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A strategic and tactical management approach to select optimal N fertilizer rates for wheat in a spatially variable field

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ABSTRACT

Wheat yield and protein content in a field are spatially variable due to inherent variability of soil properties and landscape. In Mediterranean environments yield variability in space and time is caused by irregular weather patterns, particularly rainfall, and by position in the landscape. A tested crop simulation model, SALUS, was used to select optimal nitrogen fertilizer rates using strategic and tactical approaches in a spatially variable field where three distinct management zones had been previously identified. The crop model was tested and then used to simulate seven N rates from 0 to 180 kg N ha^{-1} with a 30 kg N ha^{-1} increments for 56 years using historical weather data. The available soil water at the time of N sidedressing each year and each management zone was correlated with yield response to N to evaluate the possibility of using the stored soil water to tactically determine N rates. Assuming recent production costs and grain prices the simulations helped identify an optimal N rate for each of the zones based on agronomic, economic and environmental sustainability of N management. Results showed the high yielding zone had a maximum economic return and minimal environmental impact in terms of nitrate leaching by applying 90 kg N ha^{-1}annually. On the other hand, the low yielding zone had little economic returns for application higher than 30 kg N ha$^{-1.}$ When simulated soil root-zone water was low at sidedressing, a lower fertilizer rate increased profit and decreased N leaching in the medium and high yielding zones.

1. Introduction

Appropriate nitrogen (N) management is one of the main challenges of agriculture production and for the environment. Under field conditions N losses are mainly due to nitrate leaching, volatilization of ammonia from leaves of N-rich plants, and nitrous oxide emissions (Basso and Ritchie, 2005; Robertson et al., 2000). To reduce such losses a better and more efficient way of applying N is necessary. From an economic point of view, the optimal N fertilizer amount should be the rate at which the farmer's financial return is maximized, also known as Economic Optimum Rate (EOR). The optimal N amount (N_{opt}) varies between site location and between years (Mamo et al., 2003; Sambroski et al., 2009), for the same field cropped with the same cultivar the N_{opt} is not constant across the field because of the spatial variability of crop growing conditions and soil properties (Pierce and Nowak, 1999). Applying spatial variable rate of N_{opt} is challenging because it deals with the adoption of site specific practices that aim at maximizing crop N uptake, minimize N losses, and optimize indigenous soil N supply.

Spatial variability information can be obtained by using global position systems (GPS), yield monitoring, geographic information systems (GIS) and remote sensing (RS), and then managed with site-specific management (SSM) practices, where the level of an input, such as N is varied within each management zone (Pierce and Nowak, 1999). Management zones represent an area of the field in which the combination of the yield-limiting factors is almost homogeneous and a given rate of an input is adequate (Doerge and Gardner, 1999). The overlay of various thematic maps (spatial variability of soil properties, crop growth, grain yield) can be used to divide the field into uniform management zones (Fridgen et al., 2004; Miao et al., 2006; Basso et al., 2009). However, SSM can be useful in optimising the input for crop production only if the assessment of such variability is sufficiently accurate (Pierce and Nowak, 1999). Various authors have proposed criteria for the delineation of management zones (Mulla, 1991; Basso et al., 2001; Fleming et al., 2001; Ferguson et al., 2004; Schepers et al., 2004; Chang et al., 2004; Inman et al., 2005; Franzen et al., 2002). Yield monitors show spatial patterns of the distribution of grain yield within a field. Spatial

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variability of crop yield can be stable over time or vary of several degrees from year to year (Pierce and Nowak, 1999; Lawes and Roberston, in press). Yield maps need to be analysed and interpreted for managing the observed variability, otherwise they are not useful. Understanding the N_{opt} application requires long-term studies because it is affected by temporal and spatial interactions of soil-plant-atmosphere system. Although spatial maps of soil and crop properties are easy to derive with the modern tools (Basso et al., 2010a; Zhang et al., 2010), temporal variability is still not receiving enough attention (McBratney et al., 2005).

Crop simulation models can be used to simulate long-term effects of water and N and their temporal interactions on daily crop growth and development rates through the growing season (Batchelor et al., 2002). Such models have been extensively tested and applied under a wide range of environmental conditions (Singh, 1985; Carberry et al., 1989; Jagtap et al., 1993; Kiniry et al., 1997; Garrison et al., 1999; Miao et al., 2006; Basso et al., 2007, 2009; Senthilkumar and Aruna Geetha, 2009; Basso et al., 2010b). However, crop simulation models cannot simulate every position in the field because of the costs associated with gathering data and the availability of detailed inputs. Paz et al. (1999) divided the field into a grid in which the model was run, while Basso et al. (2001) divided the field into few management zones delineated from a remotely sensed index of similar crop response and executed the model in each of these zones. An attempt of dividing the field into spatially and temporally stable zones is described in Basso et al. (2007) and Basso et al. (2009), where the combination of GIS tools, remotely sensed data, and crop models was used to identify spatially and temporally stable zones.

Soil water availability is another important parameter to consider when making decisions about the N_{opt} application rates. Soil water can be highly variable within a field because of variation in rainfall, topography, and soil properties (Batchelor et al., 2002) and it affects the amount of crop N uptake during the growing season. For example, the demand for N by wheat crops growing in rainfed environments is generally high in late winter and spring when the crop is growing rapidly. In such cases it is difficult to match crop demand with soil supply (Angus, 2001). Asseng et al. (2001) analysed the influence of N management practices on wheat crops on areas with different soil available water using long-term simulation modelling. They found that nitrogen use efficiency (NUE) varied across the different zones as a function of soil water-holding capacity, N management, and growing season rainfall. The quantification of the variation of NUE over time would have been difficult to estimate from field experiments alone because crop simulation models quantified crop response to water and N stresses over different climatic scenarios of a rainfed environment (Asseng et al., 2001). In southern Italy, split application is the common fertilization practice among wheat producers. Farmers typically apply about 30% of N at planting and the remaining at DC 30–33 (Stem elongation; Zadoks et al., 1974) regardless of the spatial and temporal variability of fields and the level of plant available soil water content at the time of the second fertilizer application.

The use of a crop models to simulate the spatial and temporal distribution of soil water content can add valuable information for choosing N_{opt} to apply for the second N application. In this study we present a procedure for the selection of N_{opt} fertilizer rates to be applied spatially on previously identified management zones using the output of a long term simulation and different levels of plant available soil water at the time of the second N application.

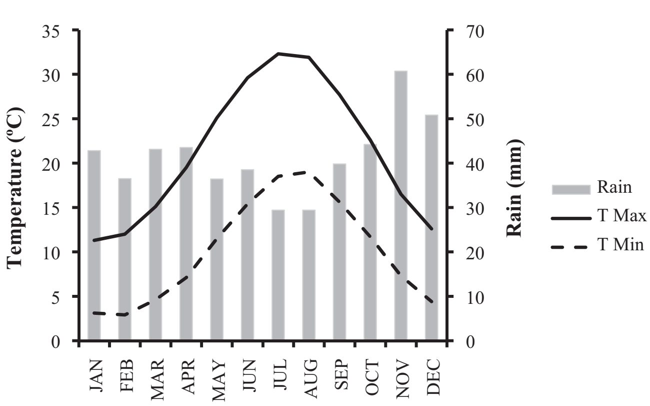

Fig. 1. Monthly averages maximum and minimum temperatures (bars) and rainfall (solid line) for St. Agata delle Tremiti (FG, Italy) for the 56 years used for the simulation.

2. Materials and methods

2.1. Site description

The study was carried out on a 10 ha field with rolling landscape, located in the S. Agata delle Tremiti, Serracapriola (FG) (41°53′46″N, 15°13′53″E; 58 m a.s.l.), Foggia – Italy, during 7 crop seasons of wheat monoculture (from 2001/2002 to 2008/2009). The field was divided into 3 management zones using the 7 years of measured data; details about how those zones were derived are described in by Basso et al. (2009), and they are summarized as follows: High yielding zone (HYZ); silty loam soil, 1.3% organic carbon (OC), 150 mm m^{-1} of potential extractable soil water (PESW) defined as the difference between drained upper limit and lower limit, thus the amount of water that can potentially by used by roots; medium yielding zone (MYZ): sandy loam soil, 1.2% OC, and 130 mm m^{-1} PESW; low yielding zone (LYZ): coarse and stony soil, shallow (60 cm) and 60 mm of PESW.

The climate of the area is characterized by an average annual rainfall of about 400 mm. The annual average maximum temperature is 21 °C, with a minimum of 10 °C (Fig. 1). The sampling scheme was a 25 m × 25 m grid. There were 25 sampling points identified using of a DGPS (Trimble AgGPS 114). The points were located at the nodes of the grid and measurements were taken on the point of sampling at three different distances from the node (1, 3 and 5 m). A Digital Elevation Model (DEM) was obtained using a DGPS with sub meter accuracy. Soil electrical resistivity measurements, which are a measure of the ability of the soil to limit the transfer of electrical current, were carried after the wheat was harvested using the automatic resistivity profiling, a multi-probes system mounted behind a four-wheeler motorbike. A spatial map of the soil electrical conductivity is provided in Fig. 2a.

2.2. Agronomic management

The crop planted was durum wheat (*Triticum Durum*, Desf.) cultivar 'Quadrato' for the first 3 years, then 'Ciccio' and 'Simeto' for the other years. For both seasons the seedbed was prepared in September with a plough at a depth of 30 cm. The sowing was in December at a depth of 5 cm with 17 cm between rows. Fertilization consisted in two N split-applications, one at sowing with 25 kg N ha^{-1} as diammonium phosphate banded near the surface, and at the end of tillering with 65 kg N ha^{-1} as urea broadcast. Weed control was accomplished using RoundUp (Glifosate) and Topik + Sound (2.4D+ CLODIFOP + Metosulan) for both years. The crop was harvested each year around the first 10 days of June.

2.3. Soil sampling

The soil samples were taken in November 2001 prior to planting to determine the soil properties to use as input for the simulation model. Four depths were sampled in increments of 15 cm

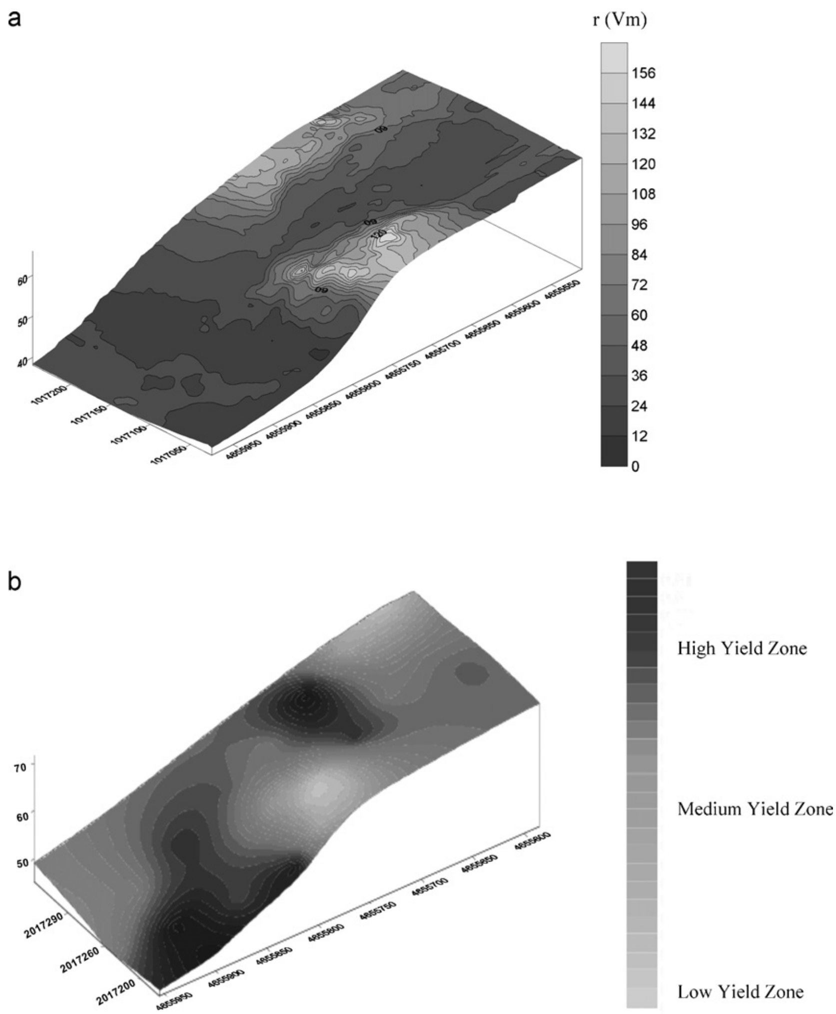

Fig. 2. (a and b) Spatial map of the electromagnetic resistivity (a); spatial yield map of the three management zones (b). Adapted from Basso et al. (2009).

up to a total depth of 90 cm. Soil texture was determined using the hydrometer method (Klute and Dirkens, 1986), OC was measured using the Walkley–Black method (Walkley and Black, 1934), total N was determined using Kjedahl method, K exchangeable, cation exchange capacity (CEC) and P exchangeable were determined with the Olsen method. Soil water content was measured using the gravimetric method every three weeks for the sampling was in 20 cm increments to a total depth of 60 cm (where possible). The sampling points located at the top of the hill in the LYZ did not allow reaching the depth of 60 cm, therefore the total depth of those sampling points reached a maximum of 40 cm. Below 40 cm there is a hard layer of compacted soil and rock making sampling and likely restricting root growth.

2.4. Yield monitoring

Yield data were recorded by using a New Holland TX 64 combine equipped with a yield monitor system (grain mass flow and moisture sensors). Site coordinates for each yield measurement were determined with a differentially-corrected (OmniSTAR Signal) Trimble 132 receiver. The SMS software version 3.0^{TM} (AgLeader Tecnology, Inc.) was used to read the yield data (expressed at 14% dry matter). Yield data semivariograms were created using GS+ software version 5.3^{TM} (Gamma Design Software, 1999). A spatial map of grain yield for the three management zones is provided in Fig. 2b.

2.5. Crop model description

Simulation runs were performed using the SALUS model for wheat (Basso et al., 2006; Senthilkumar et al., 2009; Basso et al., 2010b). The process-oriented model simulates plant growth and development responses to environmental conditions (soil and weather), using genotype and several management strategies.

The weather data required for the model includes daily values of incoming solar radiation (MJ m^{-2} day^{-1}), maximum and minimum temperature (°C) and rainfall (mm). The measured weather was provided by the meteorological station sited near the experimental field. Soil input data (sand, silt, and clay content, bulk density, organic carbon) were determined after collecting soil samples at the selected 25 locations. Soil water limits, such as saturation (SAT), defined as the water content of the soil when 92% of the total porosity is occupied by water (8% assumed to be occupied by entrapped air), drain upper limit (DUL) defined as the water content of the soil when drainage by gravity becomes negligible, and lower limit (LL) – defined as the soil water content when plant roots cease to extract water. The difference between DUL and LL is defined as the plant extractable soil water, although water held above DUL while draining is also available for plant use. DUL and LL were estimated from soil texture, bulk density and, where present, stone content using the procedure of Ritchie et al. (1999). The soil water limits used for the simulation varied spatially using site-specific input according to the observed data of soil texture, soil depth, and coarse fraction.

Model performance was evaluated using the root mean square error (RMSE). Simulated yields were compared with measured yield for the study site. Additional testing of the model was carried by out by Basso et al. (2010a, 2010b) using long-term yield data collected at variety trials experiments of the CRA-Cereal Institute since 1976. The CRA experimental fields are located 60 km south of the field study and soil and weather inputs data were made available by researchers at the CRA (Basso et al., 2009).

2.6. Procedure for selecting optimal N fertilizer rates

Seven nitrogen (N) fertilizer rates (0, 30, 60, 90, 120, 150, and 180 kg N ha^{-1}) were selected to simulate the impact of N fertilizer on yield, N leaching, and net economic return for 56 years of available weather record. The selected N rates were simulated for the previously identified management zones (Basso et al., 2009). The spatial and temporal variability of yield, nitrate leaching, and economic return was assessed using the simulated cumulative probability analysis for each of the three zones. The N fertilizer rate selected from the seven simulations for each of the zones was based on the yield response to N, amount of N leaching, and marginal net return (MNR). The MNR was calculated with the following equation:

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

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_x 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 production of wheat (e.g., tillage, planting, weed control, fertilization and harvesting). The N fertilizer rates were simulated as a split application in accordance to farmers' management practices of the area. The MNR is calculated at the time of second N application, taking into account the cost of the N applied before sowing and the fixed costs. The Common Agricultural Policy (CAP) subsidies for farmers were not considered in this analysis.

3. Results

The soil electrical resistivity map is shown in Fig. 2a with low values of resistivity in the lower portion of the field and higher values in the mid-right part of the field. Grain yield is higher on the lower portion of the field and lower in the mid-right part of the field (Fig. 2b). High electrical resistivity values correspond to a greater resistance of the soil in transmitting the electrical signal due to higher presence of air or stones. The mid-right portion of the field is characterized by a shallow soil profile with a large presence of stones. On the other hand where values of resistivity are lower indicates the presence of a continuous soil medium with higher soil water holding capacity.

The measured and simulated wheat yield for 7 years on the study site and 33 years on the CRA station are shown in Fig. 3. Overall, there is a good agreement between measured and simulated grain yield with a slight over estimation for the HYZ and MYZ and under-estimation in the LYZ. The RMSE between measured and simulated yield was 452 kg ha^{-1} for the whole field. In the HYZ the RMSE was 390 kg ha^{-1}, while in the MYZ and LYZ was 280 and 620 kg ha^{-1}, respectively (Fig. 3a). The validation of measured and simulated yield for the 33 years is shown in Fig. 3b. The RMSE was 320 kg ha^{-1} demonstrating the general reliability of the simulation for this study

Simulated grain yield and N leaching using the 56 years weather data are given in Tables 1 and 2. The high yield zone (HYZ) had higher average, maximum and minimum yields with yield increasing from a minimum of 2092 kg ha^{-1} for the 0N to a maximum of

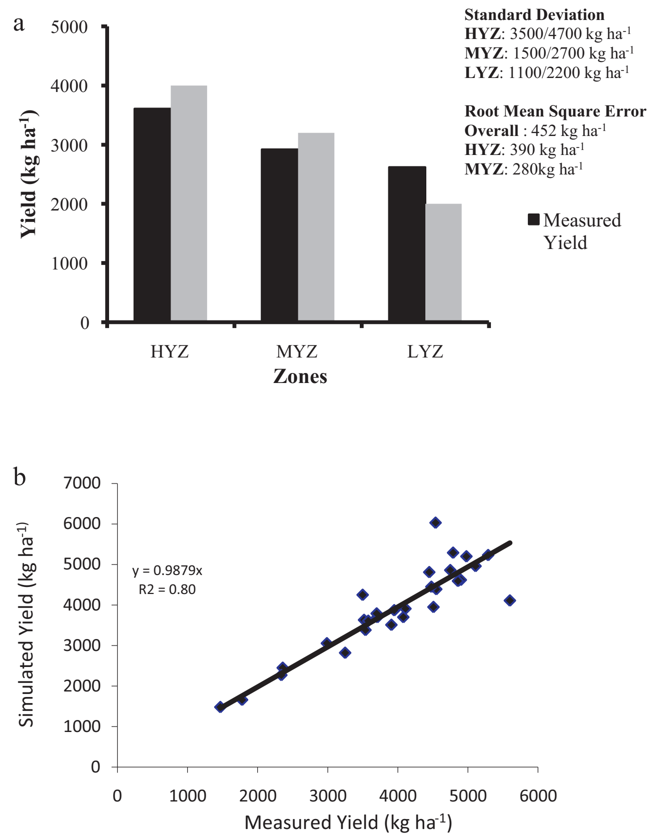

Fig. 3. (a and b) SALUS validation for the study site using 12 years of weather data (a); 33 years of the weather and observed yield data from the CRA wheat experimental station (b).

3794 kg ha^{-1} for the 120N, and then decreasing by 12 and 6 kg ha^{-1} for the 150 and 180N, respectively (Table 1). Yield values of the medium yield zone (MYZ) were slightly lower than the HYZ. Yield for 0N in the MYZ was 741 kg ha^{-1} lower than the yield in HYZ. Grain yield increased to a maximum of 3692 kg ha^{-1} for 180N. In the low yield zone (LYZ) grain yield values ranged between 1392 and 1781 kg ha^{-1} and the latter value did not change significantly between 60N and 180N (Table 1). On the other hand, N leaching values increased from 0N to 180N for the three zones. The N leaching for the 0N was similar for all the three zones with an average value of 0.51 kg N ha^{-1}. In the HYZ leaching increased from 0.51 kg N ha^{-1} for the 0N to 26.82 kg N ha^{-1} for the 180N, reaching a maximum value of leaching of 67 kg N ha^{-1} at 180N (Table 2). In the MYZ the N leaching values were higher than the ones simulated for the HYZ, reaching a maximum of 57.13 kg N ha^{-1}for the 180N with a high value of 118 kg N ha^{-1} for the same N scenario. N leaching values for the LYZ were higher than the HYZ but lower than the values of the MYZ with the high N leaching simulated for the 180N with 52.50 kg N ha^{-1} (Table 2). The long-term simulation of plant available soil water (PASW) at spring sidedressing (second time of N application) showed a significant difference among the three zones. The LYZ showed a PASW ranging between 10 and 42 mm, the MYZ between 13 and 119 mm and the HYZ between 23 and 135 mm (Fig. 4).

Integrating the information of N leaching, grain yield and MNRit was possible to tactically choose the best N rate for each zone using the simulated PASW at the time of sidedressing. The MNR calculated from Eq. (1) at the different N rates and at different PESW at the time of the second application are shown in Table 3 for the HYZ. When the PESW was lower or equal 34 mm the MNR was negative for all the N scenarios, but the range of variation between the

Table 1
Simulated average (AVERAGE), maximum (MAX), minimum (MIN) grain yield (kg ha^{-1}) and standard deviation (SD) using 56 years historical weather data on the high yield zone (HYZ), medium yield zone (MYZ) and low yield zone (LYZ).

	Grain yield (kg ha^{-1}) 0N	30N	60N	90N	120N	150N	180N
HYZ							
AVERAGE	2092	2723	3541	3546	3794	3782	3788
MAX	4037	4921	5234	5590	5693	5520	5520
MIN	916	1414	1600	1589	1600	1600	1600
SD	579.91	684.62	1013.75	1034.84	1197.30	1170.98	1172.93
MYZ							
AVERAGE	1351	2707	3157	3496	3588	3672	3692
MAX	2314	4034	4890	5123	5234	5312	5290
MIN	500	1414	1589	1589	1589	1589	1589
SD	439.33	641.76	810.55	987.67	1015.03	1081.01	1074.93
LYZ							
AVERAGE	1392	1669	1749	1772	1778	1780	1781
MAX	3241	3241	3241	3380	3429	3429	3429
MIN	374	674	674	674	674	674	674
SD	571.19	613.31	665.01	689.17	693.33	693.77	693.72

Table 2
Simulated annual average (AVERAGE), maximum (MAX), minimum (MIN) N leaching (kg N ha^{-1}) and standard deviation (SD) using 56 years historical weather data on the high yield zone (HYZ), medium yield zone (MYZ) and low yield zone (LYZ).

	N leaching (kg N ha^{-1}) 0N	30N	60N	90N	120N	150N	180N
HYZ							
AVERAGE	0.51	21.63	22.63	24.20	25.13	26.02	26.82
MAX	1	50	53	57	60	63	67
MIN	0.02	0	0	0	0	0	0
SD	0.29	12.83	13.58	14.80	15.73	16.69	17.52
MYZ							
AVERAGE	0.51	53.07	53.82	54.95	55.73	56.46	57.13
MAX	1	99	101	105	110	114	118
MIN	0.018	2	2	2	2	2	2
SD	0.29	26.39	26.86	27.73	28.39	28.98	29.47
LYZ							
AVERAGE	0.51	42.86	44.59	47.38	49.23	50.93	52.50
MAX	1	82	87	95	101	107	113
MIN	0.02	0	0	0	0	0	0
SD	0.29	25.33	26.22	28.17	29.69	31.13	32.49

maximum and the minimum values indicated that 60N was the rate that had the highest positive and the lowest negative MNR (Table 4). Thus at sidedressing, 42 kg N ha^{-1} (the remaining 70%) in the HYZ if the PESW was less or equal to 34 mm. When the PASW was between 34 and 50 mm, 60N would be the desirable N rate to apply because the return would be higher than other possibilities (Table 5). When the PASW was higher or equal to 50 mm the highest MNR was obtained with 120N. Table 5 shows the MNR for the MYZ at three different PASW. When PASW was lower or equal to 20 mm it was best not to apply any N fertilization, while when it is between 20 and 50 mm the appropriate N rate will be 90N because in the worst case scenario it will still produce a net revenue of 69.9 € ha^{-1} (Table 5). Higher N fertilization will increase the MNR but in the worst case the net revenue will be lower than the 90N and their N leaching values are still higher than the 90N as shown in Fig. 5. For the LYZ, fertilizer should be applied when the PASW is higher or equal to 34 mm and the preferred N rate would be 60N as showed in Table 5.

The results of the tactical N decisions are shown in Fig. 5 where the MNR is presented for the three zones as influenced by PASW.

Table 3
Simulated annual average (AVERAGE), maximum (MAX), minimum (MIN) marginal net return (MNR) and standard deviation (SD) using 56 years historical weather data on the high yield zone (HYZ) at three different plant available soil water (PASW).

HYZ	PASW (mm)	Fertilization scenario 0N	30N	60N	90N	120N	150N	180N
AVERAGE MNR (€ ha^{-1})	≤34	−128.3	−38.2	−3.4	−18.1	−27.4	−39.4	−51.4
MAX MNR (€ ha^{-1})		−75.6	15.9	73.8	60.8	49.8	37.8	25.8
MIN MNR (€ ha^{-1})		−211.8	−94.4	−58.0	−72.9	−82.0	−94.0	−106.0
SD (€ ha^{-1})		45.8	37.8	47.7	50.6	47.7	47.7	47.7
AVERAGE MNR (€ ha^{-1})	34	−18.5	113.6	229.8	208.7	218.0	206.0	194.0
MAX MNR (€ ha^{-1})	to	18.8	172.1	329.1	301.8	355.6	343.6	331.6
MIN MNR (€ ha^{-1})	<50	−69.9	23.2	87.3	69.9	66.7	54.7	42.7
SD (€ ha^{-1})		29.6	49.2	84.9	75.5	97.6	97.6	97.6
AVERAGE MNR (€ ha^{-1})	≥50	164.4	332.6	586.1	579.4	655.3	638.8	628.9
MAX MNR (€ ha^{-1})		599.6	817.5	886.8	967.4	982.2	925.2	913.2
MIN MNR (€ ha^{-1})		19.8	174.0	332.8	303.9	361.0	349.0	337.0
SD (€ ha^{-1})		126.6	140.4	181.0	185.0	213.2	201.8	201.2

Table 4
Simulated average (AVERAGE), maximum (MAX), minimum (MIN) marginal net return (MNR) and standard deviation (SD) using 56 years historical weather data on the medium yield zone (MYZ) at three different plant available soil water (PASW) at time of sidedressing.

MYZ	PASW (mm)	Fertilization scenario						
		0N	30N	60N	90N	120N	150N	180N
AVERAGE MNR (€ ha^{-1})	≤20	−282.8	−38.2	−14.2	−18.1	−30.1	−42.1	−54.1
MAX MNR (€ ha^{-1})		−239.7	15.9	26.5	60.8	48.8	36.8	24.8
MIN MNR (€ ha^{-1})		−320.0	−94.4	−60.9	−72.9	−84.9	−96.9	−108.9
SD (€ ha^{-1})		27.9	37.8	38.0	50.6	50.6	50.6	50.6
AVERAGE MNR (€ ha^{-1})	0 to <50	−148.2	166.9	252.3	305.1	318.2	317.3	312.0
MAX MNR (€ ha^{-1})		−82.1	244.7	353.1	473.4	466.9	475.7	497.7
MIN MNR (€ ha^{-1})		−237.1	23.2	72.8	69.9	64.6	52.6	40.6
SD (€ ha^{-1})		49.7	60.5	73.8	107.5	117.9	125.2	130.9
AVERAGE MNR (€ ha^{-1})	≥50	7.3	403.0	552.2	676.2	693.3	721.1	714.3
MAX MNR (€ ha^{-1})		151.6	586.8	797.4	846.0	862.8	871.1	853.4
MIN MNR (€ ha^{-1})		−76.9	257.4	378.8	476.0	480.6	478.5	565.8
SD (€ ha^{-1})		74.4	97.7	116.9	115.9	107.9	118.3	95.4

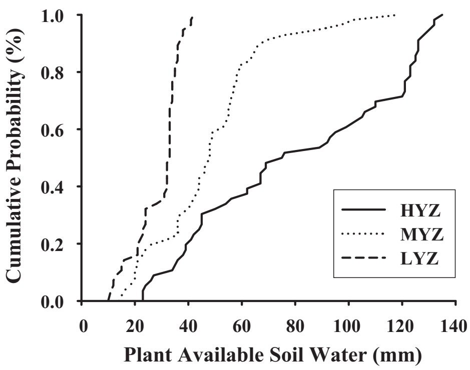

Fig. 4. Cumulative probability (%) of the plant available soil water (PASW, mm) at the second time of N application, for the HYZ (high yield zone, solid line), MYZ (medium yield zone, dotted line), and LYZ (low yield zone, dashed line).

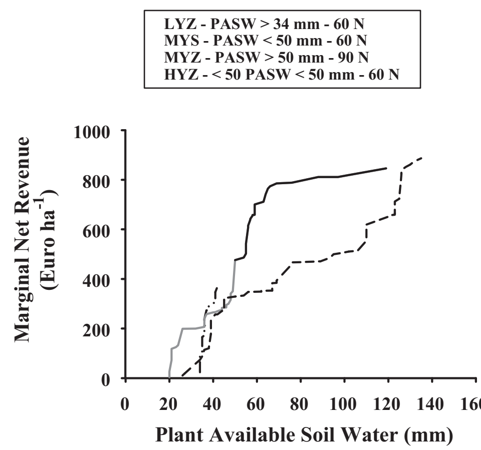

Fig. 5. Marginal net return (MNR, € ha^{-1}) as a function of the plant available soil water (PASW, mm) for the three management zones. The cut-off value of 50 mm PASW is to show the different N rates to apply for each area as a function of the MRN and the N leaching.

A threshold value of 50 mm was chosen to demonstrate the differences in N application rates when the soil water was above or below the threshold of 50 mm. For the HYZ the best N rate was 60 kg N ha^{-1}, while the N fertilizer rate to apply when PASW was lower than 50 mm was 60 kg N ha^{-1} and when it was higher than 50 mm, the appropriate rate was 90 kg N ha^{-1}. For the LYZ N application is appropriate only when PASW is higher than 34 mm with a fertilizer rate of 60 kg N ha^{-1} (Fig. 5).

Fig. 6 show the MNR vs. N leaching for the three zones and for the six N fertilization scenarios, the 0N was excluded for the computation. The MYZ had higher simulated N leaching at each N application, its MNR increased from −20 € ha^{-1} for 30N to 242 € ha^{-1} for 90N, then it decreased for the other N rates while the N leaching increased. The MNR for the HYZ reached a plateau between 120 and 150N but its difference in revenue compared with 90N is only 14 € ha^{-1} while the difference in N leaching is 0.8 kg N ha^{-1} between 90N and 120N and 3 kg N ha^{-1} between 90N and 150N. The LYZ had positive revenue only for the 60N and 90N with higher net revenue of 28 € ha^{-1} for 60N, all the other N simulated scenarios resulted in negative MNR. At higher N rates there was always higher N leaching (Fig. 5).

4. Discussion

The use of a crop simulation model on each of three separate field zones where soil properties were variable proved valuable in providing decision support for the selection of the optimal N rate to apply at sidedressing on rainfed wheat grown in the Mediterranean

Table 5
Simulated average (AVERAGE), maximum (MAX), minimum (MIN) marginal net return (MNR) and standard deviation (SD) using 56 years historical weather data on the low yield zone (LYZ) at three different plant available soil water (PASW).

LYZ	PASW (mm)	Fertilization scenario						
		0N	30N	60N	90N	120N	150N	180N
AVERAGE MNR (€ ha^{-1})	≤34	−162.1	−115.9	−118.2	−128.4	−139.6	−151.1	−162.6
MAX MNR (€ ha^{-1})		−63.1	9.4	17.7	5.7	−6.3	−18.3	−30.3
MIN MNR (€ ha^{-1})		−352.8	−286.8	−298.8	−310.8	−322.8	−334.8	−346.8
SD (€ ha^{-1})		77.6	89.1	88.8	89.6	90.0	90.5	90.9
AVERAGE MNR (€ ha^{-1})	≥34	68.6	157.4	189.4	192.3	183.2	171.7	159.7
MAX MNR (€ ha^{-1})		392.7	380.7	368.7	392.8	393.5	381.5	369.5
MIN MNR (€ ha^{-1})		−57.9	26.0	23.9	11.9	−0.1	−12.1	−24.1
SD (€ ha^{-1})		141.4	106.5	107.7	111.9	112.4	112.3	112.3

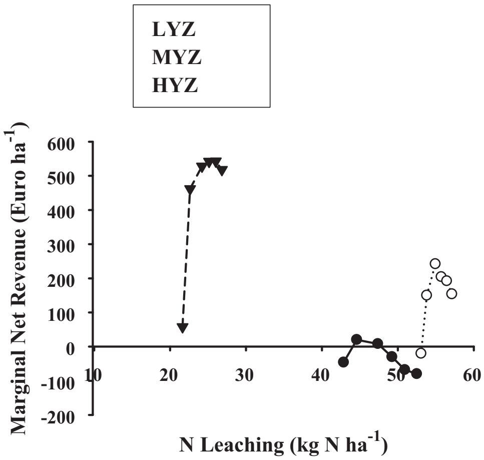

Fig. 6. Marginal net return (MNR, € ha^{-1}) and N leaching (kg N ha^{-1}) as function of N rates for the high yield zone (HYZ, solid line, closed dots), medium yield zone (MYZ, dotted line, open dots), and low yield zone (LYZ, dashed line, closed triangles). Each symbol represents the N rate starting from 30 kg N ha^{-1} until the last N treatment of 180 kg N ha^{-1}.

climate of Southern Italy. Farmers have to decide the amount of N to apply without having any knowledge of the future weather, and crop simulation models can help in making decisions about the preferred rate to optimize profits. The model runs with historical weather data over a long time to represent the diversity of weather that can be encountered for the prescription of N fertilizer rate. Overall, our results agree with the findings of Mamo et al. (2003) in which the economic optimum N rate was lower than the uniform N rate in each of the zone.

The differences in soil type and soil water holding capacity between the three zones affected the amount of N to apply at side-dressing for each zone. These two factors affected spatial variation of measured and simulated yield for the three zones as discussed in Basso et al. (2009). In most cases, spatial variability is not taken into account by farmers who fertilize the fields with a uniform N rate near 90 kg N ha^{-1}. Our results suggest that it is neither economically nor environmentally sustainable to use a fixed N rate for the whole field when considering economic and environmental constraints. The HYZ silty loam soil was more responsive to the N increases because of their higher PASW (Fig. 4). In the HYZ the differences between the maximum and minimum yield obtained for each of the N fertilization amount is significant. The minimum yield shown in Table 1 for the HYZ is closer to the minimum yield that could be obtained in the LYZ (about 600 kg ha^{-1}). The maximum yield, on the other hand, is about 2000 kg ha^{-1} higher in the HYZ. Under low rainfall years grain yield of crop growing on HYZ will be reduced because of the effects of N on the pattern of water use by a crop. Too much nitrogen can result in crops that are too vigorous in the vegetative stage and use too much water before flowering, causing premature crop senescence and low grain yield (Van Herwaarden et al., 1998; Angus and van Herwaarden, 2001; Passioura, 2006). In the LYZ when PASW below 34 mm of PASW, no N fertilizer (in contrast to what most farmers are doing) should be used since the risks of not obtaining any net capital return are high. They have shallow soil and low PASW and produce less in years with high rainfall and more in years with low rainfall as demonstrated by the minimum yield values in Table 1 and by Basso et al. (2009). Asseng et al. (2001) found similar results on a wheat growing region in a dryland area in Australia. In the LYZ there is less N leaching than the MYZ because of its soil properties and position in the landscape where surface runoff is greater than drainage. Moreover, the shallow and coarser texture soil with high percentage of stones has a low mineralization rate due the lower soil organic matter content. In the MYZ, the coarser texture along with greater drainage and higher N mineralization rates than the LYZ, had greater nitrate leaching. The problem of applying a uniform N rate can be avoided by tactical application of nitrogen fertilizer at sidedressing time, once it is known how much water crops are likely to have available for grain filling.

The results shown in this study underline the importance of integrating knowledge of the economic constraints to productivity for a given nitrogen rate and to understand the mechanisms beneath the environmental consequence of nitrogen fertilization on nitrate leaching while maintaining profitable crop yield over space and time.

5. Conclusions

This study demonstrates the possibility of using a crop simulation model to evaluate the effects of unknown weather conditions on PASW in spatially variable fields to help decide the optimal N rate to apply at DC 30–33. The inadequacy of the uniform N fertilizer application is shown by the negative MNR obtained in the LYZ when PASW <34 mm and in the HYZ where a N rate of 90 kg N ha^{-1} is enough to obtain a good MNR and a low N leaching. The combined strategic and tactical approach presented in this paper demonstrated the value of such procedure in identifying the optimal N fertilizer rate to be applied spatially Even if rainfall were to be used instead of PESW for deciding on N at sidedressing, it would not be as valuable as the simulation because of known differences in PESW in the spatially variable field. Moreover the approach used takes in consideration not only the economic return of a N rate but also the environmental impact aspect by quantify the impact of such rate on nitrate leaching. The end statements about the leaching, perhaps also in the discussion would be valuable.

In conclusion, creating an agricultural system that is economic profitable and environmental sustainable require knowledge in economy, agronomy and ecology. Research should focus on understanding the ecological bases soil-crop-atmosphere interaction, and to assess the trade-off between the profit and the environmental impacts of different management strategies in spatially variable fields.

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