Europ. J. Agronomy 33 (2010) 132–138

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Long-term wheat response to nitrogen in a rainfed Mediterranean environment: Field data and simulation analysis

Bruno Basso[a,*], Davide Cammarano[b], Antonio Troccoli[c], Deli Chen[d], Joe T. Ritchie[e]

[a] *Department of Crop Systems, Forestry and Environmental Sciences, University of Basilicata, Via Ateneo Lucano 10, Potenza, 85100, Italy*
[b] *Institute for Sustainable Resources, Queensland University of Technology, D Level 3, Gardens Point, Queensland, 4001, Australia*
[c] *Centre for Cereal Research, S.S. 16, km 675, 71100, Foggia, Italy*
[d] *Department of Resource Management and Geography, School of Land and Environment, The University of Melbourne, Parkville, 3010, Australia*
[e] *Department of Agriculture and Biosystems Engineering, University of Florida, Gainesville, USA*

ARTICLE INFO

Article history:
Received 6 August 2009
Received in revised form 14 April 2010
Accepted 19 April 2010

Keywords:
Nitrogen management
Wheat
Southern Italy
Long-term simulation modelling
SALUS

ABSTRACT

Appropriate nitrogen management is one of the main challenges of agricultural production and for the environment. The objectives of this study were to evaluate the efficiency of crop N uptake in a long-term wheat crop in a Mediterranean environment of Southern Italy, and to identify optimal N rate for reasonable economic returns and minimum nitrate leaching using SALUS crop simulation model.

The study was part of a long-term monoculture wheat system that started in 1991/1992 season, with two levels of nitrogen (0 and 90 kg N ha^{-1}). Simulations of the treatment with no nitrogen (0 N) and 90 kg N ha^{-1} (90 N) were performed using the SALUS crop model for wheat. The model was tested against measurements of harvested grain yield, final N uptake, soil water content and total soil N. Long-term simulation over 56 years showed that grain yield median value was 3435 kg ha^{-1} for 0 N and 3876 kg ha^{-1} for 90 N. Simulation scenarios with different N rates (0, 30, 60, 90, 120, 180 kg N ha^{-1}) showed that yield response was higher for 120 N (3528 kg ha^{-1}), with the 60 and 90 N yields giving the same response, 3010 and 3054 kg ha^{-1}, respectively. The most profitable treatments were 120 N (302 Euro ha^{-1}), followed by the 60 N (220 Euro ha^{-1}). The simulation results showed that nitrate leaching was higher for the N rate of 120 and 180 with a mean annual value of 49 and 81 kg ha^{-1}, respectively. Results suggest that in such environment 60 kg N ha^{-1} can be the most appropriate as an N fertilization management due to the best trade-off between leaching and economic. Since N fertilization rates are linked to nitrous oxide (N_2O) emissions and N leaching, a trade-off between N fertilization rates profit and grain yield should be thought as way to reduce environmental pollution while keeping productivity and profit. The adoption of simulation models to approximate the best N rate for durum wheat in rainfed Mediterranean environment proved to be a useful tool for supporting management decisions through quantifying the temporal variability related to weather uncertainty as it influences on the yield and nutrient dynamics.

1. Introduction

Nitrogen (N) is one of the most important nutrients for improving crop yields. High N fertilization rates increase the overall costs and potential environmental impact due to possible nitrate leaching and soil acidification. In rainfed regions of the world, the timing and rate of N fertilizer applications is crucial for optimal yield with high protein content because the N supply should be matched with adequate water supply and synchronised with crop demand. Rainfed regions are characterised by limited and unpredictable rainfall during the growing season, making the synchronisation of N supply with N crop demand and available water supply a rather difficult task.

Nutrient management can affect the pattern of water use by a crop. Too much nitrogen, whether from fertilizer or from high mineralisation of soil organic matter, can result in crops that are too vigorous in the vegetative stage and use too much water before flowering; they can set a large number of seeds but are unable to produce enough carbohydrate to fill them adequately, either from photosynthesis after flowering or from carbohydrate stored before flowering and available for translocation (Van Herwaarden et al., 1998; Angus and van Herwaarden, 2001; Passioura, 2006) resulting in premature crop senescence, and low grain yield. This problem can be avoided or at least reduced by tactical application of nitrogen fertilizer, e.g. mid-season, when there is better knowledge of the remaining water availability for grain fill.

Split application is the common fertilization practice in wheat production in Southern Italy. Farmers often apply 30% of N at planting and the remaining 70% at DC 30 (Stem Elongation; Zadoks et al., 1974). In these environments, N fertilizer costs can reach 15% of

* Corresponding author. Tel.: +39 3204371042; fax: +39 0971 205378.
E-mail addresses: bruno.basso@unibas.it, brunobasso1@gmail.com (B. Basso).

1161-0301/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.eja.2010.04.004

total production costs and there can be large amounts of residual N from fertilization (>60%) at harvest, being available for the next crop (Corbeels et al., 1999) unless there is leaching loss during the off-season.

N fertilization rates are associated with higher nitrous oxide (N_2O) emissions from agricultural crops (Robertson and Goffman, 2007). N_2O is a potent greenhouse gas (GHG) and a review in the USA showed that it is the major GHG emitted by US agricultural activities with an annual emission of approximately 500 Gg in 2007 (EPA, 2009). Although the link between soil N and N_2O emissions means that emission of GHG from agricultural enterprises is somehow unavoidable (Mosier, 2002), a proper N management aimed at reducing its influence on N_2O emissions but retaining acceptable profitability for producers would be ideal.

Understanding the best N fertilization management would require the availability of long-term field studies. A few years of field experiments would likely not reflect the crop response information because of variation in growing season rainfall. Moreover results from trial and error field experiments are costly and may not be transferable over space or time.

Process-oriented crop growth models can be a useful alternative for simulating the long-term effects of water and N on crop yields and their temporal interactions (Batchelor et al., 2002; Basso et al., 2009a). Simulations of crop rotation have demonstrated that if the models are tested and calibrated in a given area, the simulations results can be used to explore the potential growth of the crop under different management strategies in that particular region (Norwood et al., 1990; Kolberg et al., 1996; O'Leary and Connor, 1996). Staggenborg and Vanderlip (2005) simulated different cropping systems in dry-land environment, concluding that with appropriate input data the model would lead to the same conclusions as the field studies, hence giving researcher a useful tool for understanding crop response prior to the growing season. Asseng et al. (2001) analysed the influence of N management practices on wheat crop grown on different soil types and rainfall using long-term simulation modelling. They found that yield, water use efficiency (WUE) and nitrogen use efficiency (NUE) were affected by soil water holding capacity, N management, and growing season rainfall. The quantification of the yield variation, WUE and NUE over time would have been difficult to estimate from field experiments alone.

In this study we hypothesized that a lower amount of N fertilizer may not correspond in a yield reduction. Moreover crop simulation models through a long-term simulation analysis provide a better understanding of the crop response to N rates in the environment. Higher N rates may result in unsustainable economic returns and greater environmental problems.

The objectives of this study were to (i) assess the efficiency of crop N uptake in a long-term wheat field study in a Mediterranean environment of southern Italy, (ii) identify optimal N rate in terms of economic and nitrate leaching using SALUS crop simulation model.

2. Materials and method

2.1. Site description and crop management

The field study was carried out at the Cereal Research Centre, Foggia, Italy (41°28″N, 15°32″E; elev. 75 m). The study was part of a long-term monoculture wheat system that started in 1991/1992 season, with two levels of nitrogen, 0 kg N ha^{-1} (0 N) and 90 kg N ha^{-1} (90 N). The experimental design consisted of two large plots, separated from each other by 5 m of bare soil. One plot received 90 kg N ha^{-1} as a split application for 17 years; one application at sowing with 25 kg N ha^{-1} as diammonium phosphate and the other at end of tillering with 65 kg N ha^{-1} as urea. The second plot had not received N for 17 years. Each plot was divided into three sub-plots (each 6 by 20 m). Inside each sub-plot, destructive and non-destructive measurements of crop and soil properties were collected at five different square meter areas. The sowing time window of durum wheat in the study area was between mid-November and mid-December. Durum wheat (*Triticum Durum*, Desf.; cv. Ofanto) was sown on 28 December 2006 with a row spacing of 17 cm on a clay-loamy soil according to the USDA particle-size distribution limits. In 2006/2007 a detailed sampling scheme was implemented, with measurements made at stem elongation (DC 30), flowering (DC 65), and harvest. Leaf Area Index (LAI) was collected through non-destructive measurements by using a portable LI-COR LAI 2000 (LI-COR Biosciences, Lincoln, Nebraska, USA) on five points inside each sub-plot. Above-ground crop biomass was determined after drying the fresh samples in an oven at 105 °C. Grain weight (kg ha^{-1}) was determined and other yield components measured were number of spikes/m^2, spike length, number of spikelets per spike and number of kernel per spike. Grain weight data for this experiment were available only for some of the years of the experiment.

Crop total nitrogen (g kg^{-1}), crop nitrate-N, and soil N (total N, ammonium-N and nitrate-N) were analysed by a private laboratory. From the final protein content, the grain N concentration was determined by dividing protein content by 5.7 as reported by Tkachuk (1969) and the N content in straw and chaff was assumed to be 1.5% (Ryan et al., 2009).

The crop N uptake was calculated by multiplying the total above-ground biomass by the N%. Crop N uptake was available for five years, from growing season 2002/2003 until 2006/2007.

2.2. Soil sampling

Soil samples were collected at the beginning of the growing season, and at flowering in each block for soil chemical analysis. Before sowing soil samples were take to determine texture using hydrometer method (Klute and Dirkens, 1986), soil N with the Kjedahl method, organic C with the Walkley–Black (1934) method and bulk density with the method described by Blake and Hartge (1986); and for those determinations soil samples were made at five depths (0–10, 10–30, 30–50, 50–80, 80–120 cm).

At flowering, total N was determined with the Kjedahl method. Soil N was measured to 60 cm depth. Soil water content was measured at 60 cm using the Time Domain Refractometry (TDR) technique for the following dates, 12 February 2007, 28 February 2007, 6 April 2007.

2.3. Crop growth model

We used SALUS model to simulate the wheat and fallow rotation adopted in the study. The SALUS model (System Approach to Land Use Sustainability; Basso, 2000; Basso et al., 2006; Senthilkumar et al., 2009) is designed to simulate continuous crop, soil, water, and nutrient conditions under different management strategies for multiple years. The model time step is daily and for each simulation run a different number of management strategies can be run simultaneously. This allows the user to compare the effects of each management strategy on crop and soil conditions under the same weather sequence. Model assessments provide a framework whereby the interaction between different areas under different management practices can be compared.

The components run daily for each management strategy are water balance, soil organic matter, nitrogen and phosphorous balances, heat balance, plant growth and development, and the specific management practice.

The soil water balance module is based on that used in the CERES models (Ritchie and Otter, 1985) but it differs in the calculation of infiltration, drainage, evaporation and runoff (Suleiman and Ritchie, 2003; Ritchie et al., 2009). In SALUS, a simplified time-to-ponding (TP) concept is used instead of the runoff and infiltration calculations based on the SCS curve numbers.

The soil organic matter (SOM) and nitrogen module is derived from Century model (Parton et al., 1988) but with a number of modifications incorporated. Organic matter and N mineralization/immobilization are simulated from three SOM pools (active, slow and passive) which vary in their turnover rates and characteristics C:N ratios. There are two crop residue/fresh organic matter pools (structural and metabolic), for representing recalcitrant and easily decomposable residues, based on residue lignin and N content. A surface active SOM pool associated with the surface residue pools was added to improve simulation of conservation tillage systems and perennial crops.

The soil phosphorous (P) model incorporates inorganic and organic P dynamics. Inorganic P is divided into three pools (i) labile; (ii) active; (iii) stable (Daroub et al., 2000).

Crop growth modules are based on the CERES and IBSNAT (Ritchie and Otter, 1985; IBSNAT, 1993) families which were originally developed for single years and monoculture simulations. In SALUS the models have been restructured into crop growth modules linked to the soil water, nutrient and management sub-models. Currently, SALUS crop modules include wheat, and maize. Phasic development is function of environmental variables such as degree days, photoperiod, and variety-specific genetic coefficients.

Carbon assimilation and dry matter production are a function of potential rates (which are influenced by light interception and crop growth potential which is variety-specific) which are then reduce according to water and/or N limitations. The main external inputs required for the crop growth routines are the genetic (variety-specific) coefficients and daily solar radiation as a driving variable.

Modules for other crops in SALUS are done through a process similar to the ones used in EPIC and CROPSYST (Stöckle et al., 2003) whereby the LAI pattern of a crop is input to provide a pattern of growth for a crop to intercept radiation, accumulate biomass and arrive at a yield through use of harvest index inputs.

The weather data used by the model included 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 a meteorological station sited near the experimental field for 56 years. Soil input data (sand, silt, and clay content, bulk density, organic carbon) were determined after collecting soil samples at five soil depth layers (0–10, 10–30, 30–50, 50–80, 80–120 cm) with a composite sampling scheme using an undisturbed soil core sampler. Soil water limits were calculated using the procedure suggested by Ritchie et al. (1999) (Table 1).

The model performance was evaluated using the root mean square error (RMSE):

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2\right]^{1/2} \tag{1}$$

where y_i are the observed measurements, $\hat{y}_i$ the simulated predictions and n is the number of comparisons. In addition, the relative error (R.E.) with respect to the observed mean, which compares how incorrect the simulation mean is with respect to observed mean, is calculated as follows:

$$\text{relative error}\,(\%) = \frac{|Sim - Obs|}{Obs} \times 100 \tag{2}$$

where *Sim* are the simulated mean values, *Obs* are the observed mean values.

2.4. Model testing

The model was tested against measurements of harvested grain yield, final N uptake, soil water content and total soil N, for the 0 and 90 N treatments. In addition the model was tested against 29 years of measured grain yield for the same wheat cultivar harvested in the experimental station. Measured data were available only for some of the experimental years (1991–2008). The model was tested with data available for the following years: yield data (1991/1992; 1992/1993; 1995/1996; 1998/1999; 2002/2003; 2003/2004; 2004/2005; 2005/2006; 2006/2007); final N uptake (2002/2003; 2003/2004; 2004/2005; 2005/2006); soil N (1991/1992; 1993/1994; 1994/1995; 1995/1996; 1996/1997; 2006/2007); and volumetric soil water content was tested with data from the growing season 2006/2007 and for the following dates (12 February 2007, 28 February 2007, 6 April 2007). The model was also tested for the major growth stages, stem elongation, anthesis and harvest for the growing season 2006/2007.

2.5. Simulation scenarios

The model was run in a continuous mode accounting for the soil N dynamic of the off-season fallow period. Six level of N (no N added, 30, 60, 90, 120, and 180 kg N ha^{-1}) with no supplemental irrigation selected.

Table 1
Soil physical and chemical properties for the experimental site (Foggia, Italy), collected before sowing during the growing season 2006/2007. Soil water limits and hydraulic conductivity (cm/h) have been estimated using the procedure suggested by Ritchie et al. (1999).

	Sand (%)	Clay (%)	Bulk density (g cm^{-3})	Organic carbon (%)	Soil N (g kg^{-1})	RHF[a] (%)	Coarse fraction (%)	DUL[b] (cm^3 cm^{-3})	LL[c] (cm^3 cm^{-3})	PESW[d] (cm^3 cm^{-3})	SAT[e] (cm^3 cm^{-3})	Ksat[f] (cm/h)
0–10	23	55	1.2	1.6	0.11	1.0	5	0.268	0.128	0.140	0.503	1.67
10–30	32	48	1.3	1.3	0.14	1.0	5	0.269	0.131	0.138	0.469	1.25
30–50	35	45	1.4	1.0	0.08	0.7	5	0.280	0.143	0.137	0.434	0.71
50–80	45	39	1.4	0.6	0.05	0.4	5	0.261	0.126	0.135	0.434	1.00
80–120	59	27	1.5	0.5	0.04	0.3	5	0.255	0.122	0.133	0.399	0.75

[a] Root hospitality factor.
[b] Drain upper limit.
[c] Lower limit.
[d] Plant extractable soil water.
[e] Saturation.
[f] Soil hydraulic conductivity.

Table 2
Crop N uptake for the 0 and 90 N at Foggia (Italy) for five growing season (2002–2007).

Growing season	N uptake		Difference in N uptake (kg N ha^{-1})
	0 N (kg N ha^{-1})	90 N (kg N ha^{-1})	
2002/2003	31.9	45.3	13.4
2003/2004	61.3	80.4	19.1
2004/2005	51.7	79.8	28.1
2005/2006	66.1	89.2	23.1
2006/2007	36.7	57.4	20.7

2.6. Economic analysis

For each simulation scenario the approximated net income was calculated by subtracting from the assumed price of the grain (multiplying grain yield per its current market price) the production costs, which include fertilizer costs, ploughing, sowing (that include operational costs plus seeds costs), weeds and pest control and harvest. The costs of fertilizer, agronomic practice and grain price have been obtained from the Italian farmer's association (www.coldiretti.it) and the Italian Bureau of Statistic (www.istat.it).

The statistical analysis of variances (ANOVA) was performed with GENSTAT 10th edition (Lawes Agricultural Trust, 2007).

3. Results

3.1. Assessment of N fertilization on yield and N uptake in field study

The measured yield and N uptake for five years of data are reported in Tables 2 and 3. The crop N uptake ranged from 31.9 to 66.1 kg N ha^{-1} for 0 N and 45.3 to 89.2 kg N ha^{-1} for 90 N, the difference in crop N uptake between 90 and 0 N ranged from 13.4 to 28.1 kg N ha^{-1} (Table 2). Grain yield over the five years period ranged from 1100 to 2880 kg ha^{-1} for the 0 N and from 1900 to 3600 kg ha^{-1} for the 90 N. The difference in grain yield between 90 and 0 N ranged from −900 to 1300 kg ha^{-1} (Table 3).

At stem elongation (DC 30) average crop biomass was 1045 and 1912 kg ha^{-1} for the 0 and 90 N, respectively. LAI values at DC30 were 1.06 for the 0 N and 2.7 for the 90 N. Crop N concentration ranged between 3.01 and 2.71% for the 0 and 90 N, respectively; while crop N content was 31.4 kg N ha^{-1} for the 0 N and 51.8 kg N ha^{-1} for the 90 N (Table 4). At anthesis (DC 65) average crop biomass ranged between 2876 kg ha^{-1} for the 0 N and 4868 kg ha^{-1} for the 90 N; LAI between 1.80 and 3.14 for the 0 and 90 N, respectively. Crop N concentration varied between 1.84% for 0 N and 2.37% for the 90 N, and crop N content (kg N ha^{-1}) between 53.1 and 115.3 kg N ha^{-1} for the 0 and 90 N, respectively (Table 4). Results were significantly different at $p < 0.01$ for all the variables at the two phenological stages.

The pattern of growing season rainfall (GSR) for 56 years is reported in Fig. 1. The highest GSR was observed in 1979/1980 with 595 mm of rain and lowest was observed in 1972/1973 with 231 mm of rain; annual average rainfall was 340 mm.

3.2. Model evaluation

The values of the root mean square error (RMSE) between measured and simulated results are reported in Tables 3 and 5, and an example of measured vs. observed data relationship is shown in Fig. 2b ($r^2 = 0.77$, $y = 0.94x + 194.5$, RMSE = 288 kg ha^{-1}, R.E. = 13%). Fig. 2a showed a previous model validation for the same cultivar for 29 years, from 1975 to 2003 ($r^2 = 0.82$, $y = 0.86x + 594.01$, RMSE = 480 kg ha^{-1}, R.E. = 7.3%) (Basso et al., 2009b). Measurements from different years were used for model validation (Tables 3 and 5), the RMSE for yield was 308 and 407 kg ha^{-1} with a R.E. of 14 and 12% for the 0 and 90 N, respectively (Table 3). RMSE for crop N uptake was 10 kg N ha^{-1} and R.E. 14.4% for 0 N and 7.50 kg N ha^{-1} with 6.4% of R.E. for 90 N, while soil N 12.8 kg N ha^{-1} (14.5%) for 0 N and 11.3 kg N ha^{-1} (12.9%) for 90 N

Table 3
Values of the measured yield, simulated yield, root mean square error (RMSE), and relative error (R.E.) for wheat cultivar "Ofanto" at Foggia (Southern Italy) for the growing season 1991/1992 until 1995/1996, then 1998/1999, and from 2002/2003 to 2006/2007.

Years	0 N measured (kg ha^{-1})	0 N simulated	90 N measured (kg ha^{-1})	90 N simulated
1991/1992	3400	2980	2500	2461
1992/1993	2050	1934	2250	2736
1994/1995	1630	1358	1630	1738
1995/1996	2880	2467	3380	4011
1998/1999	2880	2690	3500	3763
2002/2003	2300	2020	3000	3124
2003/2004	2800	2667	3600	3648
2004/2005	2400	2008	3300	3230
2005/2006	1800	1695	3100	3452
2006/2007	1100	1567	1900	2792
RMSE*	308 kg ha^{-1}		407 kg ha^{-1}	
R.E.**	14%		12%	

* Root mean square error.
** Relative error.

Table 4
Canopy biomass, LAI, crop N concentration and crop N content for wheat crop at Foggia (Italy) the growing season 2006/2007 as average of five replicates at stem elongation (DC30) and flowering (DC65).

Treatments and crop stage	Biomass (kg ha^{-1})	LAI (m^2 m^{-2})	Crop N (%)	Crop N (kg N ha^{-1})
DC30 0 N	1045[a] ((31.4)[b,**]	1.06[a] (0.041)[b,**]	3.01 (0.24)**	31.4 (0.84)**
DC30 90 N	1912 (54.1)	2.7 (0.147)	2.71 (0.018)	51.8 (1.29)
DC65 0 N	2876 (112.3)**	1.80 (0.108)**	1.84 (0.068)**	53.1 (3.02)**
DC65 90 N	4868 (40.55)	3.14 (0.138)	2.37 (0.123)	115.3 (5.57)

[a] The mean of the treatments.
[b] The standard error of the mean ($n = 12$).
** Significant at 1% level.

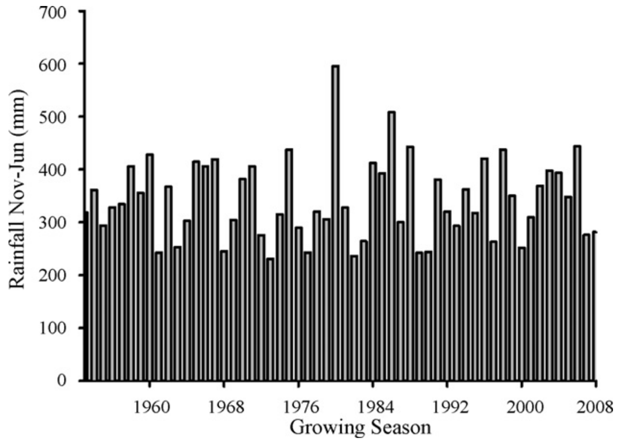

Fig. 1. Pattern of the growing season rainfall (GSR), for 56 years, from 1952/1953 to 2007/2008.

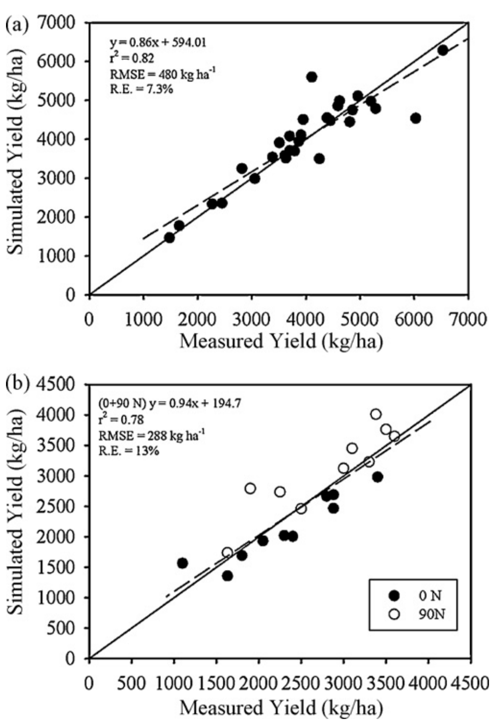

Fig. 2. Validation of SALUS crop simulation model for wheat cultivar "Ofanto" at Foggia experimental station with 29 years of measured yield adapted from Basso et al. (2009a,b) (a); simulated vs. measured grain yield for the growing season 1991/1992 until 1995/1996, then 1998/1999, and from 2002/2003 to 2006/2007 at Foggia experimental station (Southern Italy) (b).

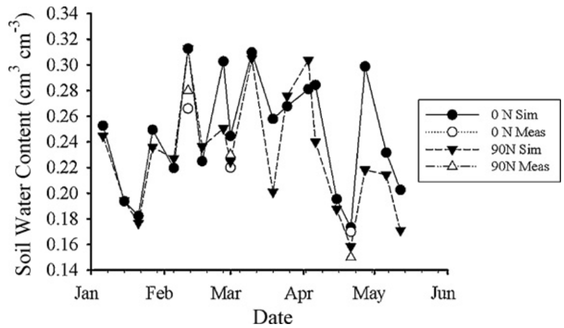

Fig. 3. Measured soil water content (SWC) with SALUS crop model for 0 N (closed dots) and 90 N (open dots), and simulated SWC for 0 N (closed line) and 90 N (dotted line) at Foggia (Southern Italy). Measurements are shown as an average of 0–60 cm on the following dates: 12 February 2007, 28 February 2007, 6 April 2007. The bar represents the standard error.

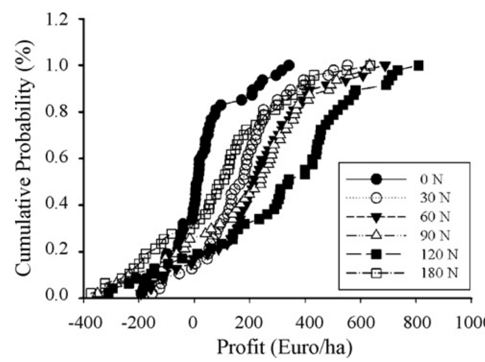

Fig. 4. Cumulative probability function (CPD) of profit for 56 years of simulations run and for six N rates at Foggia (Italy).

(Table 5). RMSE for soil water content was 0.04 $cm^3\ cm^{-3}$ (17.1%) and 0.05 $cm^3\ cm^{-3}$ (23.8%) for the 0 and 90 N, respectively (Fig. 3).

3.3. Selection of optimal N rate using simulation model data

Fifty-six years of simulations with different N rates are shown in Table 6 and Fig. 4. On average 0 N was the less productive system with an average yield of 1922 kg ha^{-1} and fertilization rates of 120 kg N ha^{-1} resulted in higher yield with an average yield of 3528 kg ha^{-1} (Table 6). The simulated results showed that the mean yield was higher for 120 N with 3742 kg ha^{-1} followed by 90 N (3327 kg ha^{-1}), 60 N (2994 kg ha^{-1}), 30 and 180 N showed similar mean values (2700 kg ha^{-1}), while 0 N showed the lowest yield mean value (1866 kg ha^{-1}). However, in 30% of the case, 120 and 60 N showed the same yield probability and in 20% of the cases 30, 60, 90, 120 and 180 N showed similar yield (Table 6).

The economic analysis is shown in Table 7 with the gain and costs associated to wheat production. The highest profit was obtained from 120 N (302.4 Euro ha^{-1}), and the lowest from 0 N

Table 5
Number of years used for model validation for the site in Foggia (Southern Italy). Observed means, simulated means, root mean N uptake (2002/2003, 2003/2004, 2004/2005, 2005/2006), soil N (0–60 cm) (1991/1992, 1993/1994, 1994/1995, 1995/1996, 1996/1997, 2006/2007); and observed and simulated crop growth stages for the growing season 2006/2007 for the 0 and 90 N treatments.

	0 N				90 N			
	Observed mean	Simulated mean	RMSE	R.E. (%)	Observed mean	Simulated mean	RMSE	R.E. (%)
N uptake (kg N ha^{-1})	52.5	59.9	10	14.4	79.8	77.1	7.5	6.4
Soil N (kg N ha^{-1})	83.2	93.2	12.8	14.5	83	93	11.3	12.9
Growth stages								
End of juvenile stage (Zadoks 10)	15 March	13 March			15 March	13 March		
Anthesis (Zadoks 60)	21 April	20 April			21 April	20 April		
Maturity (Zadoks 87)	1 June	30 May			1 June	30 May		

Table 6
Annual average values and standard deviation (S.D.) for yield, profit, N leaching, and drainage, from 56 years simulation (1992–2008) runs with SALUS crop models for the six N rates at Foggia (Southern Italy). Different upper-case letters indicate statistically significant differences (LSD test, $p \leq 0.05$).

N rates	Yield		Profit		N leaching			Drainage	
	Average ($kg\,ha^{-1}$)	S.D.* ($kg\,ha^{-1}$)	Average ($Euro\,ha^{-1}$)	S.D. ($Euro\,ha^{-1}$)	Annual average ($kg\,N\,ha^{-1}$)	S.D. ($kg\,N\,ha^{-1}$)	Cumulative (17 years) ($kg\,N\,ha^{-1}$)	Average (mm)	S.D. (mm)
0 N	1922 A	640.4	24.5	128.1	26.52 A	14.81	450	15.81 A	26.59
30 N	2685 B	791.3	166.3	158.3	27.31 A	19.92	464	14.93 A	26.64
60 N	3010 B	1007.2	220.4	201.4	30.62 B	21.39	520	16.08 A	27.22
90 N	3054 B	1235.1	186.0	247.0	32.28 B	24.41	550	18.84 B	30.08
120 N	3528 C	1433.0	302.4	286.6	49.06 C	23.78	834	16.00 A	29.13
180 N	2960 B	1175.6	87.2	235.1	81.22 D	22.17	1380	15.82 A	28.80

* Standard deviation.

Table 7
Profit calculation for the six N rates at Foggia (Italy). The net income is calculated by subtracting to grain return the aggregated costs for wheat production.

	Yield[a] ($kg\,ha^{-1}$)	Fertilizer ($kg\,N\,ha^{-1}$)	Fertilizer cost ($Euro\,ha^{-1}$)	Grain return ($Euro\,ha^{-1}$)	Ploughing ($Euro\,ha^{-1}$)	Sowing* ($Euro\,ha^{-1}$)	Harvest ($Euro\,ha^{-1}$)	Weed/pest control ($Euro\,ha^{-1}$)	Net income[b] ($Euro\,ha^{-1}$)
0 N	1922	0	0	384.4	60	120	60	120	24.45
30 N	2685	30	10.8	537.1					166.3
60 N	3010	60	21.6	602.0					220.4
90 N	3053	90	32.4	610.7					185.9
120 N	3527	120	43.2	705.6					302.4
180 N	2960	180	64.8	512.0					87.2

[a] Simulated yield.
[b] Net income calculated as follows: grain price − (fertilizer cost + ploughing + weed/pest control + sowing + harvest).
* Sowing considers the global costs (operational plus seeds).

($24.5\,Euro\,ha^{-1}$). The 60 N showed higher profit than 90 and 180 N, with 220.4, 186, and 87.2 $Euro\,ha^{-1}$, respectively (Table 7). The CPD for the profit shows that 120 N is on average the treatment that provided a higher profit. However, for 30% of the cases its profit is similar to 60 N (Fig. 4).

Simulated results for the nitrate leaching from the bottom of the soil profile (>100 cm) is shown in Table 6. The higher leaching was reported for the 180 N with a mean annual value of ($81\,kg\,N\,ha^{-1}$) followed by 120 N ($49\,kg\,N\,ha^{-1}$), 90 N ($32.4\,kg\,ha^{-1}$). The 60 N showed similar leaching results to 30 and 0 N with a mean value of 30, 27 and 26 $kg\,ha^{-1}$ respectively.

4. Discussion

The SALUS crop simulation model indicated that under the soil and weather conditions of the field site in Foggia (Italy), the N fertilization with $90\,kg\,N\,ha^{-1}$ is excessive because crops rarely take up that much. The simulation with 6 different N rates showed that yield response was not different between 90 and 60 N. Results of the simulations suggest that the 120 N is the rate that gives higher yield and higher profit, but the leaching is significantly greater than 90 and 60 N treatments. The higher nitrate leaching of 180 N simply excludes the high N rate from any possibility of N management under any perspectives: yield, profit or environment. The higher net economic return showed by the 120 N treatment is not justified if the environmental impact of nitrate leaching is considered as the results showed with the annual nitrate leaching data of $49\,kg\,ha^{-1}$. Corbeels et al. (1999) found that after rainfall on a Vertisol, 60% of residual N fertilizer remained into the soil at the end of the season, and that the fertilization with $100\,kg\,N\,ha^{-1}$ had no effects.

Moreover, higher N fertilization rates are also associated to higher nitrous oxide (N_2O) emissions from agricultural systems (Robertson and Goffman, 2007). Millar et al. (2010) discussed some strategies aimed at reducing on N_2O emissions, maintaining crop productivity and farmers' profit. This should be the consequence of a trade-off between N_2O emissions, N fertilizer management practices, and crop yield.

Therefore, choosing the appropriate N rate represent as the most tangible and manageable commodity to reduce environmental pollution from GHG emissions and N leaching. In this study, results of the long-term simulation suggest that such a trade-off is represented by $60\,kg\,N\,ha^{-1}$. This result agrees with the findings of Oweis (1997) that in the Syria reported a suggested N rate of $50\,kg\,N\,ha^{-1}$. In the same environment of the field study carried out, Rinaldi (2004) used CERES-Wheat to estimate costs and benefits of agricultural practices in relation to crop available water at sowing date, nitrogen fertilization time and amount. Optimal N fertilizer amount was $100 \pm 20\,kg\,N\,ha^{-1}$ from both productive and economic point of view. Our results provide an additional insight on the effects on N fertilization on yield and crop N uptake to the previous findings, due to the combination of long-term field measurements and simulation results of leaching data.

In conclusion, the adoption of simulation models to assess the best N rate for durum wheat in rainfed Mediterranean environment that takes into consideration both profit and leaching, proved to be a useful tool due to the inherent system approach and for the capability to quantifying the temporal variability of the final yield under different N rates.

References

Angus, J.F., van Herwaarden, A.F., 2001. Increasing water use and water use efficiency in dryland wheat. Agron. J. 93, 290–298.
Asseng, S., Turner, N.C., Keating, B.A., 2001. Analysis of water- and nitrogen-use efficiency of wheat in a Mediterranean climate. Plant and Soil 233, 127–143.
Basso, B., 2000. Digital terrain analysis and simulation modeling to assess spatial variability of soil water balance and crop production. Ph.D. dissertation, Michigan State University, East Lansing.
Basso, B., Ritchie, J.T., Grace, P.R., Sartori, L., 2006. Simulation of tillage systems impact on soil biophysical properties using the SALUS model. Italian J. Agron. 4, 677–688.
Basso, B., Cammarano, D., Chen, D., Cafiero, G., Amato, M., Bitella, G., Rossi, R., Basso, F., 2009a. Landscape position and precipitation effects on spatial variability of wheat yield and grain protein in Southern Italy. J. Agron. Crop Sci. 195, 301–312.
Basso, B., Cammarano, D., Grace, P.R., Cafiero, G., Sartori, L., Pisante, M., Landi, G., De Franchi, S., Basso, F., 2009b. Criteria for selecting optimal nitrogen fertilizer rates for precision agriculture. Italian J. Agron. 4, 159–174.

Batchelor, W.D., Basso, B., Paz, J.O., 2002. Examples of strategies to analyze spatial and temporal yield variability using crop models. Eur. J. Agron. 18, 141–158.
Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis, Part I. Physical and Mineralogical Methods: Agronomy Monograph no. 9, 2nd ed. ASA Madison, WI, pp. 363–375.
Corbeels, M., Hofman, G., Van Cleemput, O., 1999. Fate of fertiliser N applied to winter wheat growing on a Vertisol in a Mediterranean environment. Nutrient Cycl. Agroecosyst. 53, 249–258.
Daroub, S.H., Pierce, F.J., Ellis, B.G., 2000. Phosphorus fractions and fate of phosphorus-33 in soils under plowing and no-tillage. Soil Sci. Soc. Am. J. 64, 170–176.
EPA, United States Environmental Protection Agency, 2009. Inventory of US greenhouse gas emissions and sinks: 1990–2007. EPA 430-R-09-004.
IBSNAT, 1993. International Benchmark Sites Network for Agrotechnology Transfer. The IBSNAT Decade. Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, Hawaii.
Klute, A., Dirkens, C., 1986. Hydraulic conductivity and diffusivity: laboratory methods. In: Klute, A. (Ed.), Methods of Soil Analysis: Physical and Mineralogical Methods: Agronomy Monograph no. 9, 2nd ed. ASA Madison, WI, pp. 687–734.
Kolberg, R.L., Kitchen, N.R., Westfall, D.G., Peterson, G.A., 1996. Cropping intensity and nitrogen management impact of dryland no-till rotations in the semi-arid western Great Plains. J. Prod. Agric. 9, 517–522.
Lawes Agricultural Trust, 2007. GenStat tenth edition for Windows version 10.1. Lawes Agricultural Trust. VSN International, Hemel Hempstead, U.K.
LI-COR Inc., LI-COR LAI 2000, Operating manual, LI-COR Biosciences, Lincoln, Nebraska, U.S.A., pp. 1–147.
Millar, N., Robertson, P.G., Grace, P.R., Gehl, R.J., Hoben, J.P., 2010. Nitrogen fertilizer management for nitrous oxide (N_2O) mitigation in intensive corn (Maize) production: an emissions reduction protocol for US Midwest agriculture. Mitig. Adapt. Straeg. Glob. Change, doi:10.1007/s11027-010-9212-7.
Mosier, A.R., 2002. Environmental challenges associated with needed increases in global nitrogen fixation. Nutr. Cycl. Agroecosyst. 63, 101–116.
Norwood, C.A., Schlegel, A.J., Morishita, D.W., Gwin, R.W., 1990. Cropping system and tillage effects on available soil water and yield of grain sorghum and wheat. J. Prod. Agric. 3, 356–362.
O'Leary, G.J., Connor, D.J., 1996. A simulation model of the wheat crop in response to water and nitrogen supply: II. Model validation. Agric. Syst. 52, 31–55.
Oweis, T., 1997. Supplemental irrigation. A highly efficient water use practice. ICARDA Eds., 16 pp.
Parton, W.J., Stewart, J.W.B., Cole, C.V., 1988. Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5, 109–131.
Passioura, J.B., 2006. Increasing crop productivity when water is scarce—from breeding to field management. Agric. Water Manage. 80, 176–196.
Rinaldi, M., 2004. Water availability at sowing and nitrogen management of durum wheat: a seasonal analysis with the CERES-Wheat model. Field Crop Res. 89, 27–37.
Ritchie, J.T., Otter, S., 1985. Description and performance of CERES-Wheat: a user-oriented wheat yield model. In: ARS Wheat Yield Project. ARS-38. Natl. Tech. Info. Serv., Springfield, MO, USA, pp. 159–175.
Ritchie, J.T., Gerakis, A., Suleiman, A., 1999. Simple model to estimate field-measured soil water limits. Trans. ASAE 42, 1609–1614.
Ritchie, J.T., Porter, C.H., Jones, J.W., Suleiman, A.A., 2009. Extension of an existing model for soil water evaporation and redistribution under high water content conditions. Soil Sci. Soc. Am. J. 73, 792–801.
Robertson, G.P., Goffman, P., 2007. Nitrogen transformations. In: Paul, E.A. (Ed.), Soil Microbiology, Ecology, and Biochemistry, 3rd ed. Academic/Elsevier, New York, pp. 341–364.
Ryan, J., Ibrikci, H., Sommer, R., McNeill, A., 2009. Nitrogen in rainfed and irrigated cropping systems in the Mediterranean region. Adv. Agron. 104, 53–136.
Senthilkumar, S., Basso, B., Kravchenko, A.N., Robertson, G.P., 2009. Contemporary Evidence of Soil Carbon Loss in the U.S. Corn Belt. Soil Sci. Soc. Am. J. 73, 2078–2086.
Staggenborg, S.A., Vanderlip, R.L., 2005. Crop simulation models can be used as dryland cropping systems research tools. Agron. J. 97, 378–384.
Stöckle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron. 18, 289–307.
Suleiman, A.A., Ritchie, J.T., 2003. Modeling soil water redistribution during second-stage evaporation. Soil Sci. Soc. Am. J. 67, 377–386.
Tkachuk, R., 1969. Nitrogen-to-protein conversion factors for cereals and oilseed meals. Cereal Chem. 46, 419–423.
Van Herwaarden, A.F., Angus, J.F., Richards, R.A., Farquhar, G.D., 1998. Haying-off, the negative grain yield response of dryland wheat to nitrogen fertiliser. II. Carbohydrate and protein dynamics. Aust. J. Agric. Res. 49, 1083–1093.
Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining organic carbon in soils: Effect of variations in digestion conditions and of inorganic soil constituents. Soil Sci. 63, 251–263.
Zadoks, J.C., Chang, T.T., Konzak, C.F., 1974. A decimal code for the growth stages of cereals. Weed Res. 14, 415–421.