A new approach for determining rice critical nitrogen concentration

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SUMMARY

A reliable evaluation of crop nutritional status is crucial for supporting fertilization aiming at maximizing qualitative and quantitative aspects of production and reducing the environmental impact of cropping systems. Most of the available simulation models evaluate crop nutritional status according to the nitrogen (N) dilution law, which derives critical N concentration as a function of above-ground biomass. An alternative approach, developed during a project carried out with students of the Cropping Systems Masters course at the University of Milan, was tested and compared with existing models (N dilution law and approaches implemented in EPIC and DAISY models). The new model (MAZINGA) reproduces the effect of leaf self-shading in lowering plant N concentration (PNC) through an inverse of the fraction of radiation intercepted by the canopy. The models were tested using data collected in four rice (*Oryza sativa* L.) experiments carried out in Northern Italy under potential and N-limited conditions. MAZINGA was the most accurate in identifying the critical N concentration, and therefore in discriminating PNC of plants growing under N-limited and non-limited conditions, respectively. In addition, the present work proved the effectiveness of crop models when used as tools for supporting education.

INTRODUCTION

Evaluating nitrogen (N) nutritional status is a key issue for analysing, monitoring and managing cropping systems (e.g. Naylor & Stephen 1993; Senanayake *et al.* 1996; Jeuffroy *et al.* 2002; Jaggard *et al.* 2009). A reliable estimation of crop requirement allows optimization of both qualitative and quantitative aspects of production (Ghosh *et al.* 2004), and increases N use efficiency, therefore reducing the

impacts on the environment. For these reasons, different typologies of tools for supporting N management have been developed. They differ in their scope (i.e. supporting fertilization, evaluating losses and identifying scenarios suitable for specific contexts), in the reference spatial scale (e.g. field and region), in the economic and time resources they demand and in the skills required by the user. Some of these tools (e.g. leaf colour charts (LCC); Alam *et al.* 2005) are very simple and cheap, being conceived to support farmers directly for N-management at field level. Others (i.e. SPAD-502; Konica Minolta Inc., Tokyo, Japan) are more complex and use plant chlorophyll

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content – estimated through the absorbance of the leaf in the red and near-infrared regions (Peng *et al.* 1996) – as a proxy for plant N concentration (PNC) (Clark *et al.* 2005). Stroppiana *et al.* (2009) estimated rice PNC from hyperspectral radiometry, finding significant correlation between PNC and a vegetation index calculated using reflectance values measured for wavelengths of 483 and 503 nm. Among the available tools for evaluating crop nutritional status, simulation models play a major role in a variety of applications (Stöckle & Debaeke 1997; Meynard *et al.* 2001), because of their flexibility, ability to work at different spatial scale and suitability for scenario analysis. In most of the cases, they quantify crop N nutritional status through the definition of a critical N threshold (N$_{crit}$, mg/g). When PNC (mg/g) is lower than N$_{crit}$, the crop is growing under N-limiting conditions, otherwise consumption is not limiting.

Although some of the proposed crop models relate N$_{crit}$ to crop development (e.g. EPIC, Williams *et al.* 1989; DAISY, Hansen *et al.* 1991), the approach most commonly used is that based on the N dilution law (Salette & Lemaire 1981; Justes *et al.* 1994). According to this law, an allometric function is used to derive decreasing values of N$_{crit}$ for increasing values of above-ground biomass (AGB, t/ha). The theoretical explanation for the dilution law refers to the representation of the plant as composed of two N pools (Caloin & Yu 1984): one is involved in physiological activities such as photosynthesis and nutrient uptake, the other consists of mechanical and vascular structures (Seginer 2004). The two N pools change their relative weight with crop ageing because of (i) the self-shading of leaves and (ii) the allocation of resources to plant components with different N concentrations: mainly to leaf blades (high N concentration) during early growth stages and to stems (low N concentration) in later stages. Self-shading of leaves results in the lower canopy layers experiencing a decrease in the red/far-red ratio because of a preferential absorbance of red photons by chlorophylls in the upper layers. Changes in this ratio trigger senescence processes aimed at recycling N-rich compounds, which are no longer needed in the shaded leaves. These are reallocated to younger leaves, thus reducing the global need for N by the whole plant (Seginer 2004).

Although the N dilution law is adopted by some of the most widely used crop models (e.g. CropSyst; Stöckle *et al.* 2003) and parameterizations for a variety of crops are available (e.g. Greenwood *et al.* 1990), the estimation of its empirical coefficients is quite complex, requiring various experiments with at least 4–5N application rates (e.g. Justes *et al.* 1994). Moreover, it is characterized by a level of empiricism that makes too implicit the representation of the two processes used to give theoretical support to the law itself (i.e. self-shading and allocation of

photosynthates to organs with different N concentration).

The current paper presents the results of the project Modelling critical N concentration for agronomic management (MAZINGA), carried out with students of the Cropping Systems Masters course of the University of Milan with the aim of developing new approaches for the simulation of rice N$_{crit}$. The proposed model is evaluated using field data collected in Northern Italy and compared with other existing approaches.

MATERIALS AND METHODS

Approaches compared in this study

The dilution law (Salette & Lemaire 1981) is based on the following equation:

$$N_{crit} = a \times AGB^{-b} \qquad (1)$$

where *a* and *b* are empirical coefficients derived from field experiments carried out under different N fertilization treatments, as proposed by Justes *et al.* (1994). The *a* and *b* values used in the present work (5·18 and 0·52, respectively) are those proposed by Sheehy *et al.* (1998) and are considered reference values for rice.

The approach implemented in the EPIC model (Williams *et al.* 1989) derives N$_{crit}$ using the following equation:

$$N_{crit} = b1 + b2 \times e^{-b3 \times HUI} \qquad (2)$$

where HUI (0·0–1·0) is a heat unit index, equal to the ratio of the current thermal sums to the thermal sums to reach maturity, defined as Zadoks Growth Stage (ZGS) 92 (Zadoks *et al.* 1974); *b*1, *b*2 and *b*3 are coefficients (0·005, 0·045 and 2·197 in the present study) derived by forcing Eqn (2) to return species-specific tabulated PNCs for HUI values of 0·0, 0·5 and 1·0 (Williams, personal communication).

The DAISY model (Hansen *et al.* 1991) forces an allometric relationship between N$_{crit}$ and growing degree days (GDD; °C-day) to return the PNC values of 30 and 10 mg/g, respectively, for 100 °C-day and GDD to reach maturity (ZGS = 92).

The approach proposed in the present study (MAZINGA) reproduces the effect of leaf self-shading in remobilizing (recycling) N from senescent leaves through an inverse of the fraction of radiation being intercepted by the canopy:

$$N_{crit} = \frac{N_{mat}}{1 - e^{-k \times LAI}} \qquad (3)$$

where N$_{mat}$ (mg/g) is a parameter indicating the critical N concentration at physiological maturity (ZGS = 92), $1 - e^{-k \times LAI}$ is the fraction of solar radiation intercepted by the canopy, *k* (–) is the

Table 1. *Datasets used for the evaluation of the models under test*

Experiment no.	Location	Latitude N Longitude E	Year	Soil texture	Sowing date	Nitrogen treatments (urea)	Number of N applications	Sample size	Variety
1	Vignate	45°29′ 9°22′	2002	Sandy loam	29 Apr	0, 150 kg N/ha	3	20 plants/ plot	Thaibonnet
2	Opera	45°22′ 9°12′	2002	Loam	29 Apr	0, 150 kg N/ha	3	20 plants/ plot	Sillaro
3	Opera	45°22′ 9°12′	2004	Loam	24 May	0, 160 kg N/ha	2	27 plants/ plot	Gladio
4	Milan	45°26′ 9°09′	2006	Sandy loam	12 Apr	0, 170 kg N/ha	2	27 plants/ plot	Libero

extinction coefficient for solar radiation, and LAI (m^2/m^2) is the total leaf area index. Values of 10 mg/g and 0·5 were used for N_{mat} and k (Confalonieri *et al.* 2009), respectively.

Since all the approaches would lead to positive infinity for values of their driving variable (AGB, HUI, GDD and LAI) approximating zero, the minimum between their N_{crit} values and 36 mg/g was used (Confalonieri & Bocchi 2005).

Experimental data

Data used to evaluate the different approaches for identifying the critical N curves were collected in four experiments (Table 1). These experiments were not designed to collect data to determine the parameters of the curves (in this case, at least five different N application rates would have been needed to parameterize the dilution law curve with sufficient accuracy), but simply to test and compare the different models for the estimation of N_{crit}.

The experiments are representative of the conditions experienced by rice growing in the eastern part of the north-west Italian rice district (Piedmont–Lombardy), responsible for more than 0·40 of the total European rice production. Indica-type cultivars were used in all experiments (Table 1). Rice was scatter seeded and grown under continuous flooding conditions in Vignate, Milan and Opera during 2004 (Expts 1, 3 and 4, respectively; see Table 1). For Expt 2 (Opera, 2002), rice was row seeded and the field was flooded at the 3rd leaf stage (ZGS = 13).

During the 2002 and 2006 experiments, three levels of N fertilizer (Table 1) were used in a completely randomized block design with three replicates. The same scheme (completely randomized block) was used for the 2004 experiment, but with two levels and four replicates. Where more than two N levels were set, only the maximum and the minimum were used in the present study (Table 1). Nitrogen fertilizer was always distributed as urea by splitting the total amount

(Table 1) in three events (pre-sowing, mid-tillering, ZGS 22 and panicle initiation) in the 2002 experiments, and in two (a single top-dressing fertilization at panicle initiation) events in the others.

For all the experiments, the soil presented a medium organic N content (1·3 mg/g in Opera 2004 and Milan 2006, 1·5 and 1·2 mg/g for Vignate 2002 and Opera 2002, respectively).

Possible differences among observers were reduced (i) by always using the same sampling protocol: sample size determined according to Confalonieri *et al.* (2006), an aggregated sample of three randomly selected sub-samples for each plot, harvesting the whole plant and division (at the collar) of the above- and below-ground parts of the plants in laboratory and (ii) by supervising all the sampling activities. All the analyses were carried out at the laboratory of the Department of Plant Production of the University of Milan.

In all the experimental fields, diseases and weeds were controlled by two treatments with tricyclazole (at ZGS 31 and 45) and with propanil (at ZGS 12 and 22; Imazamox for Expt 4); treatments with alphacipermetrine prevented pest damage.

Total plant and soil N contents were estimated with an elemental analyser (NA 1500 series 2 NC, Carlo Erba, Italy), whereas soil $N-HH_4^+$ and $N-NO_3^-$ were measured with a continuous flow analyser (Flow Comp 1500, Carlo Erba, Italy).

Evaluation of the different approaches

The evaluation of the different approaches for N_{crit} was carried out using two methods. The first was the graphical method proposed by Stöckle & Debaeke (1997). N_{crit} curves were plotted on charts together with PNC values collected from plants growing under N-limiting conditions and on fully fertilized plants. The ideal condition was considered the one where PNC values from plants growing under N-limited (white symbols in Fig. 1) and N-unlimited (grey

Table 2. *Evaluation metrics calculated for the PNC data staying on the 'wrong side' of the critical N (N_{crit}) curves (see Fig. 1); their projections on the N_{crit} curves were used as simulated data to calculate the indices of agreement*

	PNC* values on the wrong side of the critical curves					
Model	Total number	high†	Low‡	RRMSE§	EF**	CRM††
MAZINGA	17	0·53	0·47	0·26	0·66	− 0·05
Dilution law	19	0·05	0·95	0·26	0·62	− 0·17
EPIC	20	0·15	0·85	0·20	0·77	− 0·14
DAISY	23	0·70	0·30	0·24	0·70	0·11

* PNC (mg/g).
† PNC values from unfertilized plants: they should be below the curves.
‡ PNC values from fully fertilized plants: they should be above the curves.
§ RRMSE; 0 to $+\infty$; the closer values are to 0, the better the model.
** Modelling efficiency; $-\infty$ to 1; optimum = 1.
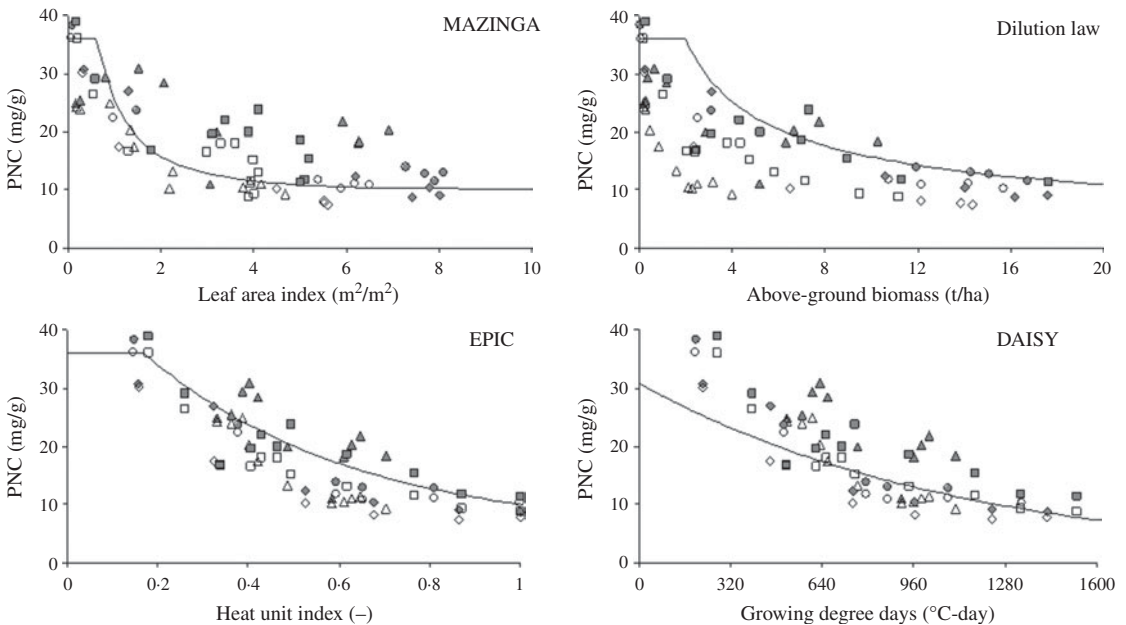†† CRM; $-\infty$ to 1; optimum = 0; if positive indicates model underestimation.

Fig. 1. Performance of the model MAZINGA (see Eqn 3) in estimating critical N curve. Comparison with the dilution law, EPIC and DAISY approaches. Plant N concentration (PNC; mg/g) on the *y*-axis. Grey and white symbols refer to PNCs determined, respectively, on plants grown under non-limited (fully fertilized) and N-limited conditions. Different symbols refer to different experiments (Table 1): circles, rhombus, triangles and squares refer to Expts 1, 2, 3 and 4, respectively.

symbols) conditions were below and above the N_{crit} curve, respectively. Different symbol shapes in Fig. 1 refer to different experiments (Table 1). The second evaluation method aimed at quantifying different typologies of error and it was based on the following assumptions: (i) errors are calculated on PNC values staying on the 'wrong side' of the N_{crit} curves and, for these PNCs, (ii) the 'true' values are the corresponding points on the N_{crit} curves. Error was quantified using relative root mean square error (RRMSE; minimum and optimum = 0; maximum $+\infty$), modelling efficiency (EF; $-\infty$ to 1; optimum = 1; if positive, indicates that the model is a better predictor than the average of measured values) and coefficient of residual mass (CRM; $-\infty$ to 1; optimum = 0; if positive indicates model underestimation).

RESULTS

Figure 1 shows a considerable over-estimation of the N_{crit} curve for the dilution law. Although less important, the EPIC approach also showed some over-estimation. On the other hand, DAISY under-estimated the N_{crit} curve, although the situation appeared to slightly improve in the last part of the crop cycle. Under the conditions explored, the approach proposed in the present study was the one showing the best performance, with a balanced distribution of the PNC values above and below the N_{crit} curve.

Table 2 confirms the improvement of the MAZINGA approach, which presented the lowest number of points (17) on the 'wrong' side of the curve (i.e. those appearing above the curve that were expected to appear below it, and *vice versa*) and a balanced distribution of over-estimated (expected below the curve but above) and under-estimated values (0·53 and 0·47, respectively). The tendency of the dilution law and of the EPIC approach in over-estimating the critical N concentration already discussed (Fig. 1) is confirmed by the proportions of PNC values on the wrong side of the curves. The values from fully fertilized plants that are below the critical N curves are 0·95 and 0·85 for the dilution law and EPIC. The DAISY model appeared less unbalanced than either the dilution law or the EPIC approach, with 0·70 of the values from unfertilized plants above the critical N curve. However, the DAISY approach was the one with the largest number of values on the wrong side of the curve (23).

DISCUSSION

The dilution law and the DAISY approach were less accurate in the first part of the crop cycle, when top-dressing fertilization (usually at the panicle initiation, ZGS = 31, sometimes at tillering, ZGS = 20) is carried out. This is important since inaccuracies in the estimation of N requirements at these times could nullify the usefulness of models as diagnostic tools for supporting N management in cropping systems. Moreover, most of the total N present in the plant at maturity is taken up before flowering (Ntanos & Koutroubas 2002; Lin *et al.* 2006; Zhang *et al.* 2007; Acreche & Slafer 2009). Thus, errors in the first part of the crop cycle could have a considerable impact also on the accuracy of the estimates of the N budget terms. EPIC and MAZINGA appeared to have a more constant behaviour along the crop cycle.

Although the two approaches deriving N_{crit} from development, i.e. EPIC and DAISY, presented the highest number of values on the wrong side of the curve (20 and 23, respectively), measured PNC values appeared less spread around their curves (Fig. 1) compared to the other two approaches. This is the reason why they produced the best values of RRMSE and EF, since the larger number of points on the wrong side of the curves is counterbalanced by a general closeness of the points to the curve.

In spite of its higher accuracy compared to the other tested approaches, the model MAZINGA does not include any empirical coefficient, being based only on canopy extinction coefficient for solar radiation and leaf area index, both easily estimable using simple instrumentation (Stroppiana *et al.* 2009). This makes the model MAZINGA easy to use, both within crop models and as diagnostic tool for supporting N fertilization. The results achieved in the present work may be applicable to other herbaceous species.

The didactic experience of carrying out a (small) modelling research project with students can be considered fully satisfying (a new approach was proposed), and follows some similar activities recently carried out (Antunes *et al.* 1998; Graves *et al.* 2002), with models used as tools in education.

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