizer input. The lack of a specific relationship between yield and N_2O emission in Italy, we were obliged to use the specific emission factors for N_2O emission in arable land with fertilizer addition. In general, increased N loss with higher yields has been reported by Kanampiu, Raun, Johnson, and Anderson (1997) and increased N_2O emissions specifically have been reported in a number of papers (Hoben, Gehl, Millar, Grace, & Robertson, 2010; Ma et al., 2009; McSwiney & Robertson, 2005; Sehy, Ruser, & Munch, 2003). In all cases, a non-linear curve best describes the N_2O flux response to increasing amounts of N, and with small increases in applied N resulting in proportionately higher N_2O fluxes at higher N application rates. Grace et al. (2011) estimated the annual fertilizer induced N_2O emissions from maize as the product of total harvested area of grain in any year, total N applied, total number of days in respective years (365 or 366), and the average daily N_2O flux as detailed in Hoben et al. (2010) after correcting for background emissions.

The average daily N_2O flux is then converted into the amount of CO_2 equivalent emitted (kg CO_2e ha^{-1}) by multiplying the flux by 296 (McSwiney & Robertson, 2005).

3. Results

The differences between simulated and measured maize yield for the six years of study are shown in Fig. 1. There is a high correlation between simulated and measured yield demonstrating the consistency of the model used ($y = 1.02x - 493$; $r^2 = 0.92$; RMSE = 398.7 kg ha^{-1}). The long-term simulation of yield at different N rates showed significant differences in yields as a function of the quantity of N applied to the crop (Table 1). An application rate of 50 N showed lower yield with values ranging from 6.1 to 8.1 t ha^{-1} (Fig. 2). Maize yield increased with increasing application rates of N except for the 250 N application rate which equalled the yield resulting from the 200 N application rate in 90% of the cases (Fig. 2). On average, yield values for the two N rates are 11.6 t ha^{-1} for 200 N and 11.7 t ha^{-1} for the 250 N with the latter scenario showing higher a coefficient of variation (Table 1). The range of yield variation for the 250 and 200 N was 9.0–14.9 t ha^{-1} and 8.9–13.8 t ha^{-1}, respectively (Table 1). The cumulative probability function of the MNR for the different N rates is shown in Fig. 3. The patterns of MNR for the 25 years of simulation are similar to the yield pattern. The 50 N rate showed the low MNR and 200 and 250 N the higher MNR (Fig. 3). However, it is interesting to note that 250 N has a higher coefficient of variation, 13.3% against 12.2% for 200 N, and lower MNR minimum than the 200 N (Table 1). MNR for the 250 N was higher only in 10% of the cases over the simulated years (Fig. 3).

The spatial distribution of the two HS and LS areas is shown in Fig. 4a and b. The HS is located in the upper portion of the field and on both sides of the mid-portion of the field (Fig. 4a). The LS is located in the bottom and middle part of the field (Fig. 4b). Each zone has a distinct soil texture and organic matter (OM) content as shown in Table 2 for three soil depths (0–15 cm; 15–30 cm; 30–45 cm). Sand, loam, and OM are statistically different among the zone at each given depth. Clay did not vary significantly among the two zones. Table 2 shows soil properties at depth of 45 cm because the HS zone had a deeper exploitable soil profile than the LS with the volume available for allowing root growth of 60 cm for the HS and 45 cm for the LS (Basso et al., 2007). Long term simulations of maize yield within the two zones are shown in Fig. 5. Overall, increasing the N rate from 200 to 250 kg N ha^{-1} did not guarantee an increase in yield in 90% of the cases (Fig. 5). In the LS zone, 250 N showed higher yield only in 40% of the cases while in the HS only 10% of the cases (Fig. 5). The

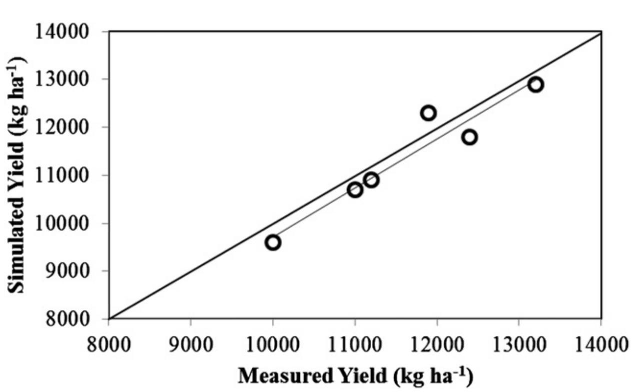

Fig. 1 – Simulated vs. measured yield for the six years of experimental data using the SALUS crop model. (Regression parameters: $y = 1.02x - 493$; $r^2 = 0.92$; RMSE = 398.7 kg ha^{-1}).

Table 1 – Average, standard deviation, maximum and minimum values, and coefficient of variation for maize yield and marginal net return for the five nitrogen rates simulated for the whole field with 25 years weather data.

N rates	(kg N ha^{-1})	50 N	100 N	150 N	200 N	250 N
Yield (t ha^{-1})						
Average	(t ha^{-1})	7.2	8.8	10.1	11.6	11.7
STDEV		0.6	1.5	1.2	1.5	1.6
Max		8.1	11.0	11.7	13.8	14.9
Min		6.1	6.4	7.7	8.9	9.0
CV	(%)	8.5	17.0	11.9	12.8	13.8
Marginal net return (€ ha^{-1})						
Average	(t ha^{-1})	1650.2	1938.8	2171.6	2426.0	2405.4
STDEV		121.4	298.8	241.9	296.6	320.5
Max		1835.0	2380.0	2485.0	2870.0	3055.0
Min		1435.0	1460.0	1685.0	1890.0	1875.0
CV	(%)	7.4	15.4	11.1	12.2	13.3

STDEV: Standard deviation; Max: Maximum value; Min: Minimum value; CV: coefficient of variation.

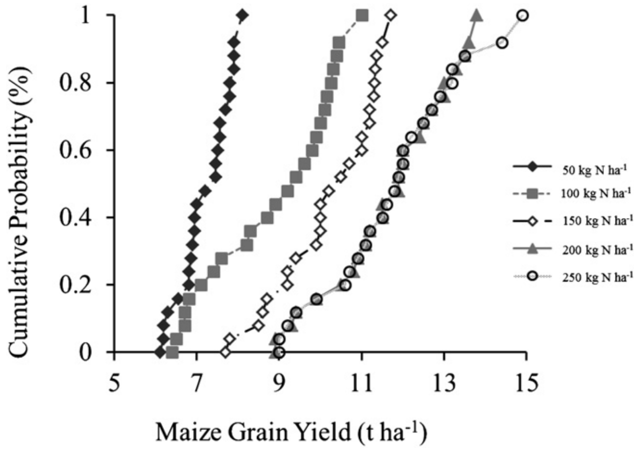

Fig. 2 – Cumulative probability (%) of maize grain yield ($t\,ha^{-1}$) at the four N scenarios (50, 100, 150, 200 $kg\,N\,ha^{-1}$), and at the farmer's rate (250 $kg\,N\,ha^{-1}$) as simulated by SALUS model using 25 years of historical weather data.

coefficient of variation was lower for the 200 N HS with 12.1% and higher for the 250 N HS with 14.8% (Table 3). MNR was on average higher for the HS zone, with values ranging from 1550 to 2650 € ha^{-1} for the 200 N and 1485 to 2875 € ha^{-1} for the 250 N (Table 3). In the LS, there was no significant difference in MNR between the two N scenarios and their pattern of variation followed the yield pattern variation (Fig. 6). Figure 7 shows the cumulative probability of N leaching in the two zones and for the two N scenarios. On average, the values of simulated N leaching for the HS were 16.4 and 19.3 $kg\,N\,ha^{-1}$ for the 200 N rate and the 250 N rate, respectively (Table 3). The coefficient of variation was higher for the 200 than the 250, but the amount of N leached for the 250 N was higher than 200 N in 80% of the cases, while 200 N showed high N leaching in only 20% of the cases (Fig. 7). For the LS zone, the 250 N rate showed significantly high N leaching, with 31 $kg\,N\,ha^{-1}$ on average and a range of variation between 9 and 66 $kg\,N\,ha^{-1}$

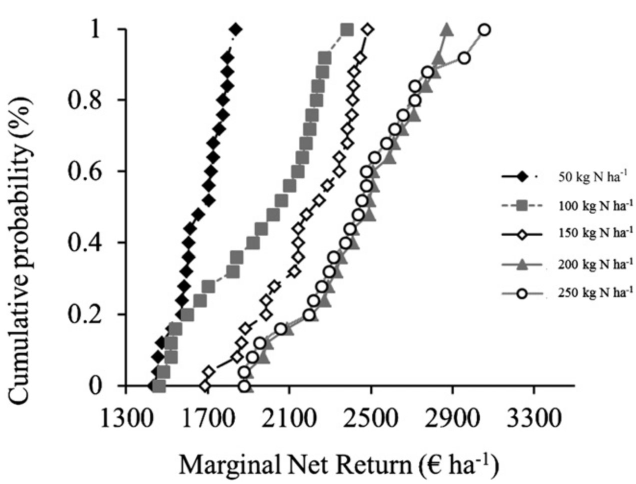

Fig. 3 – Cumulative probability (%) of marginal net return (MNR, € ha^{-1}) at the four N scenarios (50, 100, 150, 200 $kg\,N\,ha^{-1}$) and at the farmers' rate (250 $kg\,N\,ha^{-1}$) as simulated by SALUS model using 25 years of historical weather data.

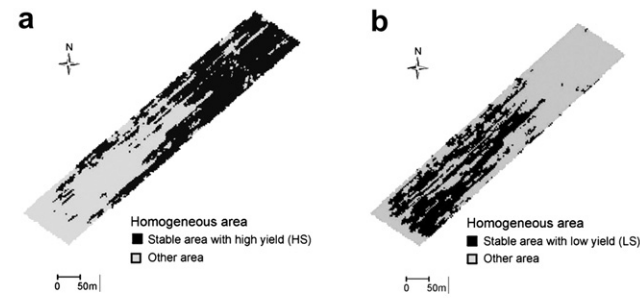

Fig. 4 – Spatially and temporally stable zone with black area showing high yield values (HS) (a); spatially and temporally stable zone with black area showing low yield values (LS) (b). Adapted from Basso et al., 2007.

(Table 3). The cumulative probability function showed that N leaching for the 250 N rate is similar to 200 N rate only in 10% of the cases, while the 200 N rate showed a significantly higher N leaching values only in 15% of the cases (Fig. 7).

Nitrous emission increased from 0.28 $kg\,N_2O\,ha^{-1}$ for the 50 $kg\,N\,ha^{-1}$ rate to a maximum of 1.41 $kg\,N_2O\,ha^{-1}$ for the 250 $kg\,N\,ha^{-1}$ rate (Table 4). The amount CO_2 equivalent increased linearly with the increase of N rates. It increased from 83.5 (50 $kg\,N\,ha^{-1}$) to 417.5 $kg\,CO_2e\,ha^{-1}$ (250 $kg\,N\,ha^{-1}$) (Table 4). Maize yield reached a plateau at 200 $kg\,N\,ha^{-1}$ but CO_2e emissions increased by 83.5, when increasing the N rate from 200 to 250 $kg\,N\,ha^{-1}$ (Fig. 8).

4. Discussions

This research presented a modelling approach for selecting the most sustainable N fertilizer rate on two spatially and temporally stable zones of a maize field. The alternative to this approach, which accounts for the interaction between soil, plant, climate and management for 25 years is a long-

Table 2 – Soil texture and organic matter (OM) measured for the two stable zones, high yield zone (HS) and low yield zone (LS).

		Zone	HS	LS
Clay	0–15 cm	(%)	39	41
Sand			25^{a}	14b
Loam			35^{bc}	45^{a}
OM			3.73^{a}	2.39^{b}
Clay	15–30 cm	(%)	38	41
Sand			24^{a}	14^{b}
Loam			38^{b}	45^{a}
OM			3.71^{a}	1.81^{bc}
Clay	30–45 cm	(%)	40	44
Sand			21	15
Loam			39	41
OM			3.61^{a}	1.89^{b}

Superscript alphabets represent statistically significant differences between the soil texture and the OM for each depth (LSD test, $P \leq 0.05$).
Adapted from Basso et al., 2007.

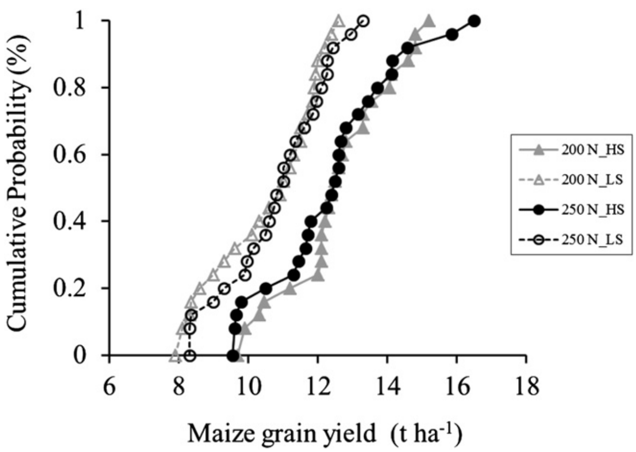

Fig. 5 – Cumulative probability (%) of maize yield (t ha^{-1}) at the 200 kg N ha^{-1} and 250 kg N ha^{-1} for the two spatially and temporally stable zones, high stable (HS) and low stable (LS) as simulated by SALUS model using 25 years of historical weather data.

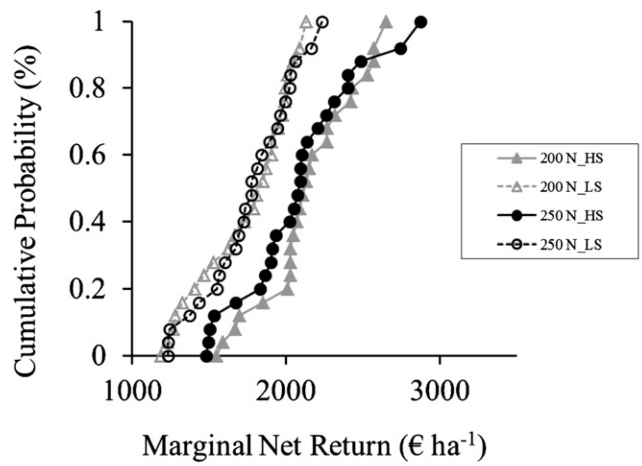

Fig. 6 – Cumulative probability (%) of marginal net return (MNR, € ha^{-1}) at the 200 kg N ha^{-1} and 250 kg N ha^{-1} for the two spatially and temporally stable zones, high stable (HS) and low stable (LS) as simulated by SALUS model using 25 years of historical weather data.

term study, where despite the enormous value in having such an experiment, the cost for running and maintain are prohibitive. By running a validated model with a long-term weather data recorded from a local weather station, the model results can simulate the situation when the farmer would have information on the future weather. The probability that one application rate will perform better than another, within a satisfactory threshold selected by the farmer (i.e. satisfied if one rate is better than the other 75% of the time), provides the means for the farmer to reduce their risk in making their selections.

Simulation of maize yield with long-term weather data showed the temporal variability of yield response at different N rates. The differences are due to the effects of long-term weather data on the average yields as showed in Fig. 2 and Table 1. Such effects are more significant on the two stable zones defined by Basso et al. (2007) because of the influence of two different soil conditions that are averaged out when the model is run on the whole field. The differences in soil compaction and the volume available for root growth influenced crop response to N and water. Yield response to N fertilizer for the two zones, LS and HS, shows that current

Table 3 – Average, standard deviation, maximum and minimum values, and coefficient of variation for the five nitrogen rates simulated for the two zones, high stable (HS) and low stable (LS) with 25 years weather data.

N rates	(kg N ha^{-1})	200 N_HS	200 N_LS	250 N_HS	250 N_LS
Yield (t ha^{-1})					
Average	(t ha^{-1})	12.6	10.6	12.4	10.8
STDEV		1.5	1.5	1.8	1.4
Max		15.2	12.6	16.5	13.3
Min		9.7	7.9	9.6	8.3
CV	(%)	12.1	14.2	14.8	13.2
Marginal net return (€ ha^{-1})					
Average	(t ha^{-1})	2130.5	1723.1	2057.3	1744.3
STDEV		304.8	300.5	366.4	286.2
Max		2650.0	2130.0	2875.0	2235.0
Min		1550.0	1190.0	1485.0	1235.0
CV	(%)	14.3	17.4	17.8	16.4
N leaching (kg N ha^{-1})					
Average	(t ha^{-1})	16.4	22.0	19.3	31.0
STDEV		11.9	13.7	10.2	17.0
Max		54.0	65.0	55.9	66.0
Min		5.0	8.7	9.5	9.0
CV	(%)	72.8	62.3	52.9	54.7

STDEV: standard deviation; Max: maximum value; Min: minimum value; CV: coefficient of variation.

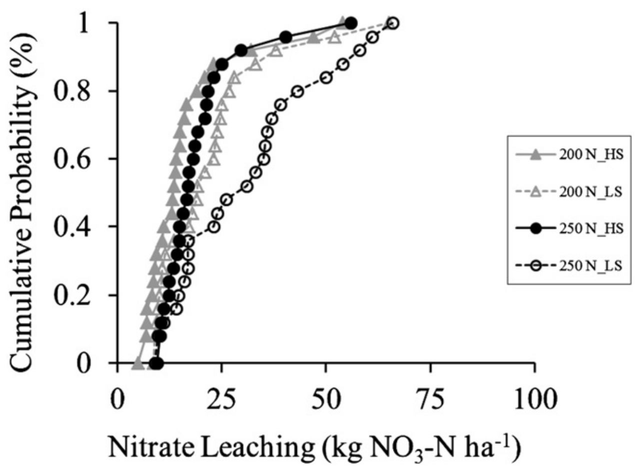

Fig. 7 – Cumulative probability (%) of nitrate leaching ($kg\ NO_3$-N ha^{-1}) at the 200 kg N ha^{-1} and 250 kg N ha^{-1} for the two spatially and temporally stable zones, high stable (HS) and low stable (LS) as simulated by SALUS model using 25 years of historical weather data.

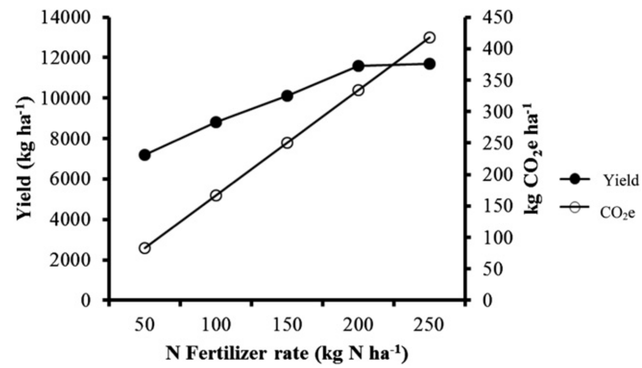

Fig. 8 – Relationship between maize yield N fertilization amount and between kg CO_2e emitted at each N fertilization amount.

rates of 250 kg N ha^{-1} can be reduced without affecting yield and net return. In the LS application of fertilizer at 250 kg N ha^{-1} it does not translate into a higher yield throughout most of the years (97% of the cases).

Several authors have discussed the implication of choosing variable rate management of nutrients, tillage, and plant population (Basso et al., 2007; Basso, Ritchie, et al., 2011; Basso, Sartori, et al., 2011; Miao et al., 2006; Paz, Batchelor, & Jones, 2003). Link et al. (2006) showed that especially due to an environmental compensation payment policy the application of variable rate management in maize resulted in higher MNRs. For this study, the environmental protection “factor” follows the EU nitrate directive (91/676/EEC) that allows farmers to apply a maximum of 60 kg N ha^{-1} of inorganic N along with 170 kg N ha^{-1} of manure in the nitrogen vulnerable zones. This makes an amount of N to be applied of 230 kg N ha^{-1} for farms in those sensitive areas. It is clear that in this particular case the N applied slightly exceed the limit set by the EU, but this does not translate into a N leaching value that exceeds the EU target of 11.3 mg l^{-1} NO_3-N (data not shown, the maximum NO_3-N is around 10 mg l^{-1} NO_3-N for the 250 N in the LS zone). These results agree with the findings of Ten Berge, Van Deer Meer, Carlier, Baan Hofman, and Neeteson (2002) were an amount of manure of up to 400 kg N ha^{-1} could be applied in certain systems without exceeding the EU threshold limit of 11.3 mg l^{-1} NO_3-N. This occurred because such a limit is influenced by the amount of irrigation water applied and the soil type. Roitero (2010) found in the Veneto Region on loamy soils that up to 340 kg N ha^{-1} could be applied without exceeding the EU limit when the total amount of water (irrigation + rainfall) is below 1100 mm. In this case study the farmer did not apply more than 1100 mm and that is also why N leaching did not reach the EU limit.

The CO_2e emission increased linearly with increase in N fertilizer but the maize yield reached a plateau at 200 kg N ha^{-1}. The integration of such information with the results of the yield and marginal values discussed above indicated that the fertilizer rate of 200 kg N ha^{-1}, well below the EU threshold, lowered the amount of N leached and emitted from the soil and maximizes MNR without causing any yield reduction. When the two fertilizer rates are modelled on the two spatial zones the HS and the LS we found that the higher N rate is always the less productive. This is more evident in the LS zone where an amount of 250 kg N ha^{-1} causes higher leaching and does not result in any increase of MNR. The amount of N emitted from the soil is a function of several parameters such as soil properties (clay content, bulk density, organic C, and so on), crop management, soil temperature, soil water, soil oxygen, soil N, and C available (Chen et al., 2008). Results of this study agree with the findings of Grace et al. (2011) in which any small increases in applied N resulted in proportionately higher N_2O fluxes at higher N application rates. In both zones, the amount of N that maximizes the income, does not reduce the yield and causes lower environmental impact (leaching and greenhouse gas emission) is the 200 kg N ha^{-1}.

Table 4 – Average seasonal nitrous oxide fluxes (N_2O) calculated for each N treatment and the amount of carbon dioxide equivalent (CO_2e) for each N treatment.

N (kg N ha^{-1})	N_2O (kg N_2O ha^{-1})	CO_2e (kg CO_2e ha^{-1})
50	0.28	83.5
100	0.56	167.0
150	0.85	250.5
200	1.13	334.1
250	1.41	417.6

5. Conclusions

The potential of using a crop model as a decision tool for improving farmer’s economic return by maximizing yield or reducing input while protecting the environment was demonstrated. The crop growth simulation model allowed for deriving valuable information needed to decide on the optimal N rate to apply on spatially and temporally stable zones of a field. The long-term simulation of maize yield and N leaching showed the variability of yield response at different N rates. Derived differences are due to the effects of long-term weather data on the average yields. Such effects are more significant on the stable zones of, for example high and low yields, because of the influence of different soil conditions that are averaged out when the model is run on the whole field. The differences in soil compaction and the volume available for root growth significantly influence crop response to N and water. The use of a crop simulation model on spatially and temporally zones within the field allowed for the identifying of the best N fertilization rates and provides farmers with a decision support in order to reduce the level of risk.

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