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Developing a tactical nitrogen fertilizer management strategy for sustainable wheat production

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ABSTRACT

Syncronizing plant available water with soil nitrogen (N) remains a critical aspect of agronomic management to enhance crop yield, grain quality, farmers' profit, and environmental sustainability. Their interaction is essential expecially in landscapes characterized by a highly spatial and temporal range of pedoclimatic conditions. To support farmers in making more informed decisions, validate dynamic process based crop simulation models have been successfully used to optimize N fertlization. In this study, we aimed to develop a tactical N fertilizer management strategy to increase profitability, improve grain quality and reduce N losses. The SALUS model was tested against measured durum wheat grain yield and grain quality data collected across independent farmers' fields in Tuscany (Italy). The model was then used to optimize N fertilization under different potential plant extractable soil water (PESW) conditions at the second topdressing N fertilization timing. The model was tested against measurements of grain yield and protein concentration at harvest, as well as phenological stage, biomass, and plant N content during the growing season. Simulations were carried out for 30 years of available weather, using different N rates. The simulations allowed the identification of optimal N rates for each PESW condition and soil type concerning economic and environmental sustainability. Results showed higher yield and higher leaching for the silty clay soil (Quercia; QUE) than for the loamy soil (Arbia; ARB). No major differences were predicted for protein content across soils. Profitability and emissions increased as N rate increased. The N fertilization strategy locally adopted by farmers was also analyzed across different PESW conditions at 2nd topdressing fertilization in comparison to other adopted N management strategies (timing of application and fertilization rates). The model showed that the conventional fertilization strategy does not maximize socio-ecological benefits, but was also the lowest among all the strategies tested. The maximum economic benefit for farmers was reached by applying 90 kg N at 1st and 60 kg N at 2nd topdressing fertilization, both in dry (due to sufficient soil water storage in the soil) and wet years. These results provide valuable insights for developing strategies that balance sustainability, resilience, quality, and profitability in wheat crop production in central Italy.

1. Introduction

Durum wheat (*Triticum turgidum* L. var. durum) is one of the main crops grown in Italy and in Tuscany region (Belaid, 2000; Fabbri et al., 2020; Xynias et al., 2020). Historically, durum wheat producers in central Italy scheduled input applications based on calendar days rather than on weather and phenology information. However, previous studies found that in-season pedoclimatic information can improve economic, environmental, and social outcomes of input management (Hirte et al., 2021; Basso et al., 2011; Beillouin et al., 2018). The economy of farmers is mainly influenced by the increase of grain yield and protein concentration of durum wheat, especially when contracts include a quality premium (Morari et al., 2018). Environment, genotypes, nitrogen (N) fertilization, and N and water availability in the soil are the main factors influencing wheat production and its quality (Gerba et al., 2013). In particular, N fertilization and availability are influenced by

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pedoclimatic condition, whose evaluation is important expecially in the Mediterranean environment characterized by uncertain weather and variable soil conditions. Crops' nitrogen use efficiency (NUE) is mostly dictated by soil water availability, and water dynamic (excess) is the cause for N losses in most soils due to leaching, or water deficits for the inability of the crop to use it, making it susceptible for leaching during the off-growing season. Efficient N management is challenging due to its dynamics in the soil, given that it is easily lost to the environment through leaching or denitrification (Basso and Ritchie, 2005; Fageria and Baligar, 2005; Beman et al., 2005; Ortiz-Monasterio and Raun, 2007; Cavigelli et al., 2012). It is reported that 70% of N fertilizer applied to agricultural soils is not used by crops and is instead lost to the environment as leaching and released into the atmosphere principally as nitrous oxide (N_2O), representing a pollution factor (Subbarao et al., 2017; Basso et al., 2019). The excessive use of N synthetic fertilizers in cereals is one of the main contributors to N_2O and CO_2 emissions from agriculture (Akhtar et al., 2020), as well as NO_3 leaching (Fang et al., 2008).

In Italy, as in most other countries, traditional N fertilization application methods and rates are mainly dictated by economic returns, indicating that the ratio of fertilizer cost to crop price still favors excessive application (Palm et al., 2004). However, European policies and new strategies are being implemented to address the problem (EU, 2020).

Soil-climate interactions and nutrient availability for crops must be analyzed to develop strategies to manage N efficiently. The weather conditions in the days following N application have been considered the main factor influencing yield, protein content, and N losses (Tremblay and Bélec, 2006). As well, Campbell et al. (1995) reported that soils in dry conditions can be vulnerable to substantial N losses, especially if no rainfall occurs shortly after N application (Addiscott and Powlson, 1992). In this context, weather conditions are a critical source of information for N management, but are subject to variability and uncertainty. The implementation of appropriate application rates based on the availability of water for crops, coupled with long-term field, weather, and soil data is essential for reducing losses and optimizing crop production (Basso et al., 2011; Krüger et al., 2013; Brogi et al., 2020; Johnston and Poulton, 2018).

Crop simulation models reproduce yield and nutrient loss outcomes using regional field spatial variability and historical weather data, and can aid to develop optimal management strategies (O'Leary and Connor, 1996; Basso et al., 2010; Dumont et al., 2016; Albarenque et al., 2016). Simulation models have been developed for different cropping systems, combining the simulation of crop productivity and nutrient cycles, and are powerful tools for assessing potential adaptation strategies for better N management (Chenu et al., 2017; Nendel et al., 2014; Sela et al., 2018; McNunn et al., 2019; Liang et al., 2016). While many economic evaluations of optimum N rate have been simulated, quantitative crop production is nearly always the only consideration (Stapper and Harris, 1989; Basso et al., 2011; Zhang et al., 2019). However, in durum wheat production the economically optimal N supply is dictated by the shape of yield-protein relationship and the market premium, which discounts prices based on protein content (Baker et al., 2004).

We posed the following research question: To what extent does yield and grain quality response to N fertilizer rate and time vary given that soil water is dynamic and N uptake may not be available to plants, not for the low N content in the soil but rather for the lack of soil water available to roots and the lack of synchronization between N supply and crop demand?

The objective of this study was to identify the N fertilization strategy (time and application rate) that maximizes economic returns through improved crop yield and grain quality while reducing N losses in Tuscany, Italy. We examined how this optimum changes with different levels of plant extractable soil water at the time of topdressing N fertilization. This is a critical aspect of the paper because yield and grain quality response to N fertilization varies depending on soil water available to the crops. We used the previously validated SALUS model to quantify the conditions that would lead to the maximum N response and economic return.

We used a 4-year experimental dataset of 29 commercial durum wheat fields in Tuscany, Italy, to develop cultivar parameters for durum wheat for the wheat model in SALUS (Basso and Ritchie, 2005) and tested the model to demonstrate the scalability of the approach we used.

2. Materials and methods

2.1. Description of the area of study

The area is characterized by a typical Mediterranean climate, with a mean annual daily temperature of about 13.6 °C and an average annual rainfall of about 715 mm, mostly distributed during winter and autumn (Orlandini et al., 2011). Daily temperature and rainfall data during the study period are reported in Fig. 1.

Durum wheat (*Triticum durum*, Desf.) production data were obtained from a previous study (Fabbri et al., 2020) carried out during 4 cropping seasons (from 2009/2010–2012/2013) in Val D'Orcia, in the province of Siena (Tuscany, Italy). According to Gardin and Vinci (2016), soils are mainly characterized by two distinct types: "Quercia" (QUE) and "Arbia" (ARB). QUE soils (Vertic Haplustepts, fine, mixed, mesic; Soil Taxonomy, 2003) are generally deep, silty clay, strongly calcareous. ARB soils (Fluventic Haplustepts, fine-silty, mixed, mesic; Soil Taxonomy, 2003) are calcareous, deep and loamy soils, originated from alluvial deposits. The soils' physical and chemical characteristics are reported in Table 1.

2.2. Agronomic management of the experimental fields

We analyzed datasets comprising 6, 10, 6 and 5 fields for the 2009/2010, 2010/2011, and 2011/2012, 2012/2013 growing seasons, respectively. Each commercial field was sown with two durum wheat varieties (Miradoux and Claudio). The fields were tilled in September with a conventional moldboard plow to a depth of 30 cm. During the 4 growing seasons, the sowing time windows ranged from mid-October to mid-December, and the harvest from the end of June to mid-July, respectively. An inter-row spacing of 0.13 m and a seeding density of 600 seed m^{-2} were used. Fertilization consisted of different N application rates ranging from 90 to 170 kg N ha^{1} , split into three applications, sowing, first and second topdressing fertilization, and using different N fertilizers. For all fields, phosphorus was broadcasted and incorporated into the soil before seeding as triple superphosphate at the rate of 92 kg ha^{-1} (P_2O_5). During the growth cycle, plants were randomly sampled (0.4 m^2) in three replications at different phenological stages (BBCH-scale) to monitor the dry matter weight (DM; Mg ha^{-1}) and the nitrogen concentration (Nc; g kg^{-1}) of the aboveground biomass. The DM was measured after oven-drying the samples at 105 °C until reaching a constant weight according to Ceotto et al. (2013). The N content of the samples was determined using a CHNS analyzer (CHN-S Flash E1112, Thermo-Finnigan LLC, San Jose, CA, USA) (Soofizada et al., 2022). At harvest, wheat samples were collected in three replications to determine the aboveground biomass (DM; Mg ha^{-1}) and the grain yield (Yg; Mg ha^{-1}). FOSS Infratec™ 1241 Grain Analyzer (Tecator, Hoganas, Sweden) was used to measure the grain protein (Gp; %) concentration at harvest.

2.3. Crop simulation model and calibration

The SALUS crop model (Basso and Ritchie, 2005; Basso et al., 2006) was used to simulate durum wheat production. The model is designed to dynamically simulate different crop, soil, water, and nutrient conditions, under various management practices, for multi-year periods (Pezzuolo et al., 2014). Simulations of different management practices (planting dates, irrigation, fertilization, etc.) can be run simultaneously. The model simulates daily water balance, soil organic matter, N and

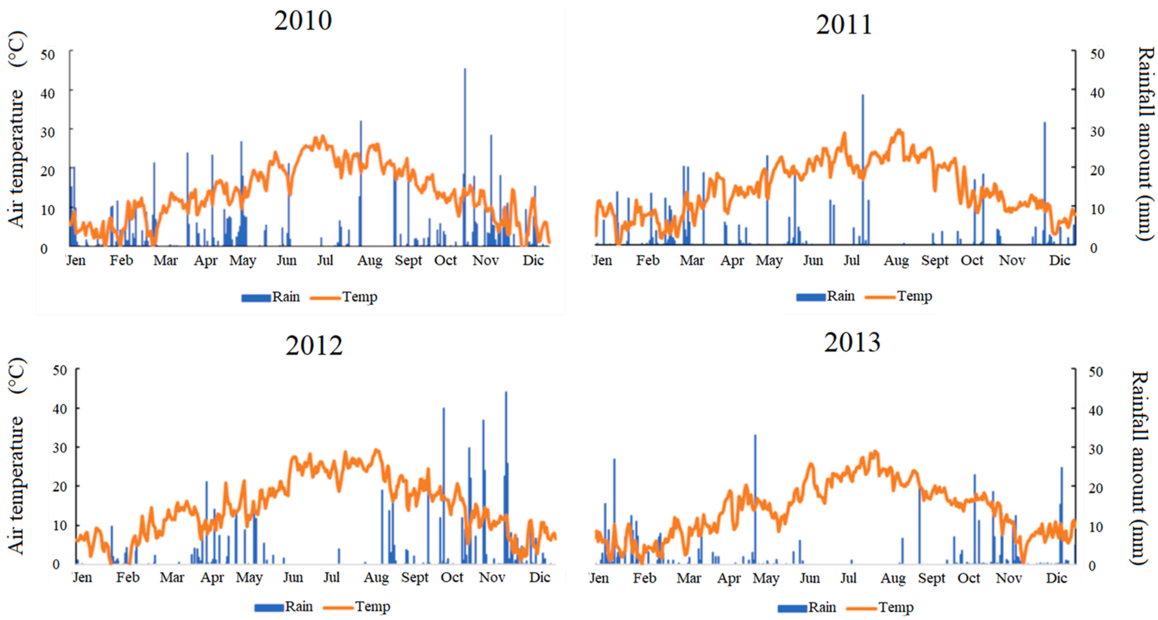

Fig. 1. Average daily air temperature and rainfall amount at the study site during the study period (2010–2013).

Table 1
Main chemical and physical properties for type of soil. QUE refers to soil Quercia and ARB refers to soil Arbia.

Soil	Layer (cm)	LL*	DUL	SAT	BD	Silt (%)	Clay (%)	CaCo	OC	SHF	SWCN	TotN	ph
QUE	20	0.17	0.31	0.47	1.3	41.7	41.8	127	1.62	1	0.399	0.09	7.9
	45	0.16	0.24	0.43	1.4	56.1	42.3	137	1.22	0.5	0.399	0.04	7.8
	80	0.12	0.19	0.43	1.5	50.5	42.5	137	0.58	0.3	0.224	0.01	7.9
	140	0.13	0.2	0.4	1.6	50.9	41.4	150	0.41	0.1	0.262	0.01	7.9
ARB	40	0.1	0.3	0.5	1.2	61	21.7	152	0.9	0.5	1.4	0.1	7.8
	65	0.1	0.3	0.5	1.2	61	21.7	152	0.9	0.5	1.4	0.1	7.8
	95	0.1	0.3	0.5	1.3	63	18.7	184	0.4	0.3	0.1	0	7.8
	115	0.2	0.3	0.5	1.3	50.9	41.4	150	0.4	0.1	0.6	0	7.8

*LL refers to lower limit (cm^3/cm^3); DUL refers to drain upper limit (cm^3/cm^3); SAT refers to saturation (cm^3/cm^3); BD refers to bulk density (Mg/m^3); OC refers to organic carbon (%); SHF refers to soil hospitality factor (cm/h); SWCN refers to hydraulic conductivity at saturation (cm h^{-1}); TotN refers to total nitrogen content (%).

phosphorus balances, heat balance, plant growth, and development (Basso et al., 2010; Liu and Basso, 2020). The meteorological data used by the model include daily values of incoming solar radiation (MJ m^{-2}), maximum and minimum temperature (°C), and rainfall (mm). In the present study, the meteorological data were obtained from a meteorological station near the experimental fields (SIR, 2019). Soil input data (sand, silt, and clay content, bulk density, organic carbon) were obtained from the Tuscany soil map (Gardin and Vinci, 2016). The model considers three soil water limits, namely saturation (SAT), drain upper limit (DUL), and lower limit (LL). DUL and LL were estimated from soil texture, bulk density, and, where present, stone content using the procedure of Ritchie et al. (1999) and Basso et al. (2011). Model calibration was performed using grain yield (Yg), dry matter (DM), and grain protein (Gp) data from 2009/2010–2012/2013 at harvesting and crop DM and nitrogen content (Nc) data during the crop cycle. SALUS-wheat uses sets of coefficients to define the different cultivar phenological characteristics, crop growth, and yield in the time domain (Table 2). The model was calibrated to simulate both durum wheat cultivars used in this experiment. The cultivar coefficients for phenological development, grain production, and N concentration were based on previous SALUS-wheat model calibrations (Basso et al., 2011; Liu and Basso; , 2020) adapted to reflect local ecophysiological traits using as guide expert knowledge and fit to the experimental data.

Goodness of fit was quantified by three model evaluation statistics: percent bias (PBIAS; Eq. 1), the root mean square error (RRMSE; Eq. 2) and the ratio of the root mean square error to the standard deviation of measured data (RSR; Eq. 3). The performance ratings as regard RSR are considered between 0 and 0.50 as "very good", between 0.50 and 0.60 as "good", between 0.60 and 0.70 as "satisfactory" and > 0.70

Table 2
Species and cultivar parameters used in for the calibrated SALUS model.

Crop Parameters	Abbreviations	Units	Value
Base temperature for development	TbaseD	C°	2.5
Radiation use efficiency	RUE	g/MJ	2.55
Days under base temp needed to complete Vernalization	Vcoef	d	25
Lethal temperature (50% pf the plants are killed)	LT50c	°C	-20
Upper limit of photoperiod sensitivity range with respect to the rate of induction	PhHig	Hr	19
Delay in development stage per hour of photoperiod change	DelpH	d/h	14
Development time required for grain fill, from end of ear growth to physiological maturity	Legg	leaf equivalent	12
Daily rate og kernell fill at optimum temperature	krPGR	g kernel/d	0.0004
Phyllochron at 14th day	Phy14	°C-day/leaf	65
Max. N conc in vegetative organs	MxNVg	g/g	0.045
Max. N conc in grain	MxNKr	g/g	0.028
Multiplier for the minimum permissible N concentration in plant with respect to the optimum	MnNMlt	unitless	0.5

"unsatisfactory" (Massetti et al., 2020; Napoli and Orlandini, 2015). RMSE values equal or higher than 1.0 were considered "unsatisfactory", values lower than 0.3 were considered "good", while values around 0.1 were considered "very good" as reported by Fabbri et al. (2020).

$$PBIAS = \frac{\sum_{i=1}^{n}(Yobs - Ysim) \times 100}{\sum_{i=1}^{n} Yobs} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i}^{n}(\mathrm{Yobs} - \mathrm{Ysim})^2}{n}}; \; RRMSE = \mathrm{RMSE} \times \frac{100}{\mathrm{YMobs}} \quad (2)$$

$$RSR = \frac{\sqrt{\Sigma_{i=1}^{n}(Yobs - Ysim)^2}}{\sqrt{\Sigma_{i=1}^{n}(Yobs - YMobs)^2}} \quad (3)$$

where Yobs refers to the observed data, Ysim refers to the simulated data, YMobs refers to the mean of the observed data.

2.4. Procedure for selecting optimal N fertilizer rates

Six nitrogen (N) fertilizer rates (30, 60, 90, 120, 150, and 180 kg N ha^{-1}) were selected to simulate responses in terms of N leaching, yield, and protein content. The results were used to choose the rate that maximizes the economic net return for farmers, using 30 years of meteorological data. A 30-year (1988–2019) daily weather database was used in this study as inputs for the crop model. Data were downloaded from the SIR website (SIR, 2020), using a meteorological station located in Pienza (SI) (N 43° 4' 44.1332", E 11° 40' 44.0666"). The data were recorded at the on-site agro-climatic station, which provided daily maximum and minimum temperatures and rainfall. Solar radiation information for the study zone was derived from the NASA-power database (https://power.larc.nasa.gov) (Stackhouse et al., 2015). The sowing time for wheat was set at 1st November and the harvesting at 10 July. Social return to N application (SnR; € ha^{-1}) was calculated considering the economic advantage from grain sale (varying according to yield and protein content), the cost of fertilizer (FC; € kg^{-1} NH_4NO_3) and the social cost due to N surplus (SocialC; as CO_2 and N_2O eq. kg ha^{-1}).

The SnR was calculated with the following equation (Eq. 5):

$$SnR=(GP \times Yg)-(FC \times rate)-SocialC \quad (5)$$

The CO_2 emission equivalent (kg ha^{-1}) equations are reported in Eq. 6 and N_2O emission equivalent in Eq. 7.

$$ECO_2=CO_2EF*AN \quad (6)$$

$$EN_2O=N_2OEF*AN \quad (7)$$

$$SocialC=(ECO_2*0{\cdot}038+EN_2O*15{\cdot}01) \quad (8)$$

Where, ECO_2 and EN_2O are the emitted carbon dioxide (kg $ha^{-1}y^{-1}$) and the emitted nitrogen oxides (kg $ha^{-1}y^{-1}$), respectively; CO_2EF and N_2OEF are the emission factors for the carbon dioxide (0.2 kg C kg N^{-1}) and nitrogen oxide (0.01 kg N_2O kg N^{-1}) according to the IPCC (2006), respectively; AN refers to the nitrogen fertilizer applied; 0.038 (€ kg^{-1} CO_2) and 15.01 (€ kg^{-1} N_2O) are the conversion factor to calculate the social cost for each emitted kilogram of carbon dioxide and nitrogen oxide, respectively. However, the social cost was calculated only considering the CO_2 and N_2O gasses emission, while no leaching, due to the social cost methodology used, and in that methodology no monetary value has been attributed to NO3 − losses (Keeler et al., 2016).

In addition, SnR was calculated considering three fertilizer costs, to simulate the real variation of fertilizer prices in the last decade. SnR^1 was calculated using the fertilizer cost (Np; 0.4 € kg^{-1} NH_4NO_3) obtained by Borsa Merci di Roma (Chamber of Commercial Trade, 2020); SnR^2 was obtained using 0.6 € kg^{-1} NH_4NO_3 and SnR^3 was calculated using 0.8 € kg^{-1} NH_4NO_3 (MO CAMCOM, 2021). Grain prices (GP; 0.26 € kg^{-1} for minimum 11% Gp, 0.27 € kg^{-1} for minimum 12% Gp, and 0.28 € kg^{-1} for minimum 13% Gp) were obtained from the Borsa Merci di Bologna (Chamber of Commercial Trade, 2020). The SocialC was calculated using the coefficients referred by Keeler et al. (2016) as reported in formula (Eq. 8).

2.5. Simulations for different management scenarios

Model simulations for different management scenarios were conducted to predict the optimum N management strategy for wheat in the Val D'Orcia area. To evaluate the effects of N fertilization on crop production we explored a wide range of seasonal N rates (from 0 to 300 kg ha^{-1}, with 5 kg N ha^{-1} increments in each simulation), different application times (sowing, first and second topdressing) applied in different soils (ARB and QUE). The strategies tested (from A to E) are reported in Table 3. The fertilization planning criterion was selected to reflect the common practices adopted by farmers in the study area, through previous assessments. Strategy A was selected as the business-as-usual practice locally adopted by farmers to fertilize durum wheat. However, the management of farmers could address variation, based on evident choices. There are three schools of thought on that subject: low nitrogen use efficiency at sowing time (small crops unable to use it); high nitrogen use efficiency during tillering (crops need nutrients to grow in number of culms) or high nitrogen use efficiency during stem elongation (crops need nutrients to grow vertically). For that reason, we tested different strategies (B-E), other than A. The empirical cumulative density analysis was used to characterize the distribution of probable soil water content before the second topdressing fertilization event, increasing the likelihood of seeing a response to the final N fertilizer application. For this analysis, weather years were classified as terciles according to their average PESW 20 days before at 2nd topdressing fertilization. Tercile breaks across all soils corresponded to 85% and 95% of PESW, thus years in which PESW < 85% were classified as "dry", PESW > 95% as "wet", and the rest were classified as "normal".

For each strategy, the grain protein concentration (Gp; %), optimum N rate (ONr; kg N ha^{-1}), N surplus (Ns; kg N ha^{-1}), social return to N application (SnR; € ha^{-1}), and grain yield (Yg; Mg ha^{-1}), were analyzed. The optimum fertilizer rate was selected considering the amount of N able to maximize economic net return for farmers. The analysis of the results was performed for each of the three classified soil moisture conditions at 2nd topdressing fertilization (dry, average and wet).

N surplus was calculated by subtracting N outputs (N content in grain and biomass) from N inputs (N rate applied). N surplus includes all N losses (emission, leaching, …) resulting in a global analysis of losses. N surplus evaluation provides an overall analysis of the nitrogen not used by crops, considering the whole ecosystem's losses (N inputs minus the sum of N offtake, N emission, and N surface runoff).

3. Results

3.1. Model evaluation

The measured and simulated phenology and productivity parameters

Table 3
Nitrogen management strategies used to run SALUS simulation over the years. N management strategy A refers to the business-as-usual practice adopted by farmers, B-E refers to no common strategies adopted.

N management strategy	Sowing (1st Nov)	First topdress (20th Feb)	Second topdress (30th Mar)
A	20%	40%	40%
B	20%	50%	30%
C	20%	80%	0%
D	0%	20%	80%
E	0%	50%	50%

are shown in Table 4. The model showed some difficulties in estimating the number of days required to reach the end of vegetative growth (R^2 =0.70), suggesting that the model was more accurate than precise. This is confirmed by the four statistical criteria resulting good for Pbias and RRMSE, while not satisfactory for RSR. On the contrary, there is a good agreement (R^2 =0.91) between the measured and simulated number of days after planting to reach the end of vegetative growth and anthesis with a slight over-estimation of about 1.8 d and a RRMSE of 6.8 d. The model performance in estimating the number of days after planting to reach the end of vegetative growth and anthesis was good according to RRMSE and very good according to Pbias, RSR and NSE. Results indicate a high correlation between simulated and measured DM (y = 0.72x + 2.9; R^2 = 0.76; RMSE = 2.26 Mg ha^{-1}) and Y (y = 0.81x + 0.74; R^2 = 0.69; RRMSE = 0.68 Mg ha^{-1}) thus supporting the model consistency. These results are supported by the four statistical criteria which indicate good performances in terms of accuracy and precision for both DM and Yg.

There was a good correlation between simulated and measured Nc values from stem elongation to heading (y = 0.78x + 0.23; R^2 = 0.76; RRMSE = 0.55%), while the model was not able to correctly simulate the Nc values from heading to full maturity (y = 0.3015x + 0.829; R^2 = 0.42; RRMSE = 0.76%). Also, Pbias, RRMSE, and RSR confirmed that the model performance was good in estimating the Nc values from stem elongation to heading, while the model was not satisfactory in simulating the Nc values from heading to full maturity. The poor precision in simulating the N content after heading also affected the simulation of Gp. Even though a good correlation was found between simulated and measured Gp values (y = 0.84x + 2.84; R^2 = 0.61; RRMSE = 1.43%), the model performances were very good according to PBIAS and RRMSE, while not satisfactory according to RSR.

3.2. Simulation of different fertilization strategies and PESW

Table 5 reports simulated grain yield (Yg; kg ha^{-1}), protein content (Gp; %), and N leaching (kg ha^{-1}) using 30 years of weather data and two soil conditions with different N management scenarios. QUE soils showed the highest yield in comparison to ARB soils, ranging between 1685 (0 kg N ha^{-1}) and 5704 (180 kg N ha^{-1}). Regarding QUE soils, Yg increased by about 500 kg grain from 30 to 180 kg N ha^{-1}. However, the increase in yield ranging from 0 to 180 kg N ha^{-1} was more consistent in ARB soils than in QUE soils. On the other hand, protein content showed similar values in both soils, decreasing the percentage as N fertilization rate increased and showing slightly lower values for ARB soil. The protein content values ranged from 17% (30 kg N ha^{-1}) to 15% (180 kg N ha^{-1}). Predicted N leaching values increased from 30 N to 180 N for both soils. The results showed a lower N leaching for ARB soil, ranging from 2.6 to 4.76 (kg N ha^{-1}) than for QUE soil, ranging from 6.57 to 9.50 (kg N ha^{-1}). QUE soil and ARB soil reported a maximum leaching value for 180 kg N ha^{-1} of about 22.62 and 14.50 kg N ha^{-1}, respectively.

The long-term simulation of plant extractable soil water (PESW) at second topdressing fertilization (March) showed differences between the two soils. QUE soil showed a PESW ranging between 0 and 100 mm, on the other hand, the values for ARB soil ranged between 20 and 120 mm (Fig. 2).

N surplus, Yg and Gp information were combined to calculate the optimal N rate that maximize SnR, considering the soil types and PESW during the second topdressing fertilization. SnR (€ ha^{-1}) computed using three different fertilizer costs have been reported in Table 6 for QUE soil and Table 7 for ARB soil. Results showed that regardless of PESW conditions, SnR increase as N rate increase. Analyzing results from Table 6 (QUE soil), the PESW in March ranging from 40 to 70 mm showed a significant SnR increase from 30 to 60 kg N ha^{-1}, while standing from 60 to 90 kg N ha^{-1}. Moreover, from 150 to 180 kg N ha^{-1} SnR variations were not significant. When PESW was > 70 mm, the maximum rate applied (180 kg N ha^{-1}) was able to maximize the SnR for farmers, in comparison to lower PESW conditions. In Table 7 (ARB soil) the SnR was maximum applying 180 kg N ha^{-1} for PESW > 90 mm. Analyzing the three different fertilizer costs (0.4, 0.6 and 0.8 € kg^{-1} NH_4NO_3) in QUE soil, the economic evaluation shift from the lowest benefit considering fertilizer cost of 0.8 € kg^{-1} and the highest benefit for fertilizer cost of 0.6 € kg^{-1}, the economic benefit considering a fertilizer cost of 0.4 € kg^{-1} was intermediate concerning the others. On the other hand, considering the three fertilizer costs in ARB soil, the lowest economic benefit was obtained for the fertilizer cost of 0.4 € kg^{-1} and the highest for 0.6 € kg^{-1}.

3.3. Assessment of the optimal N rate using 30 years of simulation data

Results about the locally adopted management strategy (A) simulation scenarios are reported in Fig. 3. The SnR (€ ha^{-1}) increased with the N application rate (SnR = 6.38 N rate - 44.0; R^2 = 0.99) from 0 to 200 kg ha^{-1} and then flatten. The Yg (kg ha^{-1}) increased as the N application rate increased following an almost linear relationship (Yg = 0.0279 N rate + 2.0561; R^2 = 0.99) until 180 kg ha^{-1} where the linear relationship changed assuming a less steep angle (Yg = 0.0058 N rate + 5.4525; R^2 = 0.9664). The Gp (%) decreased as the N application rate increased (Gp = −0.0123 N rate + 12.029; R^2 = 0.84) until 80 kg N ha^{-1}, then the relationship became positive (Gp = 0.0296 N rate + 8.248; R^2 = 0.99) until 275 kg N ha^{-1} and then plateaued. On the other hand, N surplus (kg N ha^{-1}) seemed to rise with a constant trend (N surplus = 0.3864 N rate - 32.536; R^2 = 0.99) from 0 to 300 kg N ha^{-1}.

A comparison between strategy A and the other N management strategies was performed (Fig. 4). The Yg resulted slightly higher for B (+ 0.09 Mg ha^{-1}) and C (+ 0.12 Mg ha^{-1}) strategies under dry conditions, resulting in higher SnR (+22.2 and +78.7 € ha^{-1}, respectively) in comparison to strategy A. In addition, B and C strategies, where no N was applied at 2nd topdressing fertilization, showed similar ONr and lower N surplus (−2.44 and −0.5, respectively) in comparison to strategy A. Regardless of soil conditions, strategies D and E, where no N was applied at sowing, showed the lowest ONr (−12.196 and −10.77 kg N ha^{-1}, respectively in comparison to strategy A) and the lowest Ns (−12.9 and −11.1 kg N ha^{-1}, respectively in comparison to strategy A). Instead, in dry conditions, strategies D and E produced the lowest Y (−0.24 and −0.19 Mg ha^{-1}, respectively in comparison to strategy A), and as a consequence the lowest MNR (−11.2 and −5.17 € ha^{-1}, respectively in comparison to strategy A). The Gp in strategy C, D and E resulted slightly lower than strategy A by about − 0.14, − 0.03% and 0.11%,

Table 4
Measured versus SALUS model simulated days after planting (DAP) to reach the end of vegetative growth and anthesis, dry matter (DM), grain yield (Yg), nitrogen content (Nc) from stem elongation to heading, nitrogen content from heading to full maturity and grain protein concentration (Gp). RRMSE is the relative root-mean-square error; Pbias is the percent bias; RSR is the RMSE-observations standard deviation ratio.

Variable	Measure unit	Average measured values	Average simulated values	Pbias	RRMSE	RSR
$DAP^{\text{to reach the end of vegetative growth}}$	d	152.48 (15.9)	148.19 (7.77)	-2.80%	7.30%	0.7
$DAP^{\text{to reach the anthesis}}$	d	179 (15.99)	177.11 (10.79)	-1.10%	3.80%	0.42
DM	Mg ha^{-1} y^{-1}	7.59 (4.27)	8.42 (3.53)	10.90%	29.80%	0.53
Yg	Mg ha^{-1} y^{-1}	4.33 (1.04)	4.25 (1.01)	-2.00%	14.00%	0.58
$Nc_{\text{from stem elongation to heading}}$	%	2.55% (0.9%)	2.23% (0.81%)	-13.00%	22.00%	0.61
$Nc_{\text{from heading to full maturity}}$	%	1.93% (0.71%)	1.41% (0.33%)	-27.00%	40.00%	1.07
Gp	%	12.91% (1.72%)	13.7% (1.83%)	6.21%	11.06%	0.84

Table 5
Simulated mean, maximum (max), minimum (min), and standard deviation (sd) for grain yield (Yg; kg ha^{-1}), protein concentration (Gp; %), and nitrogen leaching (kg ha^{-1}) using 30 years of historical meteorological data on two soils (QUE refers to Quercia soil and ARB refers to Arbia soil) located in Val D'Orcia area. The fertilizer was applied using Strategy A (sowing 20%; 1st topdressing 40%; 2nd topdressing 40%).

Variable		N fertilization rate (kg ha^{-1})						Soil
		30 N	60 N	90 N	120 N	150 N	180 N	
Yg (kg ha^{-1})	mean	1685	2357	3109	3798	4774	5704	ARB
	sd	217	255	376	486	668	719	
	max	2627	3455	4575	5976	7059	8184	
	min	1331	1950	3218	3296	3992	4163	
Gp (%)	mean	17.4	17.2	16.4	15.7	15.1	14.6	
	sd	0.2	0.3	0.5	0.7	0.9	1	
	max	17.5	17.5	17.2	16.7	17.1	17.5	
	min	16.9	16.3	14.9	13.6	13.4	13.2	
N leaching (kg N ha^{-1})	mean	2.6	2.71	3.08	3.34	3.99	4.76	
	sd	2.26	2.38	2.72	3.23	3.36	3.53	
	max	10.36	9.63	9.94	12.79	13.17	14.5	
	min	0	0	0	0	0	0	
Yg (kg ha^{-1})	mean	2107	2857	3607	4386	5282	6072	QUE
	sd	793	817	857	857	936	1117	
	max	5710	6585	7378	7863	7905	7925	
	min	1349	2072	2317	2361	2791	2907	
Gp (%)	mean	17.17	16.78	16.12	15.61	15.28	15.45	
	sd	0.69	0.78	0.86	1.02	1.31	1.47	
	max	17.49	17.49	17.49	17.49	17.49	17.49	
	min	14	13.86	14.2	13.56	13.46	13.22	
N leaching (kg N ha^{-1})	mean	6.57	7.05	7.53	8.14	8.71	9.5	
	sd	5.59	5.69	5.82	5.9	6.1	6.37	
	max	19.53	19.85	20.71	20.98	21.51	22.62	
	min	0	0	0	0	0	0	

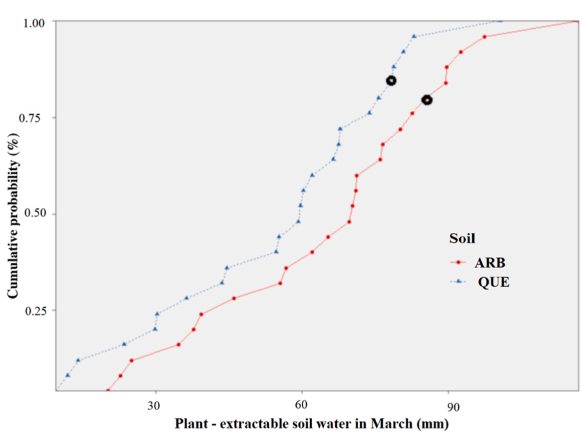

Fig. 2. Cumulative probability (%) of the potential extractable soil water (PESW, mm) for 30 years of simulations run and four soils (ARB= Arbia; QUE = Quercia) of the study area at the 2nd topdressing N application (in March). The culumative probability is calculated as the number of observations less than or equal to a given observation divided by the total number of observations. The upper limit of plant available soil water (PASW, mm) is reported as a black dot for each soil.

respectively, while no differences were found for strategy B and across the different soil conditions. Regardless of the soil conditions, results showed that the MNR was higher for strategies B, C, D, and E in comparison to strategy A (of about 9.02, 58.10, 24.6, 31.33 € ha^{-1}, respectively).

In Fig. 5 the optimum N rate application before and at 2nd topdressing fertilization was reported, able to maximize the economic return to N application for farmers. For dry and wet soil moisture, the best N rate was applying 90 kg ha^{-1} before and 60 kg ha^{-1} at 2nd topdressing fertilization time; for average mosture conditions the best N rate was 120 kg ha^{-1} before 2nd topdressing and 80 kg ha^{-1} at 2nd todress fertilization.

3.4. Nitrogen nutrition status

In Fig. 6 (up) the nitrogen nutrition status of durum wheat during the development stages was reported, from the field data collected during 2010/2013 experimental fields in Val D'Orcia area. The nitrogen nutrition reference curve for durum wheat was developed in Fabbri et al. (2020) (a) and was used to calculate the nitrogen nutrition index (NNI) (b). In Fig. 6 (down) the NNI condition simulating the different soil water content conditions (dry, average and wet) was reported, for each N management strategy (A-E). When the soil was dry (<85% water content) the NNI at optimum N rate was equal to 1 (no surplus or deficit of N) for strategies D and E, while a slight N surplus was evident adopting strategies A, B and C at optimum N application rate. Considering average soil moisture conditions (85–95%) and wet soil conditions (>95%), for all the strategies a little surplus of N was shown, even if under 1.2. No strategy showed crops N deficit when under N applications at optimum rate suggested by the simulation.

4. Discussion

SALUS showed good results in predicting DM dynamics and Yg, while showed a lower performance of N uptake after heading across the whole dataset. The latter was probably due to the different varieties used in the field trials, whereas crop characteristics for model calibration were not variety specific. In fact, Makowski et al. (2006) showed that winter wheat genotypes variance is explained principally by the efficiency of N remobilization to the grain and the shoot–root ratio for N partitioning. In addition, the N accumulation in grain simulated by the model is based on the kernel number per unit area (Ritchie et al., 1985). In this sense, the error in kernel number prediction per unit area might be compensated by the simulated kernel size, which results in good Yg predictions. However, grain N cannot be compensated by model elaboration, and an error in kernel number prediction might influence N concentration and grain protein results (Asseng et al., 1998). Yet, the results for N evaluation were satisfactory, demonstrating more accuracy than precision. In fact, the deviation from the mean result was acceptable and therefore the model can be considered suitable for analysis in long-term simulation scenarios. To simulate the soil water content

Table 6
Simulated annual mean (μ), maximum (M), minimum (m) Social Net Return (SnR) and standard deviation (sd) using 30 years historical weather data on the Quercia soil (QUE) at three different plant extractable soil water (PESW mm). The Social Net Return was calculated considering three different wheat selling scenarios (SnR^1 considering a fertilizer cost of 0.4€ kg^{-1} NH_4NO_3; SnR^2 for 0.6 € kg^{-1} and SnR^3 for 0.8 € kg^{-1}). The fertilizer was applied using Strategy A (20% at sowing; 40% at 1st topdressing; 40% at 2nd topdressing).

PESW (mm)		N fertilization rate (kg N ha^{-1})																	
		30			60			90			120			150			180		
		SnR^1	SnR^2	SnR^3	SnR^1	SnR^2	SnR^3	SnR^1	SnR^2	SnR^3	SnR^1	SnR^2	SnR^3	SnR^1	SnR^2	SnR^3	SnR^1	SnR^2	SnR^3
< 40	μ	485	500	444	626	656	545	778	823	657	896	956	736	1115	1190	915	1283	1373	1044
	sd	142	142	142	142	142	142	186	186	185	213	213	211	281	281	278	372	372	368
	M	731	746	690	850	880	769	1005	1050	884	1099	1159	938	1454	1529	1252	1729	1819	1487
	m	287	302	246	443	473	362	462	507	343	424	484	268	495	570	301	477	567	246
40–70	μ	550	565	510	734	764	653	889	934	768	1089	1149	928	1265	1340	1064	1259	1341	1041
	sd	305	305	305	328	328	328	318	318	318	303	303	303	278	278	277	489	511	434
	M	1508	1523	1467	1707	1737	1626	1882	1927	1761	1972	2032	1811	1938	2013	1736	1846	1936	1604
	m	407	422	367	552	582	471	688	733	567	810	870	650	804	879	606	804	894	569
> 70	μ	428	443	387	617	647	536	792	837	671	968	1028	807	1186	1261	986	1377	1467	1137
	sd	19	19	19	25	25	25	42	42	42	87	87	86	185	185	184	206	206	205
	M	453	468	412	665	695	584	864	909	742	1131	1191	970	1549	1624	1347	1803	1893	1561
	m	400	415	359	588	618	507	739	784	618	873	933	713	990	1065	791	1140	1230	902

Table 7
Simulated annual mean (μ), maximum (M), minimum (m) marginal net return (SnR; € ha^{-1}) and standard deviation (sd) using 30 years historical weather data on the Arbia soil (ARB) at three different plant extractable soil water (PESW, mm). The Social Net Return was calculated considering three different wheat selling scenarios (SnR^1 considering a fertilizer cost of 0.4€ kg^{-1} NH_4NO_3; SnR^2 for 0.6 € kg^{-1} and SnR^3 for 0.8 € kg^{-1}). The fertilizer was applied using the Strategy A (20% at sowing; 40% at 1st topdressing; 40% at 2nd topdressing).

PESW (mm)		N fertilization rate (kg N ha^{-1})																	
		30			60			90			120			150			180		
		SnR^1	SnR^2	SnR^3	SnR^1	SnR^2	SnR^3	SnR^1	SnR^2	SnR^3	SnR^1	SnR^2	SnR^3	SnR^1	SnR^2	SnR^3	SnR^1	SnR^2	SnR^3
< 60	μ	217	391	335	294	526	415	380	680	515	470	840	621	593	1074	800	700	1271	944
	sd	18	39	39	21	45	45	30	66	65	30	65	64	46	101	100	75	163	162
	M	242	446	391	318	579	468	426	780	613	505	918	698	670	1241	967	808	1507	1177
	m	173	296	241	253	439	328	330	571	407	428	749	530	518	909	638	540	925	599
60–90	μ	225	408	353	315	572	461	423	772	606	521	951	731	638	1171	898	766	1413	1085
	sd	36	78	78	40	86	86	56	122	122	83	179	178	111	240	239	102	223	221
	M	341	659	604	449	860	749	594	1143	976	776	1504	1282	917	1776	1499	1063	2060	1727
	m	199	354	298	285	508	397	382	684	519	463	825	607	541	961	689	648	1159	832
> 90	μ	208	371	316	305	550	439	393	708	543	479	860	640	635	1164	890	785	1456	1127
	sd	2	4	4	11	24	24	4	8	8	19	41	41	58	127	126	55	119	118
	M	209	375	319	317	576	465	399	720	555	507	921	702	707	1320	1046	861	1621	1292
	m	205	365	310	290	518	407	390	701	535	446	789	571	564	1010	738	736	1348	1021

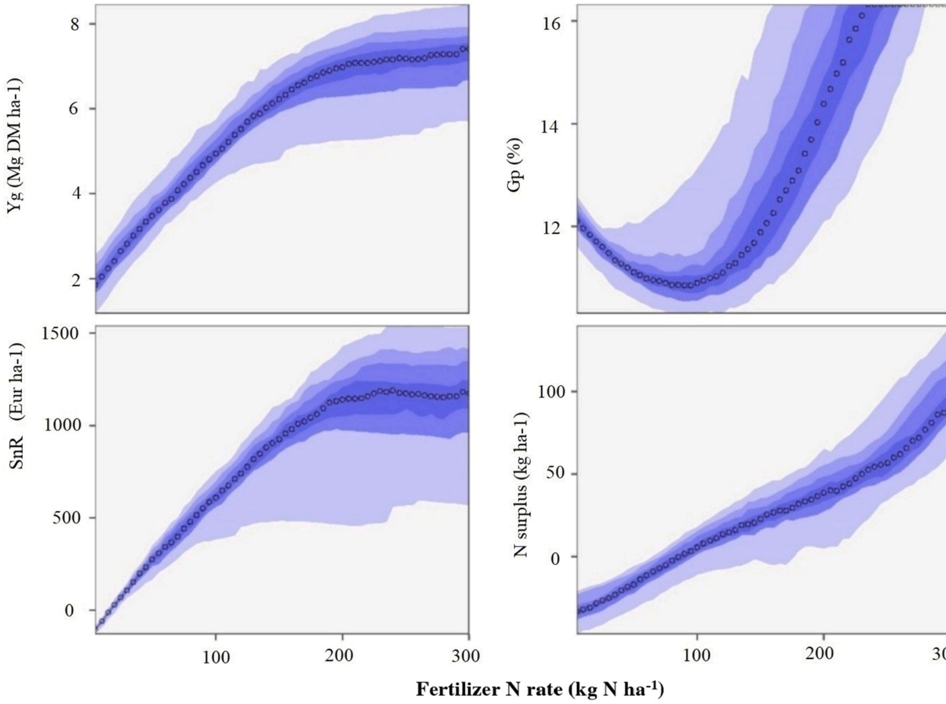

Fig. 3. Yield (Yg), return to N application, grain protein (Gp) and nitrogen surplus as function of N rates for durum wheat cultivated in Val D'Orcia area. Nitrogen (N) rate application was run starting from 0 kg N ha^{-1} until the last N treatment of 300 kg N ha^{-1}, with a 5 kg increment each simulation. The fertilizer was applied using the Strategy A (20% at sowing; 40% at 1st topdressing; 40% at 2nd topdressing).

probability we used the last 30 years weather data, that represented the most representive dataset to derive biophysical variables from impact models and considering climate change issue (Duveiller et al., 2017).

The model was also used to simulate soil water conditions during wheat 2nd topdressing fertilization, considering that in spring under Mediterranean climate the rainfall amounts are lower than in fall. However, in this study, results showed a simulated soil water deficit only in a few years, across all the soils, which may be related to soil texture characteristics (e.g. a high percentage of clay and silt), and the amount of organic matter, which positively influenced the soil water storage capacity. In addition, rainfall events in the study area usually occur in the fall and winter (Fig. 1), replenishing soil moisture during early wheat growth stages. The differences in the plant extractable soil water is probably due to the soil drain upper limit (amount of water a soil can hold against gravity) and lower limit (water remaining in the soil after crop satisfaction) across the root depth layers, which influences the amount of water that can be stored in the soil profile. The results showed the great variability of physical and chemical properties in the soils, resulting in the necessity to manage crop cultivation specifically. Soil properties and position in the landscape seem to be a very influent factor on wheat production, varying surface runoff and drainage conditions.

The soil conditions of ARB in comparison to QUE determined the variability of the results analyzed. ARB soil is loamy and present lower organic carbon than QUE soil, that probably influenced the yield. In fact, the lower soil organic matter content is responsible for lower mineralization rate in this type of soils. In QUE soils the higher N mineralization rates and water retention capacity influenced yield, but also increased N losses. N losses increased for both soils as N rate increased. N leaching was higher in QUE soil than ARB, however, the values were low for both soils. A higher rate of N losses might be occurred through denitrification than leaching, probably due to the soil texture. In fact, Köster et al. (2013) reported that total denitrification rate was highest in clay and silty soil and lowest in sandy soil. Soil carachteristics and weather influence the rate and form of N losses and the dry summer season of Val D'orcia area might be responsible of higher volatilization losses rates than leaching (Jones et al., 2013).

It is interesting to study the netincome variation applying different fertilizer costs in the evaluation of economic benefits. Nowadays, the instability of the fertilizer market is becoming more important, due to the increasingly limited resource of fertilizers. In this perspective, the market, farmers and political decisors should use crop models (integrated with pedoclimatic information) as forecascting tools to evaluate convenience in fertilizer application.

In this study it was possible to assess the social cost of N application in addition to the economic cost. Several countries are planning to introduce carbon emission pricing measures, to discourage the adoption of of high emission impact systems. For that reason, to avoid additional taxes it is important to apply the right fertilizer rate to crops and minimize losses.

Larmour (1939) reported that soil texture is one of the main factors responsible for greater variations in protein of wheat. Soils capable of retaining much moisture in a form available to the plant produce wheat low in protein and vice versa. However, no consistent differences were detected for both Val D'Orcia soils, leading to conclude that probably weather conditions were the most influent factors. The protein content results might be influenced by the simplified processes of N accumulation and translocation in wheat used by the model, not accounting for the amino acids stored in crop vegetative parts before anthesis, which are then remobilized to the grain for protein synthesis, creating a system of N uptake, storage, remobilization and synthesis (Zhu et al., 2007). The protein content is directly computed by N in grain, therefore the computation of grain N accumulation and dry matter in the model must be analyzed, as it is derived from different temperature functions. Additionally, the model simulation does not account for the realistic wheat growth behavior in N luxury conditions, where lodging problems could occur.

In this study, different soil types and water holding capacities influenced the N rates to be applied at 2nd topdressing fertilization, considering the same weather conditions during the growing season. In fact, in the literature it is reported that fertilization management must consider the physical and chemical characteristics of the soil (Agegnehu et al., 2014; Galieni et al., 2016), to avoid losses. On the other hand,

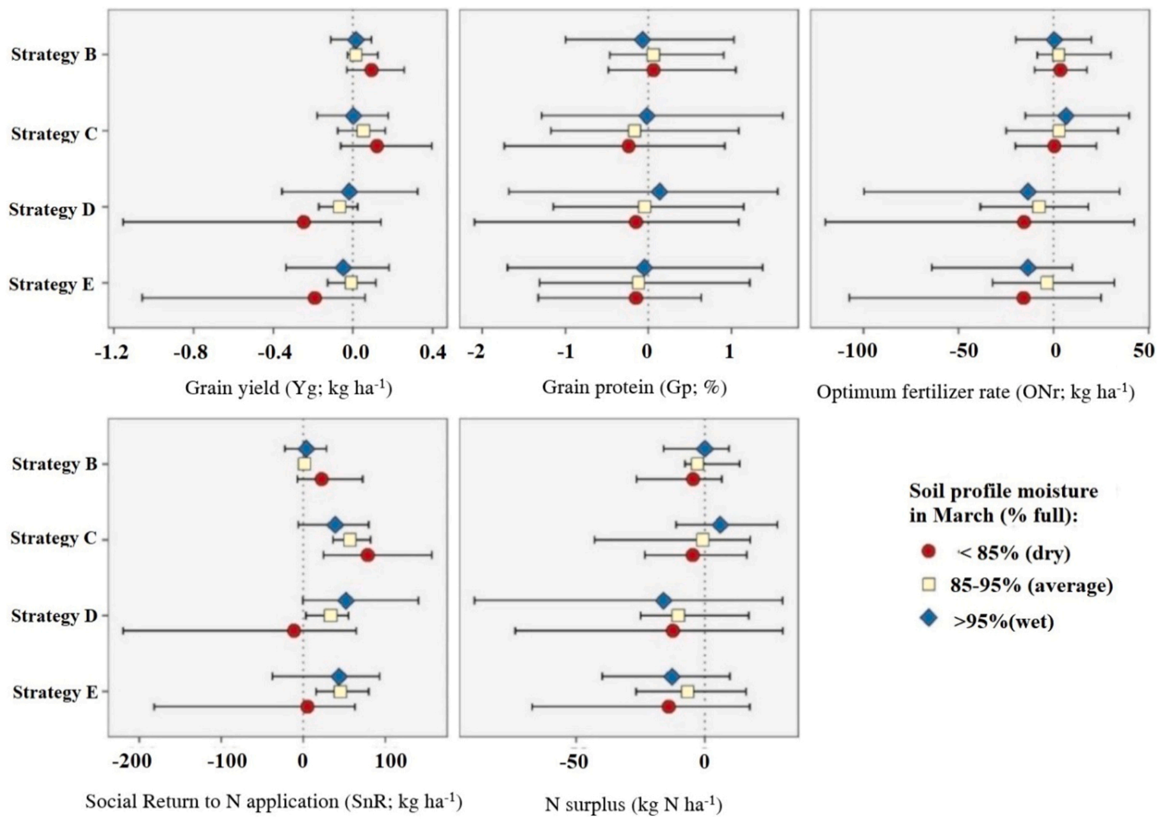

Fig. 4. Plot to compare the tested strategies (E-D) for each soil moisture profile in March with strategy A. For each variable the difference was calculated and the mean value (symbol) and ranges (error bars) were taken with respect to the strategy A. Legend: strategy A = 20% nitrogen (N) application at sowing, 40% N application at 1st topdressing and 40% N application at 2nd topdressing; strategy B = 20% N application at sowing, 50% N application at 1st topdressing, 30% application at 2nd topdressing; strategy C = 20% N application at sowing, 80% N application at 1st topdressing, 0% N application at 2nd topdressing; strategy D = 0% N application at sowing, 20% N application at 1st topdressing, 80% N application at 2nd topdressing; strategy E = 0% N application at sowing, 50% N application at 1st topdressing, 50% N application at 2nd topdressing.

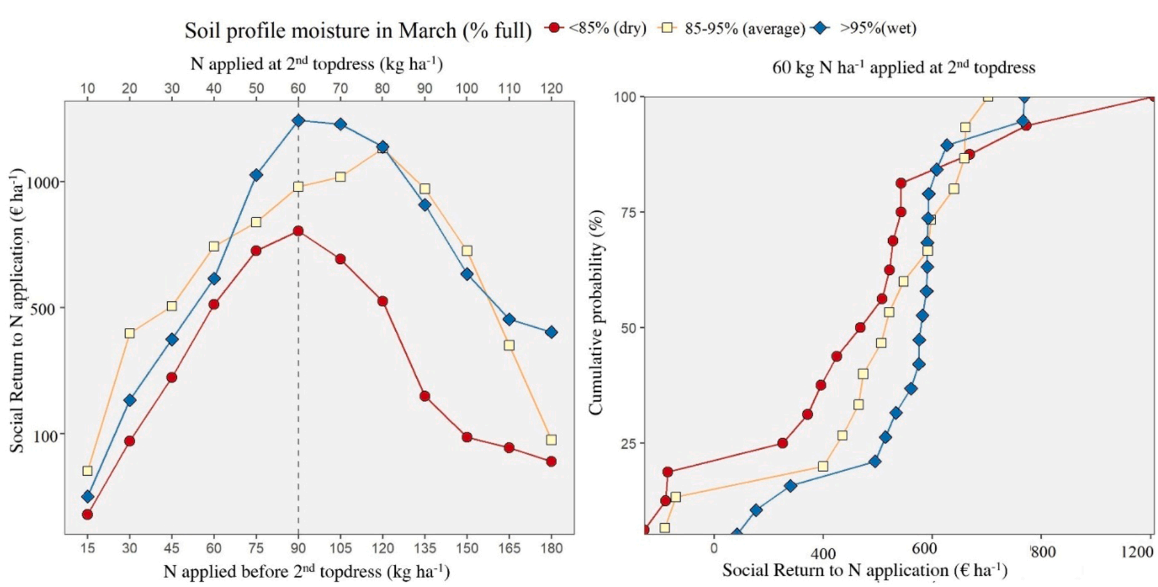

Fig. 5. Social Return to nitrogen application (SnR; € ha^{-1}) considering nitrogen (N) rate at and after 2nd topressing fertilization for each soil moisture condition. Cumulative probability (%) of the SnR applying 60 kg N ha^{-1} at 2nd topdressing fertilization on QUE soil for each moisture condition. The cumulative probability is calculated as the number of observations less than or equal to a given observation divided by the total number of observations.

when soil moisture conditions were dry, the yield and optimum N level were lower. This is probably due to the lower crop water availability, which influences N uptake. In this case, N additions are likely to be released in the environment as losses (N surplus), representing a pollution factor. In low rainfall systems, N is usually applied in limited amounts to avoid excessive vegetative growth, which can deplete

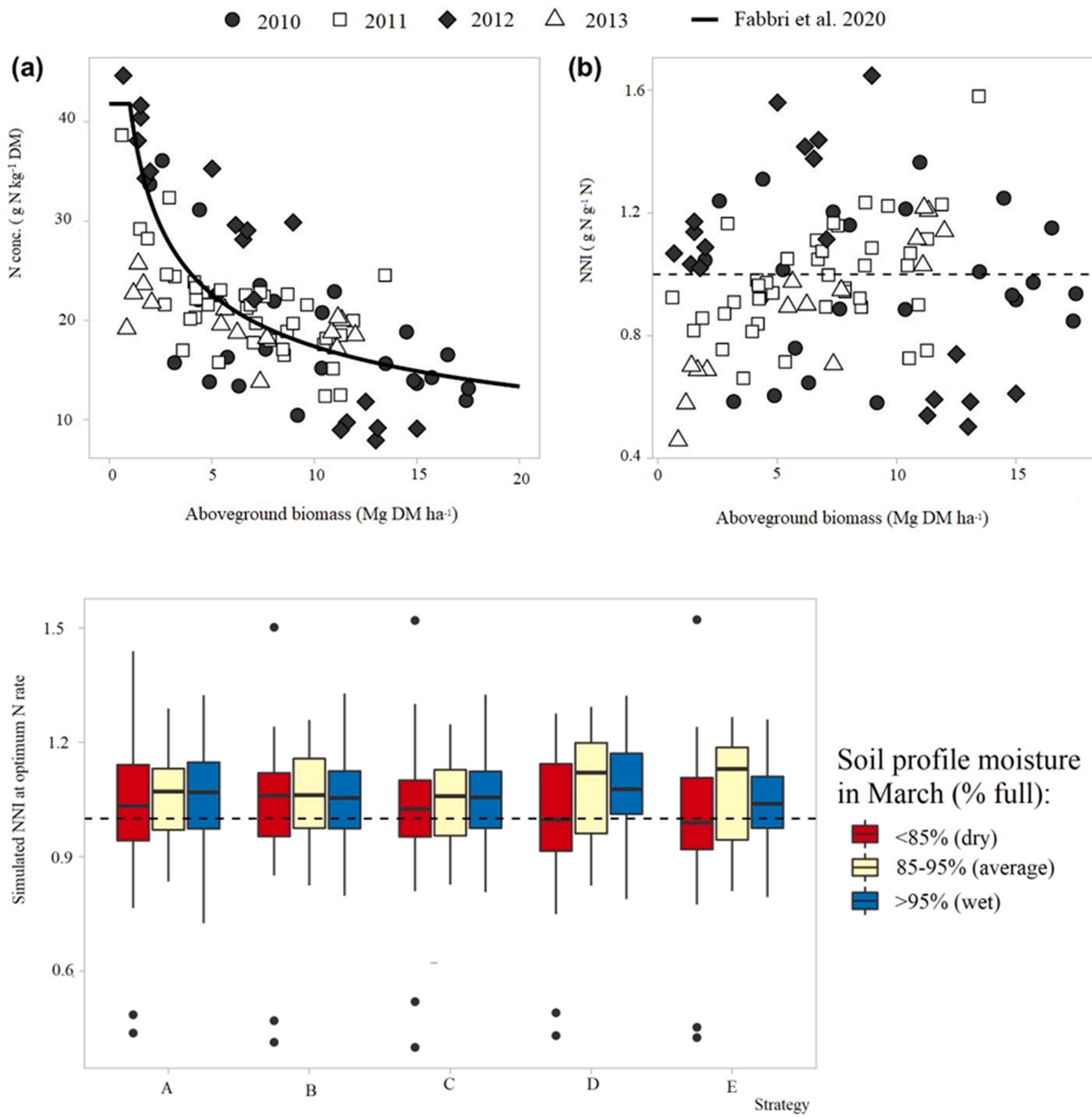

Fig. 6. Evolution of NNI during the growing season of wheat. Up: nitrogen dilution curve (a) and nitrogen nutrition index (NNI) calculation (b) from 2010/2013 experimental fields for durum wheat cultivated in Val D'Orcia area. NNI ≥ 1 indicates non-limiting nitrogen while NNI < 1 indicates N deficiency. Down: the simulated NNI at optimum nitrogen rate for the different soil water conditions in the cultivation strategies (A-E).

limited soil moisture before flowering and grain filling (Brown et al., 2005). In conclusion, the fertilization strategy traditionally adopted by farmers was not the most economical and environmental sound practice across the simulations. In fact, strategies D and E generated higher economic return to N application, with lower ONr in average or wet soil conditions. In those cases, no N was applied at sowing, representing a savings for farmers due to one less fertilizer operation, and Yg increase due to high kg of N supplied in correspondence to midseason, under high water availability. Moreover, the nutrient optimization minimized N surplus, which reduced the cost for the fertilizer, as evaluated from an economic and social point of view. In this paper, NNI was used to demonstrate effectively the N crop condition after applying nutrient optimal rates, to maximize the productivity in different soil water conditions. Kunrath et al. (2018) and then, Kunrath et al. (2020) also demonstrated that soil water deficit is the main factor responsible for decreasing crop growth and N availability because of water limits, affecting NNI. In the rainfed Mediterranean environment, López-Bellido et al. (2005) reported the inefficiency of applying N fertilizer at sowing for wheat cultivation, which can lead to lower N crop uptake than midseason applications. Also, Pampana et al. (2013) reported that the effects of splitting N fertilization on wheat are more related to weather conditions and rainfall amount. In the model simulations, splitting N fertilizer into three events (from November to March) in dry seasons resulted in higher Yg than the application only in midseason. This result might be attributed to the high kg of N supplied in 2nd topdressing fertilization in dry seasons, where the efficiency of N use by crops is reduced. Finally, grain protein simulations did not show different percentages across soil moisture conditions, which might be related to soil properties and spring temperatures. Mack (1973) reported that under high soil temperature, protein content was relatively constant despite change in soil moisture. In general, grain protein seemed more related to N rate than fertilization strategy, as also reported by Abedi et al. (2011). However, general results showed a rise in optimum N rate at increasing soil moisture, because in those conditions, the capacity of plants to use fertilizer is higher. The inefficiency of a pre-fixed traditional N management might be avoided using a combined set of information through crop modelling, reproducing crop nutrient demand. The social cost of N application should be considered, reproducing the economic trade-off from an environmental assessment perspective. Considering the time of N application and soil moisture conditions, it was possible to assess the best N rate able to maximize profit for farmers,avoiding losses that damage the environment and economy. This evalation methodology might allow farmers to use pedologic data and weather forecast, integrating information in a model with precise indications of nitrogen use efficiency. The addition of a monetary estimation of pollution allow farmers and policy makers to consider the grain market connected to environmental sustainability of grain production.

In this research we used a crop modelling system to assess strategies to manage N fertilization of durum wheat in a cultivated area of Tuscany. The long-term simulations allowed us to better study the nutrient dynamics on the soil and determine the best strategy for maximizing profits for farmers while minimizing effects on the environment. The results showed that yield, N losses increase as N rate increase for two cultivated soils in Val D'Orcia area, but the trend was different concerning the soil type and PESW conditions during 2nd topdressing fertilization. QUE soil showed a general higher social return to N application than ARB soil, In addition, applying 3 diferent fertilizer scenarions cost to the analysis the general SnR trend was different in both soils. At the end, QUE soil was analyzed ad the model has revealed that the N fertilization regime locally adopted by farmers is not ideal for achieving yield and protein content goals, in comparison with other management strategies. Simulation results showed that omitting N applications at sowing might represent a money saving for farmers and reduce N losses. However, applying 60 kg N ha^{-1} during 2nd topdressing fertilization might result the optimum strategy to enhance the social economic return for farmers regardless soil moisture conditions.

5. Conclusions

The results of the study show that in a highly spatially and temporally variable pedoclimatic condition, such as the Italian landscape, the standard application of N fertilization is inefficient, leading to N losses to the environment and not profitable economically. In-season field water and N dynamics measurements remain not feasible due to lack of practicality and high costs. In the study, recomandations were based on a systems approach in a rainfall wheat management system, where two different soils coexist. The soils were subdivided based on water conditions available to plants and the most convenient N rates were calculated. In this context, when soil water conditions are higher than 70 and 90 mm the profit increase as N application increase until a threshold, while when soil water conditions are lower than 40 and 60 mm the N application convenience is more variable, depending on the fertilizer cost. This result is of great interest nowadays, where the fertilizer cost is highly affected by social situation and resource procurements. Analysing QUE soil, the model has revealed that the N fertilization regime locally adopted by farmers is not ideal for achieving yield and protein content goals, in comparison with other management strategies. Simulation results showed that omitting N applications at sowing might represent a money saving for farmers and reduce N losses during average and wet years, while during dry years the optimal strategy may be no N application at second topdressing fertilization. Our results provide a thorogh perspective for farmers to make more informed decision based on the tradeoffs between economic profit, grain quality and environmental impact. This provides a framework to consider the social perspective to farming, a guideline for creating resilient agricultural systems, and cornerstone for future agricultural policies in Europe.

CRediT authorship contribution statement

Carolina Fabbri: Formal analysis, Investigation, Software, Visualization, Writing – original draft. **Bruno Basso**: Conceptualization, Funding acquisition, Methodology, Project administration, Software, Supervision, Writing – review & editing. **Marco Napoli**: Data curation, Formal analysis, Investigation, Methodology, Supervision, Visualization, Writing – review & editing. **Anna Dalla Marta**: Funding acquisition, Project administration, Resources. **Simone Orlandini**: Funding acquisition, Project administration, Supervision. **Rafael A. Martinez-Feria**: Data curation, Investigation, Methodology, Software, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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