

Balance Sheet Method Assessment for Nitrogen Fertilization in Winter Wheat: II. Alternative Strategies Using the CropSyst Simulation Model

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Abstract

It is important, both for farmer profit and for the environment, to correctly dose fertilizer nitrogen (N) for winter wheat growth. Balance-sheet methods are often used to calculate the recommended dose of N fertilizer. Other methods are based on the dynamic simulation of cropping systems. Aim of the work was to evaluate the balance-sheet method set up by the Region Emilia-Romagna (DPI), by comparing it with the cropping systems simulation model CropSyst (CS), and with an approach based on fixed supplies of N (T). A 3-year trial was structured as a series of N fertility regimes at 3 sites (Papiano di Marsciano, Ravenna, San Pancrazio). The N-regimes were generated at each site-year as separate trials in which 3 N rates were applied: N1 (DPI), N2 (DPI+50 kg ha⁻¹ N at spike initiation), N3 (DPI + 50 kg ha⁻¹ N at early booting). Above ground biomass and soil data (NO₃-N and water) were sampled and used to calibrate CS. Doses of fertilizer N were calculated by both DPI and CS for winter wheat included in three typical rotations for Central and Northern Italy. Both these methods and method T were simulated at each site over 50 years, by using daily generated weather data. The long-term simulation allowed evaluating such alternative fertilization strategies. DPI and CS estimated comparable crop yields and N leached amounts, and both resulted better than T. Minor risk of leaching emerged for all N doses. The N2 and N3 rates allowed slightly higher crop yields than N1.

Key-words: balance-sheet method, CropSyst, leaching, nitrogen fertilization, winter wheat.

1. Introduction

The amount of fertilizer nitrogen (N) applied to a crop has important repercussions both for the farmer profit and for the environment (Spiertz, 2002). Environmental constraints are forcing farmers in Western Europe to be increasingly precise in determining the rate and date of nitrogen fertilizer application to crops. Leaching is the major route by which nitrate enters ground and surface waters, while denitrification

and volatilization are significant sources of N₂O, an important greenhouse gas. Environmental concerns have become pressing after the European Directive 91/676 (nitrate directive) was published, which calls for the identification of pollution-sensitive zones and for strict control of fertilizer N use within those zones. This has led to a series of local initiatives with the objective of defining environmentally sound farming practices in each region (Ziegler et al., 1996;

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Spiertz, 2002; Vanden Auweele and Vanden-driessche, 2002).

Achieving synchrony between N supply and crop demand without excess or deficiency is the key to optimizing trade-offs amongst yield and environmental protection. Developing effective strategies to meet this challenge requires quantitative understanding of current levels of N use efficiency and losses in cropping systems, and the biophysical controls on these factors from adoption of improved management practices (MacDonald et al., 1989; Powlson et al., 1992; Strong, 1995; Recous et al., 1997). Fertilizer recommendations are embodied in decision rules, which prescribe a recommended nitrogen dose as a function of site-year characteristics available at the time the fertilizer decision is made. Many different decision rules can be and have been proposed (Remy and Hébert, 1977; Wehrmann et al., 1988; de Willigen, 1991; Jeufroy and Recous, 1999; Thorup-Kristensen, 2002), and it is important to be able to choose the most appropriate.

A family of methods for calculating N fertilizer requirements includes the so-called balance-sheet methods, based on a vector of crop, climate, and site-year characteristics. Such methods are widely used in Europe (e.g., Machet and Dubrulle, 1990; ITCF, 1996; Meynard et al., 1997). The Region Emilia-Romagna set up a balance-sheet method (*Disciplinare Produzione Integrata*, hereafter designated as DPI) for estimating the winter wheat fertilizer N requirements, based on the main but effective factors affecting crop nutrition (Carnevali and Sarno, 1998; AA.VV., 2000; Carnevali et al., 2000). This is a static method which gives, in its original outline, the amount of fertilizer N to be supplied at spike initiation. According to manuscript I, additional nitrogen supplies are suggested, even applied in two dressings (second application at beginning of booting), especially for great strength and high bread-making quality's cultivars. This arises environmental concerns, as extra-N supplies may at times give unacceptable risks for the environment.

A second family of decision rules is based on dynamic simulation modelling of the cropping systems (Addiscott et al., 1991; Kerserbaum and Richter, 1991; Otter-Nacke and Khulmann, 1991). A crop growth estimator, simulating crop biomass accumulation with variations

of climate/soil variables and management options, is at the core of cropping systems models. Dynamic models can be used to schedule N fertilization of field crops by simulation-based decision rules (Meynard et al., 2002), as they estimate soil profile nitrogen and crop uptake including the entire soil depth explored by roots, and using a daily frequency. Some cropping systems models make available automatic options for optimum scheduling of nitrogen fertilization, while providing insight into the system. This is the case of CropSyst (Stöckle et al., 2003), which was used in this work.

The choice of decision rules can have important repercussions on the recommended amount of N fertilizer. Evaluating different methods poses some issues on how judge them. Traditionally, this has been done by experimental trials performed at different sites over a few growing seasons (Magnickij, 1973). These studies are generally limited in scope and do not account for long-term effects (exceptional and/or cyclical weather variability) as needed for probabilistic assessments and decision making. The assessment of the impact of recommended N rates from alternative methods on crop productivity and the environment in the long time is one case where conventional experimentation is of limited use without the complement of simulation-based tools. In particular, the information gathered from field trials may be used in conjunction with computer simulation to obtain a more complete understanding of the problem and extrapolate findings in time. Cropping systems models are suitable to account for uncertainties in the weather variability when coupled to weather generators.

Aim of this paper was to evaluate, by means of a long-term simulation analysis, the static model set up for winter wheat by the Region Emilia-Romagna (DPI), comparing it with the CropSyst automatic N fertilization option and a conventional N management.

2. Materials and methods

2.1 Fertilizer nitrogen requirement

An empiric and static method developed by the Region Emilia-Romagna was used for the calculation of N fertilizer. The method, designated hereafter as DPI, has been described in manu-

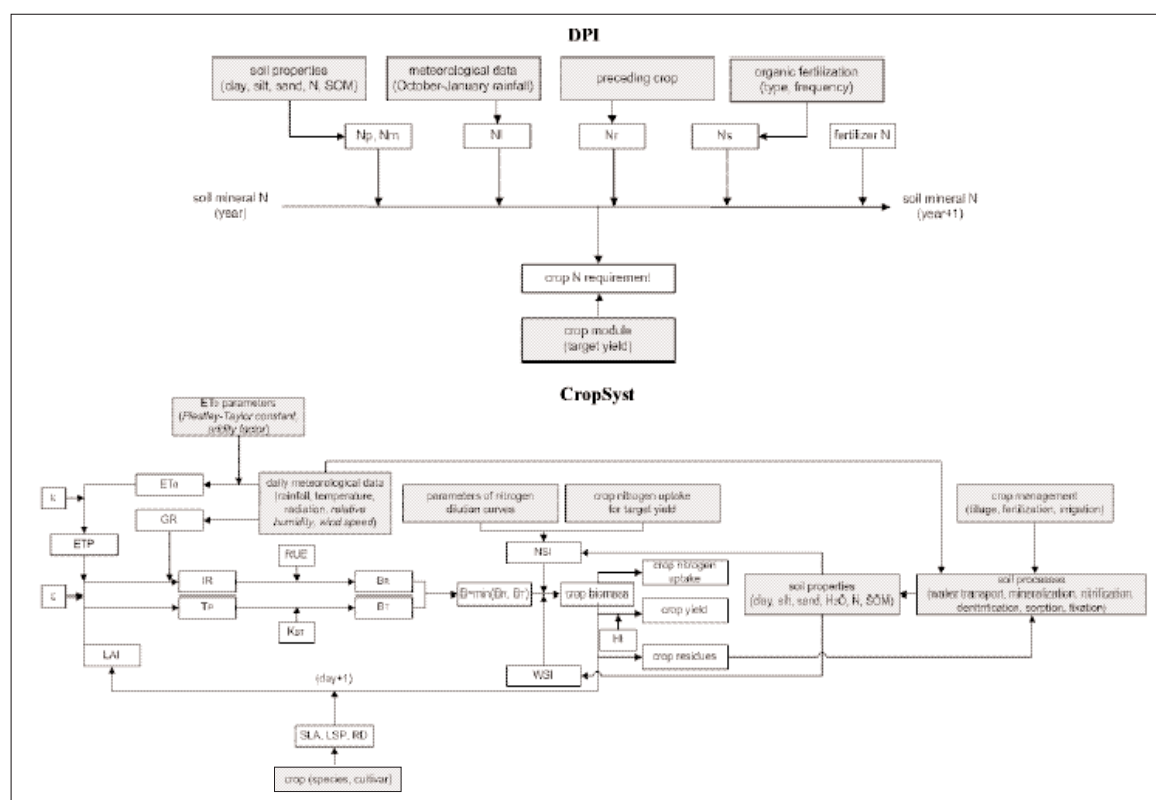


Figure 1. Diagrams of the DPI balance-sheet and CropSyst methods of nitrogen requirement. N: total soil nitrogen; SOM: soil organic matter; Np: available nitrogen at sowing date; Nm: mineralized nitrogen from soil organic matter; Nl: nitrogen lost by leaching; Nr: nitrogen from the preceding crop; Ns: nitrogen from organic fertilization; ET_0 : reference crop evapotranspiration; k: evapotranspiration crop coefficient; ETP: crop potential evapotranspiration; GR: global radiation; ϵ : extinction coefficient; IR: intercepted radiation; T_p : potential transpiration; LAI: leaf area index; SLA: specific leaf area; LSP: leaf/stem partition coefficient; RD: root depth; RUE: radiation use efficiency; K_{BT} : biomass-transpiration coefficient; B_R : radiation-limited crop biomass; B_T : water-limited crop biomass; B: potential crop biomass; NSI: nitrogen stress index; WSI: water stress index; HI: harvest index; boxes in grey: sub-model inputs; italicized words: optional inputs (ET_0 Penman-Monteith equation is applied if optional meteorological variables are available, Priestley-Taylor equation otherwise).

script I and is based on a simplified nitrogen budget over the growing season (top graph of Figure 1).

CropSyst (version 3.03.12; Stöckle et al., 2003), a cropping systems simulation model with crop growth and water and N balance capabilities (bottom graph of Figure 1), was also used to schedule N fertilizations, based on crop N requirements corresponding to known yield expectations and N budgeting simulation (Donatelli and Stöckle, 2000). The crop sub-model simulates the daily N requirements of the crop, according to water- and radiation-limited analysis, and from the changes in the critical N content of the aerial parts of the crop (Justes et al., 1994). The mineral N budget in CropSyst includes separate budgets for nitrate and ammo-

nium. Processes include N transformations, ammonium sorption, symbiotic N fixation (when required), crop N demand and crop N uptake. Nitrogen transformations (net mineralization, nitrification, and denitrification) and ammonium sorption follow the approach presented by Stöckle and Campbell (1989). Due to its ability to integrate soil water and N budgets and weather variables to produce realistic simulations of crop growth and yield, the model was found suitable to meet the requirements of this study.

2.2 Field experiments

2.2.1 Sites, years and management-regimes. We refer the interested reader to manuscript I for details on field trials. Crop and soil data for the

Table 1. Initial soil characteristics at the three sites.

Soil variable	Soil depth (m)					
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.2
Papiano di M. (09/12/1997)						
Sand (%)	12.1	14.0	9.3	5.6	4.4	10.9
Silt (%)	48.9	47.4	48.3	53.5	55.0	55.6
Clay (%)	39.0	38.6	42.4	41.0	40.6	33.5
SOM (%)	1.6	1.7	1.6	1.2	1.0	0.7
Total N (‰)	1.6	1.6	2.8	1.8	1.1	1.1
NO ₃ -N (mg kg ⁻¹)	3.9	3.4	4.0	2.6	1.4	2.8
Ravenna (03/11/1997)						
Sand (%)	9.7	9.3	8.5	3.0	7.8	9.0
Silt (%)	64.3	64.7	64.8	68.2	66.0	71.3
Clay (%)	26.0	26.0	26.7	28.8	26.2	19.7
SOM (%)	1.6	1.6	1.4	1.2	0.9	0.7
Total N (‰)	1.1*					
NO ₃ -N (mg kg ⁻¹)	3.3	3.2	12.3	1.1	0.6	10.5
San Pancrazio (31/10/1997)						
Sand (%)	20.7	16.8	13.3	14.5	27.3	11.5
Silt (%)	40.3	41.0	45.2	44.0	29.0	49.5
Clay (%)	39.0	42.2	41.5	41.5	43.7	39.0
SOM (%)	1.8	2.00	1.4	1.2	1.0	0.8
Total N (‰)	1.6*					
NO ₃ -N (mg kg ⁻¹)	4.0	4.7	6.8	28.2	7.3	1.7

* Average value across all layers of the soil profile.

modelling approach presented in this study were collected on cultivars Bolero and Pascal only. After a preliminary analysis performed at all locations, a full modelling study was carried out at three sites: Papiano di Marsciano (Region Umbria, province of Perugia, lat. 42.57 N, long. 12.22 E), Ravenna (Region Emilia-Romagna, lat. 44.00 N; long. 11.90 E), San Pancrazio (Region Emilia-Romagna, province of Parma, lat. 44.50 N, long. 10.28 E).

Initial soil characteristics are reported in Table 1. Soils are regarded as clay at Papiano di Marsciano and San Pancrazio, and loam at Ravenna. Weather data obtained from weather stations located near the experimental sites were used as a characterization of the weather conditions at each of the nine site-year combinations sampled in this study. In summary, the three locations are characterized by fairly similar climatic conditions, i.e. warm humid summers, with maximum air temperature at times higher than 35 °C, maximum relative humidity often higher than 95%, and rainfall mostly concentrated in spring and autumn. Differences in the precipitation patterns are shown in Figure 2. Within each site-year combination the man-

agement variables planting time, fertilizer N application, and preceding crop were manipulated to create a number of different management-regime treatments. Management-regime treatments for each cultivar differed among the nine site-year combinations tested, giving a total of 81 trials (Table 2).

2.2.2 Soil and crop samplings. Soil water content (m³ m⁻³) was periodically measured in the upper 0-1.2 m using the gravimetric method. Soil NO₃-N content (kg N ha⁻¹) was sampled at 0-1.2 m depth in the same period by ion selective electrode method.

Crop sampling regarded periodical measures of above ground dry matter (kg ha⁻¹), above ground nitrogen uptake (kg ha⁻¹), grain yield (kg ha⁻¹) and identification of the main phenological phases (seedling emergence, peak of leaf area index, start of flowering, physiological maturity).

2.3 The simulation study

2.3.1 Model parameters. Winter wheat parameters required by CropSyst were set based on typical field observations, or were taken from

Table 2. Experimental layout.

Site	Preceding crop	Sowing date	N schedule (kg ha ⁻¹)			
			Date	N1 rate	N2 rate	N3 rate
Papiano di Marsciano	Sorghum	09/12/1997	02/03/1998	100	150	100
			23/03/1998	50	50	100
	Sunflower	10/11/1998	09/03/1999	85	135	85
			01/04/1999	44	44	94
			09/03/2000	87	137	87
Ravenna	Sunflower	30/11/1999	30/03/2000	43	43	93
			16/03/1998	80	130	80
	Soybean	03/11/1997	20/04/1998	40	40	90
			17/03/1999	78	128	78
	Sugar beet	28/10/1998	15/04/1999	-	-	50
San Pancrazio	Tomato	29/10/1999	28/02/2000	40	40	40
			24/03/2000	78	128	78
	Sugar beet	18/11/1997	21/04/2000	-	-	50
			27/03/1998	80	130	80
	Sugar beet	30/10/1998	17/04/1998	-	-	50
			24/03/1999	63	113	63
			20/04/1999	-	-	50
	Sugar beet	01/11/1999	06/04/2000	76	126	76
			03/05/2000	-	-	50

the manual or other literature sources. A few parameters that tend to fluctuate among cultivars (e.g., above ground biomass-transpiration

coefficient) were calibrated to match selected data with model outputs. Field data corresponding to 3-year trials done in all locations were used for calibration. Crop phenology observed in the first growing season was the basis for determining the thermal time requirement for each phenological stage. Harvest dates for winter wheat occurred through July at all sites with some variations from season to season.

Parameters for potato, sugar beet and sunflower were extracted from the manual or other sources (Donatelli et al., personal communications). Weather parameters were extracted from 10-15 years of weather records (daily rainfall, minimum/maximum air temperatures, and daily incident solar radiation) and used to generate 50 years of daily records by using the weather generator ClimGen (version 4.01.05, Stöckle et al., 2001).

2.3.2 Long-term simulations. Fifty years of continuous cropping were simulated at each location. Table 3 gives the details of the N management scenarios used in this work. Three rotations, including winter wheat, that are traditionally performed in the study sites were used for long-term simulations: sugar beet-winter wheat (sb-ww), sugar beet-winter wheat-potato-winter wheat (sb-ww-p-ww), sunflower-winter wheat (sf-ww). The scenarios cover both DPI and CS strategies, according to three rate-spreading

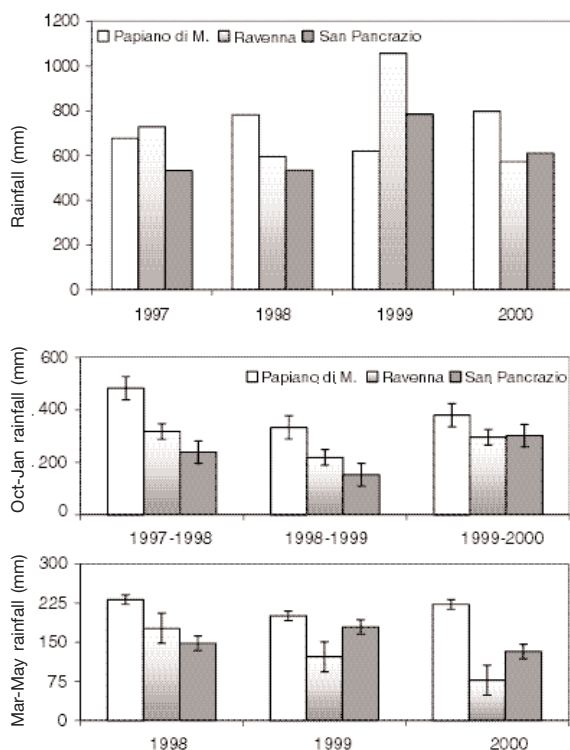


Figure 2. Annual rainfall amount (mm), rainfall amount in the period October-January, and rainfall amount in the period March-May registered at three locations during four years.

Table 3. Nitrogen management scenarios used in the simulation study.

Variable	Option	Crops			
		Winter wheat	Sugar beet	Potato	Sunflower
Rotation	sb-ww	x	x	-	-
	sb-ww-p-ww	x	x	x	x
	sf-ww	x	-	-	x
Fertilization strategy	DPI	x	-	-	-
		x	-	-	-
		x	-	-	-
	CS	x	-	-	-
		x	-	-	-
		x	-	-	-
Fertilizer N rate (kg ha ⁻¹)	conventional	x	x	x	x
	N1	DPI	-	-	-
	N2, N3	DPI+50	-	-	-
	conventional	220	100	100+50	120
Fertilizer spreading time	N1, N2	February 28	-	-	-
	N3	February 28	-	-	-
		March 21	-	-	-
	conventional	February 28	April 15	March 10	
				May 10	March 2

time combinations (N1, N2, N3). The CS strategies were achieved by setting N fertilization parameters so as to approximate, in the long-term average, the N1 and N2/N3 rates derived from DPI. A third option (“traditional”, hereafter indicated with T) was also run, by using a fixed rate of N every year, i.e. 220 kg ha⁻¹, assumed to represent a conventional N management. For crops other than winter wheat, sowing dates, fertilizer N rates and application dates were set according to typical agricultural practices of Central and Northern Italy. The crops were conducted under rainfed conditions. Gaseous losses were negligible, as expected from wheat systems where fertilizer N is incorporated into the soil and ponding is not likely to occur.

Simulations for the 50 years were performed more times, in order to obtain simulated growth for each crop in one year of the study period in the rotation. For instance, simulation of the rotation sb-ww-p-ww was performed four times: the first starting with sugar beet, the second with winter wheat preceding potato, the third with potato, and the fourth with winter wheat preceding sugar beet. Fifty-six simulations were performed at each location with CropSyst using an implementation (Steiner et al., 1991) of the Priestley-Taylor model (Priestley and Taylor, 1972) for calculating evapotranspiration and the finite difference approach (Richards, 1931) for soil water transport. Each of the combinations

was simulated for 50 years without reinitialising the state variables, thus allowing the state of the soil to evolve from season to season through the simulation. This allowed assessing the long-term impact on system performance after many consecutive simulated crop seasons. The initial soil water content of the soil profile (1.2 m depth) at the beginning of each 50-year simulation was set equal to 2/3 of the estimated field capacity. The initial nitrogen content of the soil profile was set at about 0.1% of total N, as NO₃-N. Nitrogen from crop residues was accounted for by incorporating the residues through tillage, and later biologically decaying and transforming these residues to release mineral N and add to the stable organic matter.

3. Results

3.1 Experimental observations and simulations

Long-term average rainfall at the three sites was estimated with ClimGen: 616 mm at San Pancrazio, 670 mm at Ravenna, and 720 mm at Papiano di Marsciano. Figure 2 (top graph) indicates the distribution of the rainfall amounts registered at the three sites in the years investigated. Average rainfall at the Emilia-Romagna sites was much above (+69 mm at Ravenna) or below (-114 mm at San Pancrazio) long-term average, while average rainfall at Papiano di

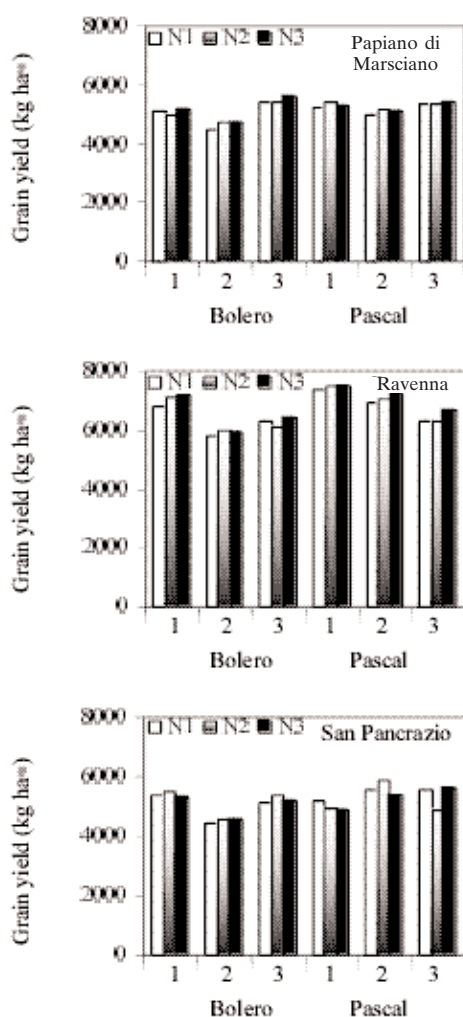


Figure 3. Grain yield (kg ha⁻¹) of two winter wheat cultivars (Bolero, Pascal) from N fertilization trials conducted at three sites (Papiano di Marsciano, Ravenna, San Pancrazio) during three growing seasons (1: 1997-1998, 2: 1998-1999, 3: 1999-2000).

Marsciano stayed closer onto long-term average (-40 mm). Bottom graph of Figure 2 reports rainfall pattern (average and standard error), as registered at each location in the months October to January (i.e., the relevant period for the calculation of fertilizer N) and March to May (i.e., including the N application period) during the 3-season trials. Total rainfall in the months October to January reached 38-55% of the annual precipitation, whereas it reached 17-29% in the months March to May. There was a greater amount of rainfall at Papiano di Marsciano than at the other locations over the months October to January (about 400 mm in

average, against 280 and 230 of Ravenna and San Pancrazio, respectively). Year-to-year variability at Papiano di Marsciano was also higher in October-January (standard error equal to 44.3 mm), while it was the smallest on yearly basis (as derived from the top graph).

Results from the N fertilizer trials showed some differences in mean grain yield among the three sites and years (Figure 3) but, in general, mean values agreed with those recorded in the official national trials (Perenzin et al., 1998, 1999, 2000). Ravenna showed major production potentialities, with about 6600 kg ha⁻¹ of grain yield in average at N rate equal to N1, against about 5000 kg ha⁻¹ and 5200 kg ha⁻¹ registered at Papiano di Marsciano and San Pancrazio, respectively. Grain yields observed with N1 at Papiano di Marsciano and Ravenna were substantially in line with the prescribed yield for DPI computations (5220 kg ha⁻¹, equal to 6000 kg ha⁻¹ with 13% standard humidity, at Papiano di Marsciano; 6090 kg ha⁻¹, equal to 7000 kg ha⁻¹ with 13% standard humidity, at Ravenna), whilst crop yield at San Pancrazio was much below the advised value (6090 kg ha⁻¹, equal to 7000 kg ha⁻¹ with 13% standard humidity). At this site, variability in winter wheat yields due to different previous crops was not accounted for, as sugar beet was the only preceding crop every year. In the other sites, it was observed as reference winter wheat yields were matched closer with other previous crops than sugar beet (sorghum at Papiano di Marsciano, tomato at Ravenna).

Manipulation of N supply across site-year combinations had a fairly small influence on mean grain yield. The high-input conditions applied at Ravenna resulted in higher mean grain yields ranging from +1.4% to +3.4% for cultivar Bolero; and from +1.6 to +4.4% for cultivar Pascal. The higher nitrogen regimes applied at Papiano di Marsciano resulted in mean grain yields lower than those at Ravenna (from +1.1 to +3.4% for cultivar Bolero; from +2.2 to 2.8% for cultivar Pascal). At San Pancrazio the grain yield variation due to high N inputs was moderately positive for cultivar Bolero (ranging from +0.6 to +3.1%), though negative for cultivar Pascal (ranging from -3.3% to -3.8%). Such unexpected negative variations are compatible with the variability registered in the data, i.e. standard error of 123.3 kg ha⁻¹ at Papiano di

Table 4. Nitrogen rates (kg ha⁻¹) applied in the long-term simulation study with *Disciplinare Produzione Integrata* (DPI) and CropSyst (CS) options at three sites and three rotations (mean and standard error). Standard errors between brackets refer to CS computations.

Rotation	DPI, CS	
	N1	N2, N3
Papiano di Marsciano		
sb-ww	79±0.9 (±1.9)	129±0.9 (±1.9)
sb-ww-p-ww	74±0.8 (±2.3)	124±0.8 (±2.4)
sf-ww	129±0.9 (±2.5)	179±0.9 (±3.4)
Ravenna		
sb-ww	87±1.4 (±1.8)	137±1.4 (±1.8)
sb-ww-p-ww	82±1.2 (±2.0)	132±1.2 (±2.0)
sf-ww	137±1.4 (±2.4)	187±1.4 (±2.8)
San Pancrazio		
sb-ww	100±1.0 (±2.1)	150±1.0 (±2.3)
sb-ww-p-ww	95±0.8 (±1.6)	145±0.8 (±1.6)
sf-ww	150±1.0 (±2.2)	200±2.2 (±3.6)

Marsciano, 242.2 kg ha⁻¹ at Ravenna, 174.4 kg ha⁻¹ at San Pancrazio.

The agreement between model outputs and field data was evaluated by the inspection of time series graphs. Typical 1-year simulated cycles, starting with emergence, for above ground crop biomass and plant nitrogen concentration at Papiano di Marsciano are published through the site <http://www.sipeaa.it/sic>. Similar results were obtained at Ravenna and San Pancrazio (unpublished). A unique set of parameters was used to model both cultivars because a clear difference in the crop outputs was not observed.

Table 5. Rainfall (mm) in the winter wheat growing season and fallow periods from the long-term simulation study at three sites and three rotations (mean and standard error).

Rotation	Season	Fallow
Papiano di Marsciano		
sb-ww	479±14.7	190±14.5
sb-ww-p-ww	474±10.5	213±10.6
sf-ww	479±14.7	240±14.5
Ravenna		
sb-ww	418±11.2	151±11.6
sb-ww-p-ww	413±8.1	180±11.6
sf-ww	418±11.2	210±12.0
San Pancrazio		
sb-ww	491±13.7	191±13.6
sb-ww-p-ww	487±9.6	210± 9.8
sf-ww	491±13.7	231±13.0

3.2 Long-term simulation study

3.2.1 Nitrogen application rates. Table 4 reports N rates applied to winter wheat, averaged across the simulated years at three sites. Larger spreading of CS N amounts is apparent from the higher standard errors, showing major sensitivity to weather variability of a physically-based model accounting for run-time soil N conditions than an empirical model. At Ravenna, to take the best example, CS N1 rates for winter wheat in the rotation sb-ww-p-ww ranged from 16 to 113 kg ha⁻¹, compared to a range of 58 to 97 kg ha⁻¹ with DPI N1.

In addition to fertilization, mineralization was the only other source of N addition considered in this study. Simulated N mineralization fluctuated between 15 and 60 kg N ha⁻¹ yr⁻¹, with no significant variation across fertilization treatments and rotations. Extreme values (about 60 kg ha⁻¹ yr⁻¹) were registered at San Pancrazio.

3.2.2 Soil water balance. Rainfall (Table 5) and evapotranspiration (Table 6) were by far the largest components of the soil water balance. Season precipitation (data not shown) presented a large year-to-year variability, fluctuating between 341 and 594 mm at Papiano di Marsciano, 361 and 696 mm at San Pancrazio, 290 and 516 mm at Ravenna. Actual evapotranspiration during the crop growth periods (data not shown) presented a large year-to-year variability as well (Papiano di Marsciano: 292-742 mm; Ravenna: 254-571 mm; San Pancrazio: 343-457 mm) and did not vary significantly across rotations or fertilization treatments. Evapotranspiration during no crop periods, mostly due to evaporation from soil and residues, was relatively low (16-31% of season evapotranspiration). The ratio between precipitation and actual evapotranspiration for crop periods (winter and spring) tended to be around 1 at all sites, fluctuating from 0.8 up to 1.5. During no crop periods (essentially summer and fall), the average ratio between precipitation and actual evapotranspiration was always larger than 1, with maximum values observed at San Pancrazio (up to 4.4 with sb-ww-p-ww, corresponding to excess water of about 240 mm). Some of the excess water became unavailable for the crop and reached the bottom of the soil profile. As a consequence of that, soil water

Table 6. Actual evapotranspiration (mm) in the winter wheat growing season and fallow periods from the long-term simulation study with *Disciplinare Produzione Integrata* (DPI), CropSyst (CS) and conventional (T) options at three sites and three rotations (mean and standard error).

Rotation	DPI						CS						T	
	N1		N2		N3		N1		N2		N3		T	
	Season	Fallow	Season	Fallow	Season	Fallow	Season	Fallow	Season	Fallow	Season	Fallow	Season	Fallow
Papiano di Marsciano														
sb-ww	452±8.5	96±8.4	451±8.5	95±8.4	451±8.5	95±8.4	458±8.4	94±8.4	457±8.4	94±8.4	457±8.4	94±8.4	449±8.8	94±8.4
sb-ww-p-ww	453±5.7	123±6.7	452±5.8	129±7.6	453±5.7	123±6.7	460±5.7	122±6.7	459±5.7	122±6.7	459±5.7	122±6.7	453±5.7	123±6.7
sf-ww	451±8.5	138±8.1	451±8.5	138±8.1	451±8.5	138±8.1	457±8.4	138±8.1	457±8.4	138±8.1	457±8.4	138±8.1	449±8.8	137±8.2
Ravenna														
sb-ww	423±8.4	81±7.4	423±8.5	81±7.4	423±6.5	81±7.4	430±8.7	80±7.4	430±8.8	80±7.4	430±8.8	80±7.4	420±8.9	80±7.5
sb-ww-p-ww	432±5.8	112±6.2	433±5.5	114±6.9	432±5.8	112±6.2	439±6.3	111±6.3	438±6.3	111±6.3	439±6.3	111±6.3	432±5.8	112±6.2
sf-ww	425±8.1	129±7.6	425±8.1	129±7.6	425±8.1	129±7.6	431±8.5	128±7.6	431±8.5	128±7.6	431±8.5	128±7.6	421±8.5	127±7.7
San Pancrazio														
sb-ww	446±7.3	74±7.6	446±7.3	74±7.6	446±7.3	74±7.6	455±7.9	73±7.6	455±7.9	73±7.6	455±7.9	73±7.6	443±7.5	73±7.6
sb-ww-p-ww	446±5.3	100±6.1	446±5.3	103±6.8	446±5.3	100±6.1	455±5.7	99±6.1	455±5.7	99±6.1	455±5.7	99±6.1	446±5.3	100±6.1
sf-ww	447±7.3	111±7.4	447±7.3	111±7.4	447±7.3	111±7.4	456±7.9	111±7.4	456±7.9	111±7.4	456±7.9	111±7.4	444±7.6	110±7.5

drainage was also a substantial component of the water balance, providing vehicle to possible N leaching. Major sensitivity to water percolation was associated to the presence of potato in the rotation at all sites, markedly at San Pancrazio (about 160 mm each year, up to almost 500 mm).

3.2.3 Crop yield. Average long-term simulation yields for winter wheat are shown in Table 7. Grain yields with N1 were in general larger than reference values for the sites, because possible stress factors are not fully accounted for by the simulation.

Little effect of N2 and N3 levels on yields was observed, compared to N1 (+10% or less with DPI; +7.5% or less with CS). Increases were more remarkable at Papiano di Marsciano with sb-ww. In general, crop yields increased by 3.5-4% or less when CS rather than DPI rules were applied. Figure 4 shows the expected mean yields and mean variances associated with the fertilization and rotation management at the three locations, according to both DPI and CS rules. At low mean yields (about 6000 kg ha⁻¹), mean variances are expected to be high with all rotations. This is depicted by the results from

Table 7. Winter wheat grain yield (kg ha⁻¹) from the long-term simulation study with *Disciplinare Produzione Integrata* (DPI), CropSyst (CS) and conventional (T) options at three sites and three rotations (mean and standard error).

Rotation	DPI			CS			T
	N1	N2	N3	N1	N2	N3	
Papiano di Marsciano							
sb-ww	5761±240.9	6325±290.3	6323±291.3	5967±246.3	6412±291.6	6415±292.0	6355±296.7
sb-ww-p-ww	6253±187.4	6454±194.8	6455±195.2	6329±182.7	6500±195.2	6500±195.2	6466±196.6
sf-ww	6286±293.2	6300±297.5	6303±296.5	6352±293.8	6344±294.8	6344±294.8	6298±297.1
Ravenna							
sb-ww	6648±178.2	7094±198.4	7093±198.1	6806±164.2	7232±192.0	7233±192.2	7099±201.2
sb-ww-p-ww	7234±126.1	7372±127.4	7372±127.4	7340±123.0	7418±127.8	7419±127.8	7371±127.7
sf-ww	7151±184.8	7141±184.9	7147±184.8	7215±182.5	7161±184.7	7163±184.6	7139±185.2
San Pancrazio							
sb-ww	6906±127.9	7042±137.3	7044±137.2	7050±136.1	7070±136.4	7070±136.4	7042±137.4
sb-ww-p-ww	7043± 67.5	7068± 68.2	7068± 68.2	7090± 67.6	7092± 67.7	7092± 67.7	7069± 68.1
sf-ww	7033±138.8	7031±138.8	7029±139.0	7055±138.3	7055±138.3	7056±138.2	7030±139.1

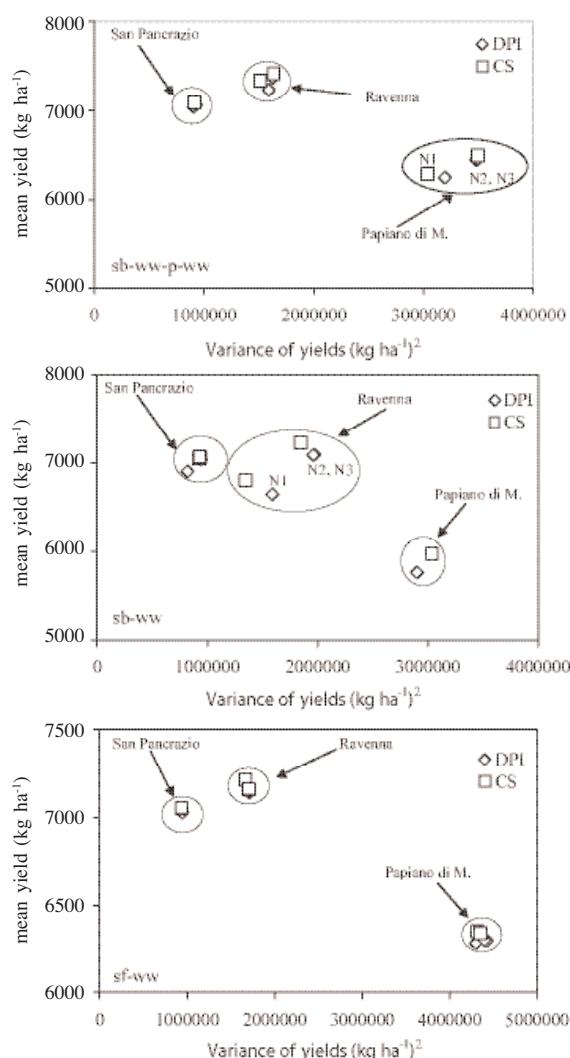


Figure 4. Simulated winter wheat yield: mean-variance plot for different locations, rotations, and nitrogen rates.

Papiano di Marsciano. Simulated yield was observed to increase with less variability at higher latitudes, little effect being related to alternative N rates or rules.

3.2.4 Nitrogen uptake and nitrogen use efficiency.

Average values of crop nitrogen uptake (Nup) were summarized in Table 8. Nup considers here above ground and root fractions. For winter wheat N uptake, the DPI references indicate N concentration of 0.6% in the straw and 1.98% in the grain. For 6500 kg ha⁻¹ grain yield (13000 kg ha⁻¹ above ground biomass at harvest), for example, these concentrations correspond to an uptake of 133 kg ha⁻¹ (harvest index of 0.50, roots not included), which compares well with

the simulated values (including roots).

N content in the biomass increased with increasing N fertilization to a fairly similar extent in the three sites. At Ravenna and San Pancrazio, Nup considerably increased in average between N1 and N2/N3 with rotations including sugar beet. For instance, +30% was observed at Ravenna and Papiano di Marsciano and +20% at San Pancrazio with sb-ww, although yields increased by only 6-7% or less, indicating larger plant N concentration for higher N rates. Conventional rates gave at times large increases of Nup, compared to N1 rates, especially at Ravenna with sb-ww, almost +50%, while yield increases were of about 4-7%. CS-based fertilization produced a generalized increase in Nup (by 5% or less), compared to DPI rules. At San Pancrazio, small or null increase of Nup observed with N2 and N3 under rotation sf-ww suggests additional N amount to N1 rates is not requested to satisfy crop requirements. A similar outcome emerged at Ravenna with CS only.

Physiological N use efficiency (NUEp, Noulas, 2002), i.e. the ratio of grain yield to total N uptake (kg kg⁻¹), was found different for different locations and fertilization methods. The general (though irregular) trend for NUEp was to decrease as N uptake increases. Lower values of NUEp were registered at Papiano di Marsciano (23-32 kg kg⁻¹), followed by San Pancrazio (33-40 kg kg⁻¹) and Ravenna (34-42 kg kg⁻¹). Table 9 shows the average ratios of fertilizer N applied to N uptake (NUEu: uptake nitrogen use efficiency, Novoa and Loomis, 1981). In average, the applied N is below the N uptake requirements in almost all cases (ratio lower than 1). N supplies at San Pancrazio only tended to be equal to crop requirements in a few cases (CS option, rates N1 and N2 with sf-ww, and conventional treatment with sb-ww and sf-ww). The agronomic efficiency of N use (NUEa: grain yield per unit of N applied, Christianson and Vlek, 1991) tended to linearly decrease with N applied (Figure 5). Lower r² values with CS data at Ravenna and San Pancrazio were mainly attributed to one point with N1, always greater than the analogous DPI point, indicating major efficiency with CS at low rates.

3.2.5 Nitrogen leaching. Table 10 shows the long-term yearly average of annual N leaching for

Table 8. Winter wheat nitrogen uptake (kg ha^{-1}) from the long-term simulation study with *Disciplinare Produzione Integrata* (DPI), CropSyst (CS) and conventional (T) options at three sites and three rotations (mean and standard error).

Rotation	DPI			CS			T
	N1	N2	N3	N1	N2	N3	
Papiano di Marsciano							
sb-ww	155±3.0	203±2.6	204±2.6	158±2.1	207±2.0	208±2.0	247±2.7
sb-ww-p-ww	193±4.3	231±2.8	232±2.8	203±4.3	238±2.0	238±2.0	247±1.8
sf-ww	213±2.7	244±2.2	243±2.3	220±2.0	247±2.5	247±2.5	246±2.7
Ravenna							
sb-ww	155±10.5	202±7.8	202±7.8	156±8.7	205±6.3	205±6.2	231±7.7
sb-ww-p-ww	200± 4.1	233±4.1	233±4.1	206±3.6	234±1.8	234±1.8	235±1.9
sf-ww	223± 6.6	234±5.9	234±5.9	231±5.3	234±5.9	234±5.9	232±6.5
San Pancrazio							
sb-ww	174±3.2	208±1.6	208±1.6	178±2.0	214±1.5	214±1.5	216±2.0
sb-ww-p-ww	206±7.4	216±4.4	216±4.4	215±4.8	217±4.4	217±4.4	217±4.4
sf-ww	215±1.9	217±2.0	217±2.0	217±2.0	217±2.0	217±2.0	216±2.0

Table 9. Winter wheat uptake nitrogen use efficiency (kg kg^{-1}) from the long-term simulation study with *Disciplinare Produzione Integrata* (DPI), CropSyst (CS) and conventional (T) options at three sites and three rotations (mean and standard error).

Rotation	DPI			CS			T
	N1	N2	N3	N1	N2	N3	
Papiano di Marsciano							
sb-ww	0.5±~0.0	0.6±~0.0	0.6±~0.0	0.5±~0.0	0.6±~0.0	0.6±~0.0	0.9±~0.0
sb-ww-p-ww	0.4±~0.0	0.6±~0.0	0.5±~0.0	0.4±~0.0	0.5±~0.0	0.5±~0.0	0.6±~0.0
sf-ww	0.6±~0.0	0.7±~0.0	0.7±~0.0	0.6±~0.0	0.7±~0.0	0.7±~0.0	0.9±~0.0
Ravenna							
sb-ww	0.6±~0.0	0.7±~0.0	0.7±~0.0	0.6±~0.0	0.7±~0.0	0.7±~0.0	1.0±~0.0
sb-ww-p-ww	0.6±~0.0	0.6±~0.0	0.4±~0.0	0.6±~0.0	0.6±~0.0	0.6±~0.0	0.6±~0.0
sf-ww	0.6±~0.0	0.8±~0.0	0.8±~0.0	0.6±~0.0	0.8±~0.0	0.8±~0.0	1.0±~0.0
San Pancrazio							
sb-ww	0.6±~0.0	0.7±~0.0	0.7±~0.0	0.6±~0.0	0.7±~0.0	0.7±~0.01	1.0±~0.0
sb-ww-p-ww	0.5±~0.0	0.7±~0.0	0.7±~0.0	0.5±~0.0	0.7±~0.0	0.7±~0.0	0.7±~0.0
sf-ww	0.7±~0.0	0.9±~0.0	0.9±~0.0	0.7±~0.0	1.0±~0.0	1.0±~0.0	1.0±~0.0

winter wheat crops in all of the rotations and fertilization options considered.

Average values from DPI did not appear different from CS-based values and both were low in many cases, while the T option tended to give important nitrogen leaching at all sites. Under T rates, winter wheat in the rotation sb-ww-p-ww had in particular the most potential for annual N leaching, which was the maximum at San Pancrazio (above 50 kg ha^{-1} in average, up to 190 kg ha^{-1}). When DPI and CS rules were applied, winter wheat in the rotation including sunflower had the most potential for annual N leaching, maximum at San Pancrazio with N2

and N3 (about $30\text{--}40 \text{ kg ha}^{-1}$ in average, up to 120 kg ha^{-1}). At this site, CS options N2 and N3 tended to be similar to T rate with the rotation sf-ww (average values), because N provided was higher than required, as suggested by crop N uptake values which did not increase with N2 and N3 (Table 9). Probability distributions (selected graphs in Figure 6) were different for different rotations, but largely similar in the shape across different sites. Conventional strategy was dominant in all cases, as its probability line fully lies to the right of other strategies.

Figure 7 shows the expected mean N leaching and mean variances associated to the fertil-

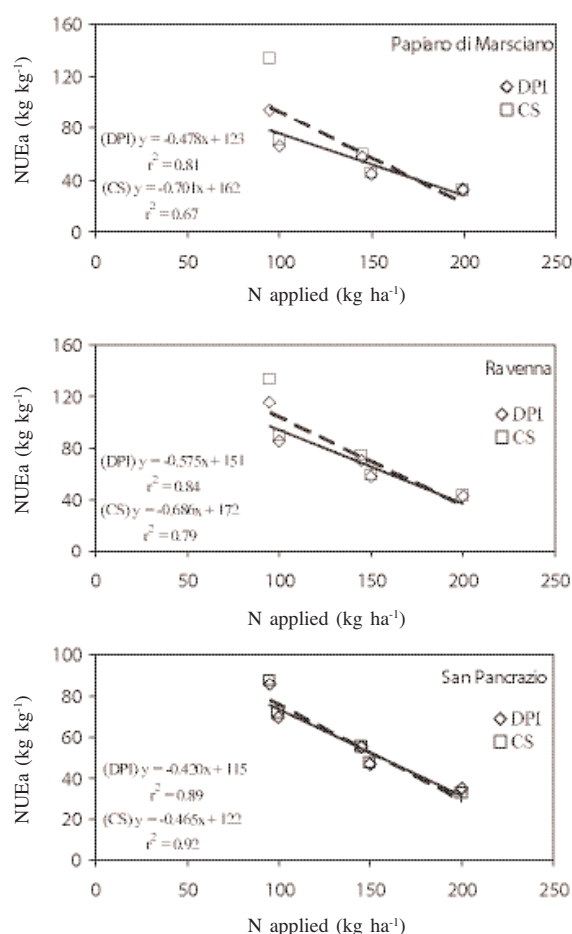


Figure 5. Simulated agronomic nitrogen use efficiency (NUEa)-nitrogen applied plot and regression lines for different locations and nitrogen rates (average across rotations).

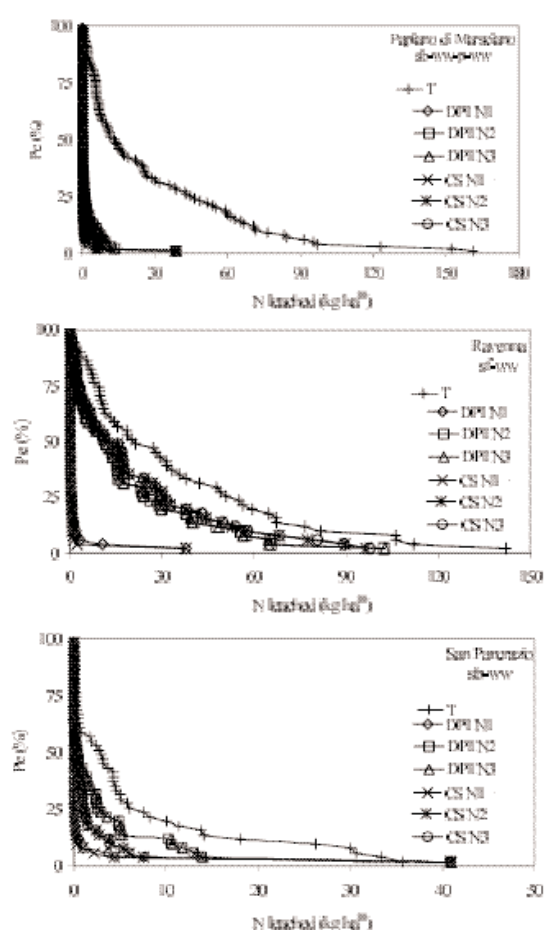


Figure 6. Simulated nitrogen leached with DPI, CS, and T options: probability of exceedence (Pe) distribution curves for three sites at selected rotations.

Table 10. Annual amount of nitrogen (kg ha^{-1}) leached from the long-term simulation study with *Disciplinare Produzione Integrata* (DPI), CropSyst (CS) and conventional (T) options at three sites and three rotations (mean and standard error).

Rotation	DPI			CS			T
	N1	N2	N3	N1	N2	N3	
Papiano di Marsciano							
sb-ww	0.8±0.8	0.8±0.8	0.8±0.8	0.8±0.773	0.8±0.8	0.8±0.8	2.4±0.9
sb-ww-p-ww	1.0±0.5	2.1±0.6	2.1±0.6	1.0±0.547	1.7±0.6	1.6±0.6	28.4±3.3
sf-ww	0.8±0.8	2.3±0.9	2.3±0.9	0.8±0.773	1.8±0.8	1.8±0.8	11.5±2.5
Ravenna							
sb-ww	0.8±0.8	0.8±0.8	0.8±0.8	0.8±0.8	0.8±0.8	0.8±0.8	13.2±2.5
sb-ww-p-ww	1.0±0.8	7.0±1.2	7.1±1.2	1.0±0.5	8.5±1.2	8.5±1.2	46.6±3.9
sf-ww	1.3±0.8	18.1±3.0	18.2±3.0	1.0±0.8	20.9±3.4	21.0±3.5	33.6±4.7
San Pancrazio							
sb-ww	1.1±0.8	3.0±0.9	3.0±0.9	1.0±0.8	1.8±0.8	1.8±0.8	6.2±1.3
sb-ww-p-ww	8.0±1.1	23.2±2.2	23.2±2.2	7.2±0.9	26.2±1.9	26.2±1.9	56.5±3.7
sf-ww	10.8±2.1	28.6±3.6	28.6±3.6	10.7±1.8	38.9±3.8	38.9±3.7	37.4±4.1

ization and rotation management explored at three sites, according to both DPI and CS. Introduction of potato (middle graph) or sunflower (bottom graph) increases the level of N leaching and mean variance (level of the risk) at Ravenna and San Pancrazio.

4. Discussion

Management practices and weather variability were the most important factors in determining the potential for grain yield and N leaching from the simulated winter wheat systems. Grain yields suggest modest increases are achieved with improved protocols derived from the balance-sheet method, and further increase with CS options rather than DPI-based fertilization rules is also expected. Both CS and DPI techniques appeared beneficial when compared to the conventional practice.

Soil water drainage and N leached from this simulation study compare well with the estimates given by Donatelli et al. (1999) from CropSyst simulations on alternative cropping systems (including winter wheat) in Emilia-Romagna. Acutis et al. (2000) report average N leaching estimates for Western Po valley, which are similar to the ones estimated here (7.0 to 79 kg ha⁻¹ yr⁻¹ as NO₃-N from rainfed maize and ryegrass-maize systems on loam soils, N fertilization in the range 200-450 kg ha⁻¹). It emerges from the N budget that changes in the uptake N efficiency (Table 9) are at times determined from variations in the fertilizer N inputs only, and it is convenient not to increase N amounts where N uptake values does not increase in that order. This was particularly clear at San Pancrazio with sunflower in the rotation (Table 8), and generated large amounts of N available for leaching (Table 10). The sunflower season appeared to be the principal contributor to N leaching at all sites, mainly at San Pancrazio. At this site, large contents of soil organic matter in the upper layers (Table 1) also tend to give important amounts of N through mineralization, available for leaching (up to 60 kg ha⁻¹ of mineralized N, against peaks of 50 kg ha⁻¹ for the other sites). Sunflower is assumed by DPI to provide null effect as residual N, thus imposing large amounts of fertilizer N for the subsequent winter wheat. An important advice from this simulation study is that DPI computation is

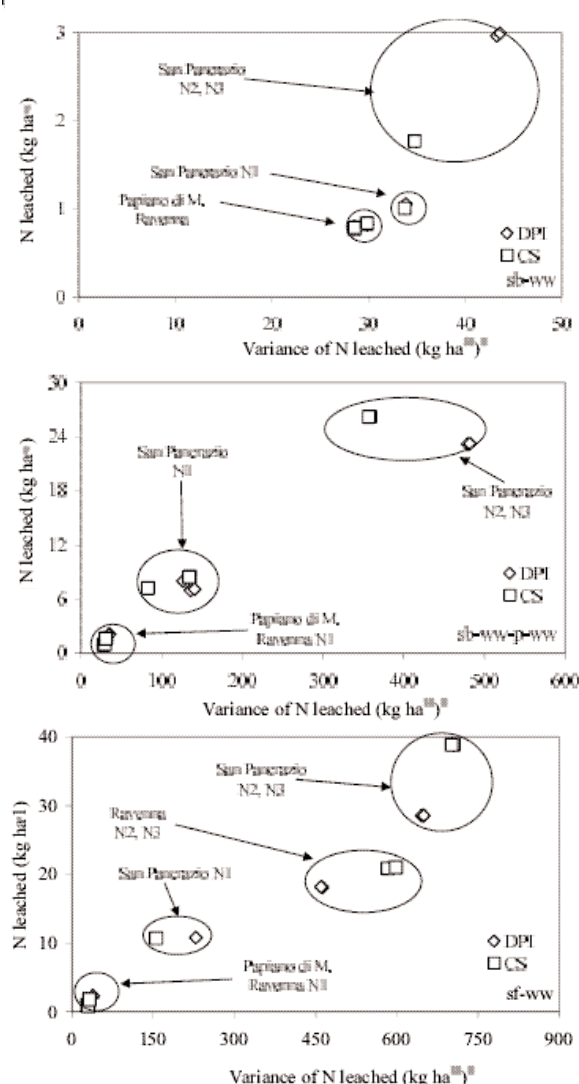


Figure 7. Simulated nitrogen leached: mean-variance plot for different locations, rotations, and nitrogen rates.

worth being reconsidered at San Pancrazio, even determining more carefully the target yield (now equal to 6020 kg ha⁻¹, the same as Ravenna). The average amounts of N leached are fairly small and, with the partial exception of San Pancrazio, below the average value of 23 kg ha⁻¹ yr⁻¹ identified by OECD (1972) for arable lands by 100 kg ha⁻¹ fertilizer N. Philipps (2000) informs of larger values (36-79 kg ha⁻¹ yr⁻¹) for typical arable crops grown in Europe.

The results of this study show that an important decision about N application to winter wheat concerns the selection of fertilizer rate. A varied range of N management scenarios have been simulated and compared, allowing an ef-

fective environmental risk by N losses from a field to be assessed using a physically-based model. These simulations contribute to a better understanding of the impact of climate variability on different fertilizer recommendations. Strategic decisions can be based upon the results of these simulations, provided that in practice a farm manager can recognise and match the actual soil type and drainage condition of the fields on which N application is to occur with the simulated field types.

CropSyst automatic routine for N fertilization allowed in general better efficiency of N use than DPI (according to different indices). However, although simplified, the DPI method showed good ability to meet crop N demand and preserve N balance in the soil. Minor differences were observed from a physically-based model, thus the DPI method can be proficiently used to orient N fertilization strategies. Such ability was substantially preserved at all sites and rotations, the perspective of little improvements being emerged for San Pancrazio only. The need to improve N rates from N1 to N2 or N3 did not emerge from this quantitative study on crop yield. Nonetheless, the little environmental risk associated to N leaching with the enhanced rates does not call to particular warnings and allows farmers to derive soil fertility management by using modified protocols of the DPI strategy. Conclusive judgements on the convenience expected from adopting modified protocols raises from grain quality analysis, varying from cultivar to cultivar as a function of N rates and application dates (manuscript I).

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