Deriving fertiliser VRA calibration based on ground sensing data from specific field experiments

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Abstract. *Nitrogen (N) fertilisation affects both rice yield and quality. In order to improve grain yield while limiting N losses, providing N fertilisers during the critical growth stages is essential. NDRE is considered a reliable crop N status indicator, suitable to drive topdressing N fertilisation in rice. A multi-year experiment on different rice varieties (Gladio, Centauro, and Carnaroli) was conducted between 2011 and 2017 in Castello d'Agogna (PV), northwest Italy, with the aim of i) establishing the best N fertilisation management to maximise crop yield, iii) defining a statistical method to obtain calibration functions establishing the* N_{PI} *as a function of NDRE measured at PI, iv) comparing the best N management based on NDRE readings. A statistical model was developed to define dose/response curve. Results suggested different fertilisation strategies depending on the rice variety. For Gladio variety, grain yield is optimised equally splitting total N amount between pre-sowing plus tillering and PI application. Conversely, considering Centauro and Carnaroli varieties, best N management suggest reducing N application at the early growth stages, increasing topdressing N fertilisation. The algorithm also allowed obtaining calibration functions for each variety, establishing* N_{PI} *as a function of NDRE values measured just before N application, with the aim of maximising grain yield. The obtained calibration functions can be implemented in variable rate application fertiliser spreader, providing an interpretative model capable of translating vigour maps into N fertiliser applications. However, calibration functions have been obtained only for Gladio, Centauro, and Carnaroli varieties, under specific environmental conditions. Further extension to other rice varieties and agro-environments is needed, and can be performed using the methodology proposed in this study, with the aim of* *promoting a widespread application of precision N fertilisation in rice.*

Keywords. *NDRE, variable rate fertilisation, site-specific N management, crop yield estimation, precision agriculture.*

Introduction

Italy is the most important European rice producer. Rice production is mainly concentrated in the north-west area. Nitrogen (N) fertilisation is the main agronomic practice that affects both rice yield and quality. Therefore, it is highly important to calibrate the application of N fertilisers during the critical growth stages to improve grain yield while limiting N losses (Yoseftabar, 2013). In rice cultivation, the total N amount is usually split in three fertiliser applications. Rice requires sufficient N input at pre-sowing and tillering stage to promote an optimal panicle density, and at panicle initiation stage (PI) to obtain a suitable number of filled spikelets per panicle (Xue *et al.,* 2014). Moreover, N fertilisation at PI (N_{PI}) can compensate for possible deficient supplies during the initial stages. Normalised Difference vegetation Index (NDVI) and Normalised Difference Red Edge (NDRE) have been shown to be reliable crop N status indicators (Muñoz-Huerta *et al*., 2013). However, NDVI sensitivity is limited in presence of abundant biomass, as a consequence of saturation effect (Kanke *et al.,* 2012). Consequently, under dense biomass, the use of NDRE is recommended, as the index can partially overcame the saturation problem (Yao *et al.,* 2014). Then, NDRE can be considered as a suitable tool to drive optimum N fertilisation in rice at PI. However, a precise rice N fertilisation management requires a quantitative estimate of the NDRE and grain yield relationship. Moreover, the optimum N management vary with rice cultivars (Bah *et al*., 2009).

The objectives of this work were to:

1. establish the best N fertilisation management, in terms of total N supply and splitting, to maximise crop yield for different rice varieties;
2. adapt the statistical model to obtain a calibration function establishing the N_{PI} as a function of NDRE measured at PI from a field trial for different rice varieties;
3. compare the best N management based on NDRE readings for different rice varieties.

Materials and methods

Experiment design and agronomic management

A multiple-year experiment was conducted between 2011 and 2017 in Castello d'Agogna (PV), north-west Italy (8° 41' 52'' E; 45° 14' 48'' N). Climate of the area is temperate, with hot summers and two main rainy periods in spring and autumn. The soil of the experiment site is silty-loam, with a low organic matter content, slight acidity, low available N, and well-balanced C/N. Traditional agronomic techniques were adopted in all the growing seasons. The trial was ploughed in spring with conventional tillage equipment, laser levelled, and then harrowed. Phosphorus and potassium were uniformly applied in all plots before harrowing. Rice was water-seeded. Water management involved continuous flooding for most of the growing season, until the final draining, with the only exceptions of short drainage periods to allow for root extension, and fertiliser and herbicide applications. Adequate measures to control diseases were undertaken throughout plant growth.

The field trial was carried out on different rice varieties belonging to different grain types (Carnaroli, Centauro, and Gladio), as they require different N rates to optimise N management. Rice varieties have been selected considering their widespread cultivation in the north-west area and their different agronomic response to increasing N levels, due to their genetic variability. The experimental setup was specifically studied to provoke different crop vigour before the last topdressing fertilisation, then evaluating the effect of increasing N_{PI} rates.

The experiment combined several rates of N supplied as the sum of N amount supplied at the pre-sowing and tillering stages ($N_{PRE+TILL}$) and different N rates supplied at PI (N_{PI}). Treatments were laid out using a split plot design with $N_{PRE+TILL}$ in the main plots and N_{PI} in the subplots. Each main plot measured 4.5*26.4 m and was divided into subplots measuring 4.5*6.6 m. Four replications for each treatment were established. In all plots, dry granular urea was used as fertiliser. N levels varied across the years. Moreover, N fertilisation was adapted considering N requirements of the different rice varieties. Further details about N management are reported in *Table 1*.

Table 1: N fertilisation used for each variety in each year of the experiment.

Rice variety	Grain type	Year	$N_{PRE+TILL}$ (kg ha^{-1})	N_{PI} (kg ha^{-1})
Gladio	Long B	2011	60-100-140-180	0-30-60-100
		2013	0-60-100-140	0-30-60-100
Centauro	Round	2014 2015	0-60-100-140-200	0-30-60-100
Carnaroli	Long A	2016	0-30-60-90	0-30-60-90
		2017	0-30-60-75-90	0-30-60-90

Field measurements

NDRE was determined to establish crop N status at PI, using Rapid Scan handheld active optical sensor (Rapid Scan CS-45, Holland Scientific, USA) that incorporates optical measurement channels at 670, 730, and 780 nm. NDRE was measured determining canopy reflectance at 730 and 780 nm. The measurements were collected by holding the instrument approximately 0.5 m above the rice canopy and walking at a constant speed along the entire length of the plot. Two measurements were taken from each sides of the plot in each treatment, to obtain a representative value for each plot. Grain yield normalised to a moisture content of 14% was determined at harvest, hand-harvesting three 0.25 m^2 areas in each plot.

Data analysis

Statistical analysis was performed using R software, version 3.4.3 (R Development Core Team, 2017).

First, General Linear Model (GLM) explained yield as a function of different N rates and splitting, with the aim of suggesting the best N fertilisation technique for each rice variety. The model was built as follows:

$$Yield = \beta_1 * N_{PRE+TILL} + \beta_2 * {N_{PRE+TILL}}^2 + \beta_3 * N_{PI} + \beta_4 * {N_{PI}}^2 + \beta_5 * N_{PRE+TILL} * N_{PI} + \beta_6 * N_{PRE+TILL} * YEAR + \beta_7 * N_{PI} * YEAR + BLOCK + YEAR \quad (1)$$

where β_1 to β_7 represent the slopes of the covariates, YEAR is the year effect related to the agro-climatic conditions and BLOCK is the block effect representing spatial variability. After that, average equation over YEAR and BLOCK was determined and the first order partial derivative was calculated with respect to N_{PI} and then set to zero, with the aim of determining the N_{PI} that maximises grain yield for each N rate supplied at pre-sowing and tillering stage.

The resulting equation is:

$$\boldsymbol{N_{PI}} = \frac{-\boldsymbol{\beta_3} - \boldsymbol{\beta_5} * \mathbf{N_{PRE+TILL}}}{2 * \boldsymbol{\beta_4}} \quad (2)$$

Next, grain yield was determined through the same GLM as mentioned above, with NDRE replacing $N_{PRE+TILL}$. This model was built as:

$$\mathrm{Yield} = \gamma_1 * \mathrm{N_{PI}} + \gamma_2 * {\mathrm{N_{PI}}}^2 + \gamma_3 * \mathrm{NDRE} + \gamma_4 * \mathrm{NDRE}^2 + \gamma_5 * \mathrm{NDRE} * \mathrm{N_{PI}} + \gamma_6 * \mathrm{NDRE} * \mathrm{YEAR} + \gamma_7 * \mathrm{YEAR} * \mathrm{N_{PI}} + \mathrm{BLOCK} + \mathrm{YEAR} \quad (3)$$

where γ_1 to γ_7 represent the slopes of the covariates.

Being the aim of optimising fertiliser application as a function of measured NDRE values, a statistical model was built excluding year, block, and their interactions.

$$\mathrm{Yield} = \gamma_8 * \mathrm{N_{PI}} + \gamma_9 * {\mathrm{N_{PI}}}^2 + \gamma_{10} * \mathrm{NDRE} + \gamma_{11} * \mathrm{NDRE}^2 + \gamma_{12} * \mathrm{N_{PI}} * \mathrm{NDRE} \quad (4)$$

where γ_8 to γ_{12} represent the slopes of the covariates.

After that, a first order partial derivative with respect to N_{PI} was calculated for *Equation 4* and then set to zero to determine the N amount that has to be supplied at PI to maximise rice grain yield. First order partial derivative with respect to N_{PI} can be expressed as:

$$\mathrm{Yield}' = \gamma_8 + 2\gamma_9 * \mathrm{N_{PI}} + \gamma_{12} * \mathrm{NDRE} \quad (5)$$

After rearranging the equation and setting the partial derivative to zero, N supply at PI can be determined as:

$$N_{PI} = \frac{-\gamma_8 - \gamma_{12} * \text{NDRE}}{2\gamma_9} \tag{6}$$

Results and discussion

Optimal fertilisation management to maximise rice grain yield

Grain yield was explained as a function of different N rates and splitting, based on the application of the GLM reported in *Equation 1. Table 2* reports the results of the statistical analysis.

Table 2: P(F) of the effects of N supply, YEAR and BLOCK on the different varieties.

Effect, covariate, or R^2	Gladio	Centauro	Carnaroli
$N_{PRE+TILL}$	0.001	0.000	0.000
$N_{PRE+TILL}^2$	0.000	0.000	0.000
N_{PI}	n. s.[1]	0.000	0.034
N_{PI}^2	0.000	0.011	n. s.
$N_{PRE+TILL}$*N_{PI}	0.000	0.000	n. s.
$N_{PRE+TILL}$*YEAR	0.001	0.000	0.000
N_{PI}*YEAR	n. s.	n. s.	0.034
BLOCK	n. s.	n. s.	n. s.
YEAR	0.014	0.000	0.000
R^2	0.789	0.779	0.505

[1]n.s. = not significant

In all the considered varieties, grain yield was influenced by N application both at pre-sowing and tillering stages, and by N supplied at PI, considering also the quadratic component. Moreover, the interaction $N_{PRE+TILL}$*N_{PI} resulted to be significant for Gladio and Centauro varieties but not for Carnaroli, revealing the possible compensation of deficient N supplies during the initial stages with larger N topdressing application at PI. Differences among years were significant for all the varieties, showing the influence of agro-climatic condition on grain yield.

Looking at the average effect over the two growing season for each variety, N amount that has to be supplied at PI stage to maximise yield as function of $N_{PRE+TILL}$ was determined according to *Equation 2*. Results are reported in *Fig. 1*.

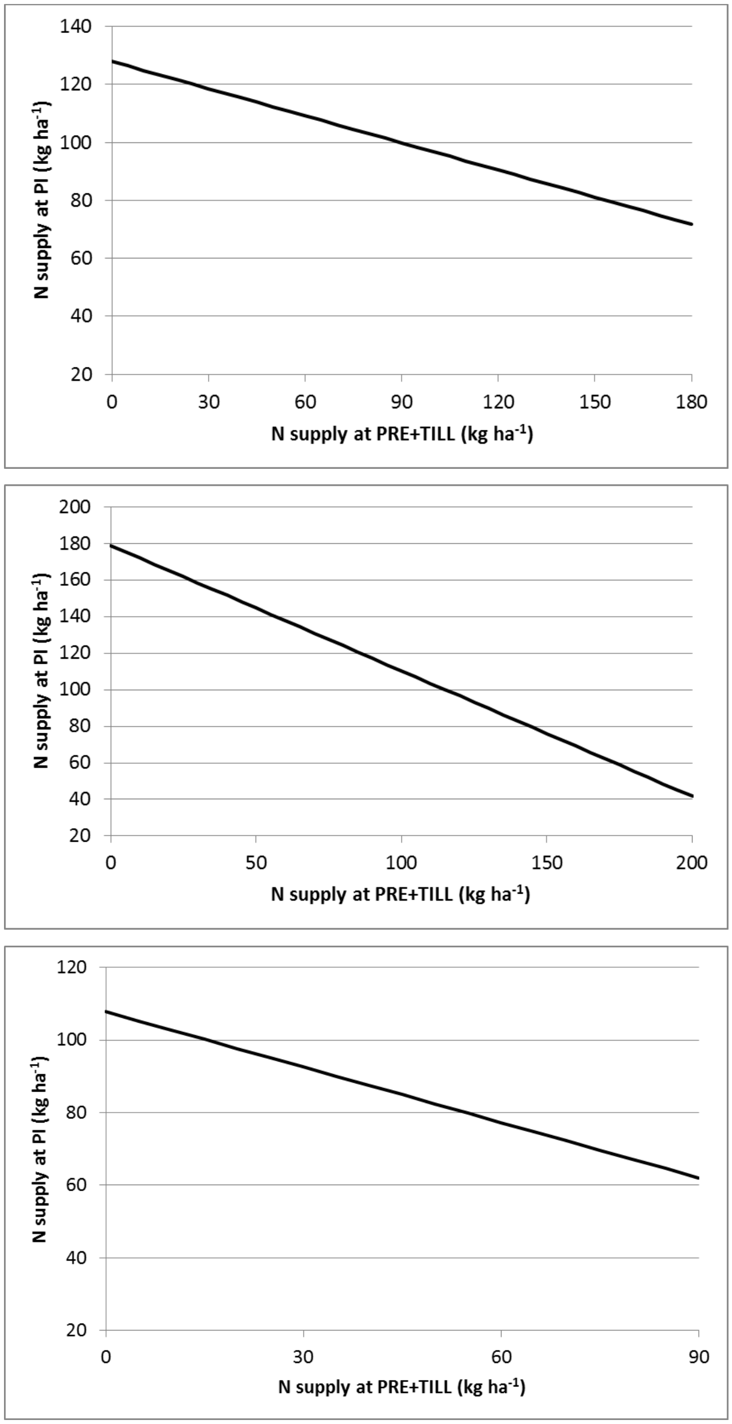

Fig. 1: N rate that has to be supplied at PI stage to maximise yield for each N amount supplied at pre-sowing and tillering stage for Gladio, Centauro and Carnaroli variety, respectively. Values are obtained on the basis of GLM application.

Consequently, the dissimilarity among the varieties appears evident, confirming previous results reported by Bah *et al*. (2009).

The optimal N management was different considering Gladio, Centauro, and Carnaroli varieties (*Table 3*).

Table 3: Optimal N management to obtain maximum grain yield, for Gladio, Centauro, and Carnaroli varieties.

Rice variety	Maximum grain yield (Mg ha^{-1})	Total N supply (kg ha^{-1})	$N_{PRE+TILL}$ (kg ha^{-1})	N_{PI} (kg ha^{-1})
Gladio	11.1	200	105	95
Centauro	11.1	190	40	150
Carnaroli	8.2	121	40	81

Gladio and Centauro varieties reached similar maximum grain yield, approximately with the same total N supply. However, the best N splitting during the growing season is different between the two varieties. In order to maximise grain yield, Gladio variety requires about 50% of the total N supply at pre-sowing and tillering stage, and 50% at PI. Instead, for Centauro variety a lower amount of N has to be supplied in the first two applications (about 20% of the total), while a larger N rate (about 80% of the total) should be supplied at PI. Maximum grain yield was reduced by 25% for Carnaroli variety, and was reached also with a lower total N amount (40% less). The optimal N management suggest to supply one-third of the total N at pre-sowing and tillering stage, and the remaining 2/3 at PI.

GLM reported in *Equation 3* was also used to investigate the capability of NDRE to determine grain yield (*Table 4*).

Table 4: P(F) of NDRE in predicting grain yield for Gladio, Centauro, and Carnaroli varieties.

Effect, covariate, or R^2	Gladio	Centauro	Carnaroli
NDRE	0.000	0.000	n. s.
$NDRE^2$	0.000	0.000	0.001
N_{PI}	0.000	0.000	n. s.
N_{PI}^2	0.000	0.001	n. s.
NDRE *N_{PI}	0.000	0.000	0.021
NDRE *YEAR	n. s.[1]	0.000	n. s.
N_{PI}*YEAR	n. s.	n. s.	n. s.
BLOCK	0.000	n. s.	n. s.
YEAR	n. s.	n. s.	n. s.
R^2	0.923	0.769	0.561

[1]n.s. = not significant

NDRE resulted to be a good predictor of grain yield, especially for Gladio and Centauro varieties, as demonstrated by R^2 higher than 0.75. NDRE, N_{PI}, and their squares were significant on predicting grain yield for Gladio and Centauro varieties, while for Carnaroli only $NDRE^2$ affected grain yield. Moreover, the interaction between NDRE and N_{PI} was significant, for all the considered varieties. This confirms that topdressing N fertilisation could compensate low NDRE values due to a deficient N supply at pre-sowing and tillering stage. Nonetheless, block effect was significant for Gladio variety, showing that NDRE values could be affected by soil variability.

Adapting calibration functions to different rice varieties

GLM showed the influence of N_{PI} and NDRE in determining grain yield. Then, first order partial derivative was calculated with respect to N_{PI} and set to zero. The aim was to determine the N amount to be supplied at PI based on the NDRE values measured in the field at the moment of N application, in order to maximise rice grain yield. This procedure led to obtain calibration functions that can be adapted to different rice varieties (*Fig. 2*).

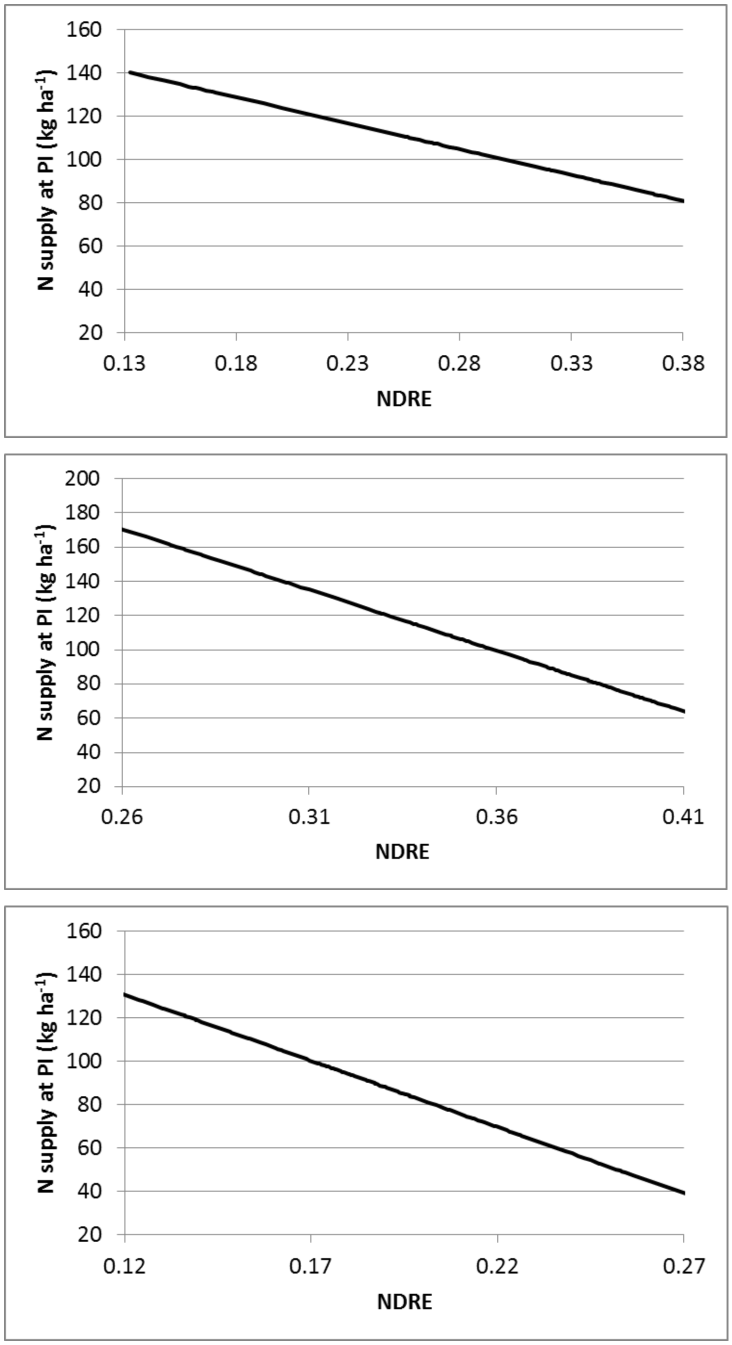

Fig.2: N rate that has to be supplied at PI stage to maximise yield for each NDRE value measured in the field for Gladio, Centauro and Carnaroli variety, respectively. Values are obtained on the basis of GLM application.

As expected, all calibration functions suggest a lower N_{PI} at increasing NDRE values, which correspond to higher crop vigour.

Best N management based on NDRE readings for different rice varieties

Best N fertilisation management based on NDRE readings was different among the rice varieties (*Table 5*).

Table 5: N_{PI} and NDRE values to obtain maximum grain yield for Gladio, Centauro, and Carnaroli varieties.

Rice variety	N_{PI} (kg ha^{-1})	NDRE value	Maximum obtainable grain yield (Mg ha^{-1})
Gladio	79	0.387	11.2
Centauro	109	0.347	11.1
Carnaroli	93	0.181	8.6

Gladio and Centauro can achieve similar maximum grain yield, but corresponding to different NDRE values (0.387 and 0.347, respectively).Consequently, for Centauro variety, N_{PI} should be increased by almost 38% over the amount requested for Gladio variety. Referring to Carnaroli, maximum obtainable grain yield is 30% lower and is achieved when NDRE is 0.181, corresponding to 93 kg N ha^{-1} supplied at PI. However, as NDRE values could be affected by soil variability, some uncertainties are associated with the suggested N_{PI} amount. Moreover, the function that describes maximum grain yield shows a smooth curvature close to the vertex. Consequently, the slope of the calibration functions can be considered almost constant, while the intercept is proportional to the grain yield goal. Hence, they can be adapted to different agro-environment taking into account the potential grain yield obtainable in specific situation.

Conclusion

The methodology proposed in the present study allowed to establish the best N fertilisation management for Gladio, Centauro, and Carnaroli rice varieties representing three different grain types. For Gladio variety, grain yield is optimised when total N amount is equally split between pre-sowing plus tillering and PI application. Conversely, considering Centauro and Carnaroli varieties, best N management suggests reducing N application at the early growth stages, increasing topdressing N fertilisation at PI. NDRE was shown to be suitable to derive calibration functions for the rice varieties considered in the present study. Calibration functions established N_{PI} as a function of NDRE values measured just before N application, with the aim of maximising grain yield. These calibration functions can be implemented in variable rate application fertiliser spreader, allowing a site-specific N management that reduce the negative environmental impact of N fertilisation. However, calibration functions have been obtained for Gladio, Centauro, and Carnaroli varieties, under specific environmental conditions. Large variability in NDRE ranges recorded in the different rice varieties demonstrated the needs to extend calibration to other varieties. The adaptation of the calibration functions can be performed using the methodology proposed in this study, with the aim of promoting a widespread application of precision N fertilisation in rice.

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