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Mid-season variable-rate algorithm for organic and mineral rice fertilization

Karen Marti-Jerez¹ · Mar Català-Forner¹ · Núria Tomàs¹ · Gemma Murillo² · Carlos Ortiz² · Marta S. Lopes³ 

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Abstract

Accurate calculation of nitrogen requirements is essential in rice fields utilizing both local manure and mineral fertilizers to mitigate nitrogen deficiencies and yield losses associated with reducing chemical fertilizer use. Traditional approaches often fail to effectively integrate organic and mineral fertilizers or adapt to the complexities of real-farm conditions. To tackle these challenges, this study introduced a novel application of the Nitrogen Fertilizer Optimization Algorithm (NFOA), leveraging remote optical sensors and Sentinel-2 satellite imagery to deliver precise, data-driven nitrogen recommendations for the effective integration of organic fertilization in rice cultivation. Fertilizer prescription maps generated by the NFOA delivered precise nitrogen recommendations tailored for diverse real-farm fields. The algorithm demonstrated strong predictive performance for yield responses to nitrogen application at critical phenological stages, such as panicle initiation and maximum tillering ($R^2 = 0.71, p < 0.0001$; $R^2 = 0.73, p < 0.0001$). Key findings demonstrate the model's ability to optimize nitrogen inputs, achieving up to a 40% reduction in surplus nitrogen while maximizing yields. By promoting a balanced nitrogen input-output equilibrium, the NFOA offers significant environmental and economic benefits, even in the context of the complexities associated with organic fertilization. In conclusion, these findings suggest that the NFOA approach is suitable for calculating nitrogen fertilizer requirements in rice fields using organic fertilization strategies, effectively accommodating the high variability in nutrient content and availability of organic nitrogen to rice crops. However, further refinement is necessary to enhance its predictive accuracy by incorporating advanced spectral indices and accounting for detailed environmental and management factors.

Keywords Fertilization prescription algorithm · Nitrogen use efficiency · Rice · Precision agriculture · Remote sensing · Organic fertilization

1 Introduction

The key challenge for achieving global food security and sustainable development lies in doubling food production, enhancing resource efficiency, and minimizing

environmental impacts (Holden et al. 2018). Nitrogen (N) is considered a fundamental mineral nutrient essential for plant growth and development owing to its direct correlation with the photosynthetic process, thereby exerting a substantial impact on both crop yield and quality (Masclaux-Daubresse et al. 2010; Chauhan et al. 2017). While increased use of N fertilizers has significantly boosted global crop yields, the rate of cereal grain yield increase has decelerated or even stalled in some regions over the last 20–30 years, despite higher N fertilizer inputs (Lopes 2022; Gulino et al. 2023). While this stagnation has been largely associated with climate change patterns, it is also at least partially attributed to excessive and poorly timed N applications, leading to low N use efficiency (NUE) and elevated environmental costs.

Rising prices, resource scarcity, and geopolitical concerns jeopardizing mineral fertilizer availability, combined with the policy directives advocating for more sustainable agricultural practices, pose a threat to meeting global

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demands and contribute to the crisis in food availability (Fixen and Johnston 2012; King et al. 2017). Manure has been proven to improve soil health and provide a broader range of nutrients. In contrast, the prolonged and extensive use of mineral fertilizers over the years has resulted in the depletion of soil fertility (Marti-Jerez et al. 2023; Tang et al. 2023). Using local manure in rice agriculture implies a proximity supply with high reserves, facilitates nutrient recycling, minimizes transportation-related environmental footprints, and addresses livestock waste management issues. However, growers face persistent challenges in establishing economically viable systems when replacing substantial amounts of chemical fertilizers with manure. This is primarily due to nitrogen deficiencies, which lead to yield losses (Schmidt and Knoblauch 2020; Peng et al. 2023). Traditionally, farmers adopt a uniform fertilization approach for each field, basing their N management decisions on yield objectives, experience, and data compiled from previous agricultural campaigns (Cai et al. 2023). This practice proves to be inefficient because N requirements vary both among and within fields and across different years (Cassman et al. 1998; Tubaña et al. 2008). These fixed N management strategies result in suboptimal NUE, diminished economic returns, and heightened environmental and health risks (Brinkhoff et al. 2021; Eckardt et al. 2023). To enhance NUE, strategic practices involve optimizing the form, timing, and rates of N applications (Yao et al. 2012; Cai et al. 2023). The employment of in-season diagnostic tools and models capable of estimating plant N requirements on a need basis holds potential to enhance the precision of N management decisions. Substantial progress has been made in remote sensing for precision agriculture in recent years (Sishodia et al. 2020). Multiple methodologies are available for determining N rates based on canopy reflectance (Chlingaryan et al. 2018). The hand-held GreenSeeker™ optical sensor emerged as a promising tool for effective N management by monitoring crop growth through remotely sensed Normalized Difference Vegetation Index (NDVI) (Yao et al. 2012; Sapkota et al. 2014). Current research explores the expansion of these techniques to the farm level through the utilization of satellite data (Yeom et al. 2018; Karthikeyan et al. 2020). Operational satellites offer remote sensing imagery with broad coverage, relatively high resolution, and timely data retrieval, facilitating the assessment of crop growth conditions in real time and offering decision-making support for farmers.

The Nitrogen Fertilizer Optimization Algorithm (NFOA) is recognized as one of the classic and extensively used remote sensing recommendation methods for many crops. The algorithm integrates remotely sensed crop spectral properties to estimate crop N status, predict in-season yield potential (YP_0) and the grain yield response to additional N

application (RI). Raun et al. (2005) demonstrated the predictability of in-season yield potential through the integration of NDVI, meteorological data and yield information, establishing reliable equations with only two years of field data (Raun et al. 2005). The NFOA algorithm was subsequently developed to accurately estimate mid-season N requirements for winter wheat, accounting for seasonally dependent crop responsiveness and within-field variability (Mulla 2013). N application rates were then adjusted based on the estimated in-season yield potential and N Response Index, incorporating grain N concentration and N recovery efficiency (Wang et al. 2019). Successive studies have validated the efficacy of these sensor-based N rate recommendation models in various crops, including corn (Tubaña et al. 2008; Wang et al. 2019; Lekakis et al. 2020) and rice (Yao et al. 2012; Yang et al. 2022).

However, most research on the NFOA algorithm focuses on mineral rice farming (Yao et al. 2012; Yang et al. 2022). Current recommendation algorithms rely on data from exclusively mineral fertilized experimental fields, resulting in a scarcity of literature addressing the adaptation of this methodology to rice crops utilizing alternative fertilization practices. Additionally, the majority of studies have considered precisely controlled mineral experimental trials for the development and calibration of recommendation algorithms, without assessing the suitability of these models in real-farm conditions (Brinkhoff et al. 2021). This lack of research hinders the implementation of the developed tools at the commercial production level, particularly in farming practices that incorporate organic fertilizers. To facilitate the transition to precise nutrient management within the rice commercial industry, it is imperative to conduct further testing and refinement of the described methods and available remote sensing tools for organic-based fertilization schemes (Fig. 1).

In this study, we assess for the first time the applicability of the remote sensing-based N rate recommendation models to sustainable rice farming systems using organic and mineral fertilizers. This involves refining previous methodologies described in the literature. Key improvements include integrating data from organic and mineral fertilized fields, developing models tailored to individual crop varieties to increase accuracy, scaling these methodologies with accessible open-access satellite data and test suitability under real-farm conditions (Fig. 2).

The main objectives are (a) to develop a refined mid-season N recommendation algorithm by expanding on NFOA methodologies tailored for sustainable farming practices; (b) to examine the feasibility of the methodologies in both mineral and organic farming systems; (c) to validate the algorithm's performance under experimental and real-farm conditions; and (d) to identify the limitations and critical aspects warranting further scrutiny for potential improvement in subsequent research endeavors.



Fig. 1 Application of pig slurry in experimental plots (Trial 2), experimental mineral fertilized plots (Trial 1) and commercial site assessed through satellite imagery (site 2). Photo credits (from left to right): Andrea Bertomeu, Karen Marti, and Oriol Ferre

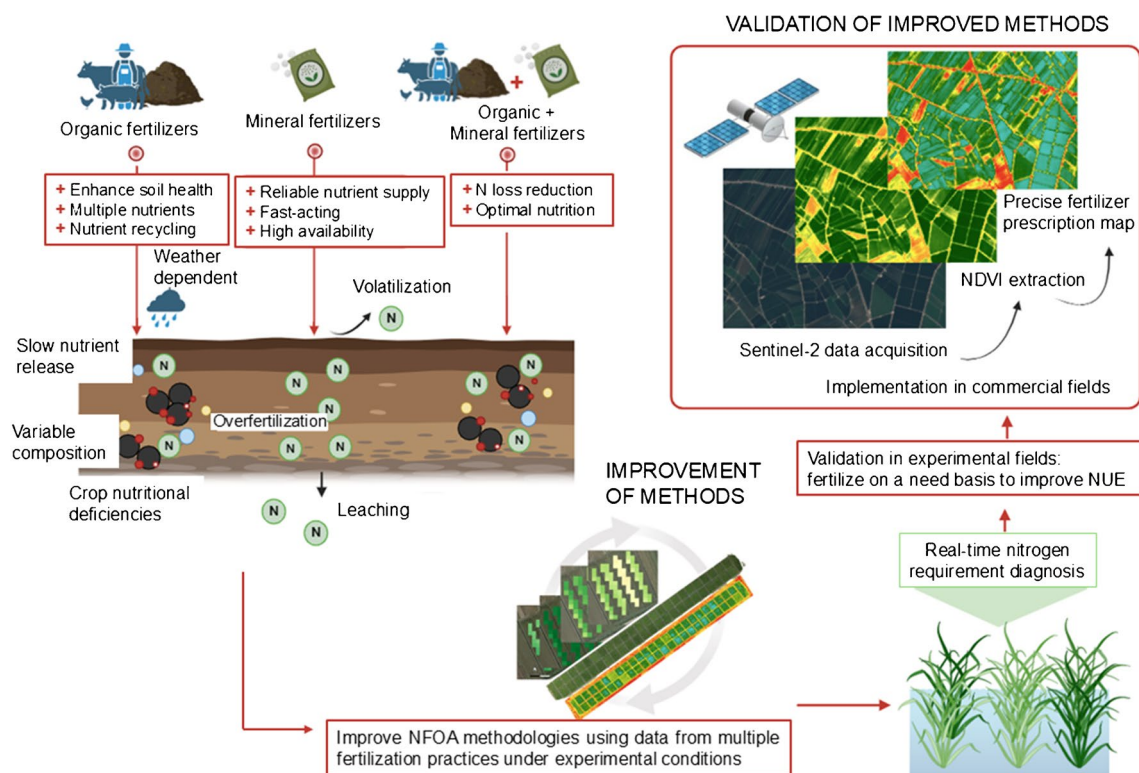


Fig. 2 An illustrative overview of the study’s roadmap: overcoming barriers to organic fertilizer adoption through the improvement of NFOA methodologies

2 Materials and methods

2.1 Study sites and general considerations

This work consolidates data from multiple growing seasons of commercial fields and field trials conducted in the Ebro Delta in Catalonia (Spain). This region, a prominent area for rice cultivation, extends over 20,400 hectares of production (DACC 2023). As a temperate Mediterranean growing region, rice is grown once per year, spanning from May to

October. The assessed fields included both organic supplemented with mineral fertilization practices (sustainable practices) and solely mineral fertilization practices. This study integrated data from four datasets: organic and mineral N rate experiments (Trials 1 and 2), NFOA algorithm performance experiment, and commercial fields. We built upon the data and findings derived from our previous research, based on a medium-term organic experiment conducted between 2017 and 2022. Further insights from this experiment are available in the publication authored by Marti-Jerez et al.

(2023). All fields were sown with the JSendra round-grain Japonica-type variety, selected for its in-depth agronomic characterization and widespread cultivation in the area, attributed to its high yield and favorable climate adaptation. Although varietal bias in spectral response is unavoidable to complete the implementation of the developed precision fertilization tool in commercial agricultural sector, varietal differences were not targeted in this work. Given that, only data from a single variety was considered.

Trial 1 (Supplementary Figure 1a) involved experimental plots subjected to direct seeding on wet land. Rice was sown at a seeding rate of 500 kg ha⁻¹ in May by broadcasting pre-germinated rice seeds on wet puddled fields, as is typical in the area. In Trial 2 (Supplementary Figure 1b), dry-direct seeding was performed at a rate of 200 kg ha⁻¹ between April and May. Flooding was delayed until tillering stage (BBCH 13–14). All plots were consistently flooded to a depth of 5–10 cm throughout the entire growing season. With respect to remaining agronomic practices, traditional methods of the region were maintained. After harvest, winter flooding with straw addition through puddling was carried out until the beginning of January. Seedbed preparation took place in March using a cultivator, followed by the application of basal fertilizer. The N source utilized for all mineral experimental treatments comprised urea for basal applications and ammonium sulfate for top-dressing applications at panicle initiation stage (PI). To avoid phosphorus (P) and potassium (K) deficiencies in mineral and non-nitrogen fertilized plots, 50 kg P₂O₅ and 30 kg K₂O per hectare, in the form of calcium superphosphate (18%) and potassium sulfate (50%), were incorporated into the soil before seeding and flooding using a rotovator. In the commercial fields (Supplementary Figure 1c), traditional practices were upheld, adhering to the methods established by each farmer based on their individual experiences and accumulated knowledge.

The specific sowing dates, along with the durations in days from sowing to field flooding, maximum tillering stage, panicle initiation stage, and harvest, are detailed in Supplementary Table 1 for each experiment conducted between 2021 and 2023 and in Supplementary Table 2 for the commercial fields.

2.2 Nitrogen management experiments

2.2.1 Nitrogen rate experiments with mineral and organic fertilizers to develop NFOA algorithm

This work considered a N rate experiment with a set of strategies adhering to mineral practices (Trial 1) and a N experiment adopting combined organic and mineral fertilization strategies (Trial 2) conducted at the IRTA Ebro Experimental Station (Catalonia, Spain). Trial 1 (Supplementary Figure 1a) involved plots entirely fertilized with chemical fertilizers from

2021 to 2022. Trial 2 (Supplementary Figure 1b) data was extracted from a medium-term experiment conducted from 2017 to 2022. For the development of the NFOA algorithm, only data from 2021 and 2022 from Trial 2 was considered. Data from other years was considered for in-season yield prediction evaluation when crop yield was not affected by factors unrelated to fertilization response. Trial 2 included two strategies partially fertilized with either chicken manure or pig slurry and one strategy entirely relying on mineral fertilization. Both trials included plots without N fertilization. Trial 1 followed a randomized complete block design with four replicates and 12 N fertilization strategies (48 plots) outlined in Table 1. The strategies encompassed different total amounts of N fertilizer, split in two or three application moments. Elemental plots in Trial 1 had an area of approximately 19 m². Otherwise, experimental design in Trial 2 followed a fully randomized block design with four sub-plots per treatment (16 sub-plots), with a plot area of 4270 m² approximately.

2.2.2 NFOA algorithm performance experiment

This experiment was conducted to assess the performance of the NFOA developed prescription model. The study performed in 2023 adhered to the same experimental design and employed the same set of mineral strategies as in Trial 1 (Table 1). However, it diverged from the prior approach by

Table 1 Nitrogen rates (kg ha⁻¹) and application details of each trial (C: control; MIN: mineral; PS: pig slurry; CM: chicken manure). The asterisk highlights the strategy assessed by NFOA in 2023 with different nitrogen rates, the total amount indicated corresponds to the nitrogen application rates employed in the 2021 and 2022 experimental datasets from which the algorithm was derived.

| Experiment | Treatment | Basal | Tillering stage | Panicle initiation stage | Total |
|------------|-----------|-------------------|-------------------|--------------------------|-------|
| Trial 1 | 1 | 0 | 0 | 0 | 0 |
| | 2 | 44 | 66 | 0 | 110 |
| | 3 | 56 | 84 | 0 | 140 |
| | 4* | 51 | 68 | 41* | 160* |
| | 5 | 68 | 102 | 0 | 170 |
| | 6 | 51 | 68 | 51 | 170 |
| | 7 | 80 | 120 | 0 | 200 |
| | 8 | 60 | 80 | 60 | 200 |
| | 9 | 92 | 138 | 0 | 230 |
| | 10 | 69 | 92 | 69 | 230 |
| | 11 | 104 | 156 | 0 | 260 |
| | 12 | 120 | 180 | 0 | 300 |
| Trial 2 | C | 0 | 0 | 0 | 0 |
| | MIN | 50 | 90 | 50 | 190 |
| | PS | 0 | 140 _{PS} | 50 | 190 |
| | CM | 140 _{CM} | 0 | 50 | 190 |

replacing the fixed uniform rate applied in strategy 4 with the amount guided by the developed algorithm. A comparative analysis of the NUE was subsequently conducted between our developed algorithm and the fixed strategies. This evaluation considered N uptake, utilization, and yield (Section 2.3.3).

2.2.3 Commercial fields

During the 2023 growing season, 12 commercial fields belonging to local farms with mineral and organic practices were assessed, collecting data from approximately 124 hectares (Supplementary Figure 1c). Among these, five farms implemented basal fertilization using manure and supplemented with mineral fertilizers before the panicle initiation phenological stage. Specifically, three farms used pig slurry, and two used chicken manure. Additionally, seven fields exclusively received mineral fertilizers. All fields were situated in the same rice-growing area as the experimental plots and cultivated with the same rice variety (JSendra). The total applied amounts of N varied from 160 to 275 kg per hectare, resulting in yields ranging from 6.85 to 8.39 tons of grain per hectare at 14% humidity.

2.3 Data acquisition

2.3.1 Handheld optical sensor data

GreenSeeker™ (505 hand-held optical sensor, N-Tech Industries, Ukiah, CA, USA) was used to measure NDVI at ground level. This active optical sensor emits short bursts of red and infrared (NIR) light, measuring the reflection from canopy to calculate NDVI using the following equation (Rouse et al. 1973)

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}} \quad (1)$$

where

NIR is emitted near-infrared radiation (780 ± 10 nm) from de sensed area and

RED is emitted red radiation (671 ± 10 nm) from the sensed area.

Two NDVI measurements were acquired using the hand-held sensor for each plot, positioned at approximate height of 50 to 60 cm above the canopy surface, with a field of view characterized by a 25-cm major axis oval. Measurements were taken at maximum tillering stage (BBCH 28–29) and panicle initiation stage (BBCH 30). Measurements were taken at approximately 72.5 and 76 days after seeding in Trial 1, 57 and 63 days after seeding in Trial 2, and 63 and 72 days after seeding in the NFOA performance experiment (Supplementary Table 1). The device generates readings at a rate of 10 readings per second. Average values were used to represent

each plot. Plants within plot borders or severely affected by factors unrelated to N effects were excluded for sampling.

2.3.2 Sentinel-2 data from commercial fields

Spectral data was collected from images acquired from Sentinel-2 L1C. Sentinel-2 features imagery with a spatial resolution of 10 m and a revisit time of 5 days, offering extensive coverage and including a total of 13 spectral bands (ESA 2023). Images with a maximum cloud coverage of 1% were procured from the Copernicus Open Access Hub on dates close to maximum tillering crop stage in each respective field (late June). All images were processed using the open-source software QGIS ver. 3.28.2 (QGIS Development Team 2022). NDVI was calculated for each commercial field following Eq. 1.

2.3.3 Agronomic and NUE parameters

In Trials 1 and 2 a comprehensive evaluation of crop development was performed based on the universal BBCH scale reported by Lancashire et al. (1991). Plant and panicle density were assessed through four or six observations (Trial 1 and NFOA algorithm performance or Trial 2) within 0.25 m² squares per plot at BBCH 14 and 73, respectively. Plant height was measured from soil to the panicle apex at BBCH 73. Grain weight was determined by harvesting the plots or sub-plots separately using a Mitsubishi trial harvester once full maturation was reached in mid-October for both experiments (adjusted to a moisture content of 14%). Additional information on agronomic parameters measured in organic plots can be found in the work by Marti-Jerez et al. (2023).

Moreover, NUE characterization was conducted as part of the NFOA algorithm performance experiment. Crop biomass samples were taken at maturity, harvesting 0.25 m² square of the total aboveground biomass at maturity from the stem base for each plot. Panicles and straw were separated by the panicle neck. Fresh and dry weight of both components were determined. Subsequently, N content was determined using the Kjeldahl method (Kjeldahl 1883) through an external laboratory (Eurofins Ambiental, S.A., Lleida). Several NUE indices were derived from this dataset, as detailed in Table 2.

2.3.4 Nitrogen fertilizer optimization algorithm construction method

The NFOA relies on the ability to estimate the potential or predicted yield in-season through remotely sensed crop spectral properties. NDVI has demonstrated a strong correlation with grain yield in multiple crops, as represented by an exponential curve (Teal et al. 2006; Oglesby et al. 2022). Raun et al. (2005) and Lukina et al. (2001) further enhanced

this relationship by adjusting NDVI readings with growing degree days (GDD) accumulated from planting to sensing, thereby creating in-season estimate of yield (INSEY). INSEY proved to be an excellent predictor of yield, considered an estimate of average daily growth rate or biomass production (Lukina et al. 2001; Raun et al. 2005; Tubaña et al. 2008). Therefore, the in-season yield potential prediction equations were formulated using INSEY, showcasing an improved correlation with measured grain yield through exponential models. Previous research that developed NFOA for transplanted rice considered the days from transplanting to sensing date to derive INSEY (Yao et al. 2012; Yang et al. 2022). This method reported the days from transplanting to sensing as a normalized divisor, effectively mitigating variability across different sites and years. In this study, conducted in a region where transplantation is not practiced and direct seeding is predominantly employed, we propose determining INSEY by considering crop growth since sowing. Thus, NDVI readings were divided by the number of growing degree days up to zero from sowing to sensing date to obtain INSEY.

N supply during the tillering stage significantly influences tiller development and rice metabolism, thus rendering this stage a pivotal moment directly impacting yield output (Yu et al. 2022). Early-season plant N status at maximum tillering stage before panicle initiation was found to be highly correlated with NDVI in our previous findings (Marti-Jerez et al. 2023). In this stage, it is anticipated to be less influenced than subsequent stages by the saturation effect observed in NDVI (Rehman et al. 2019; Jiang et al. 2021; San Bautista et al. 2022). This is attributed to the lower biomass density, allowing for a more accurate characterization of the nutritional status of the crop when comparing NDVI values with

well-fertilized plots. In addition, our study highlighted the necessity of fertilizing at an earlier growth stage than panicle initiation, a timing established in traditional agricultural practices (Girsang et al. 2023), particularly in rice fields fertilized with organic fertilizers. It provides a more flexible approach for farmers compared to delaying fertilizer application until panicle initiation. This is particularly relevant considering the potential risk of surpassing the panicle initiation stage, a period characterized by high N demand, thereby resulting in a penalty on yield. In this context, we decided to contrast in-season yield predictability at both stages.

An accurate estimation of the response of rice grain yield to applied N fertilizer is also a critical factor for the precise recommendation of NFOA. This is essential as the crop response to N fertilizer depends on the supply of N, both from fertilizer and non-fertilizer sources, in each specific year and location, influenced by climatic conditions and fertilization management practices. Previous research has demonstrated that the Response Index for a harvested crop ($RI_{Harvest}$, Eq. 2) effectively captures variations across fields and years (Johnson and Raun 2003; Raun et al. 2005).

$$RI_{Harvest} = \frac{Y_{NRich}}{Y_{Field}} \tag{2}$$

where Y_{NRich} and Y_{Field} represent grain yield in plot fertilized under non-limiting N conditions and in the adjacent plot receiving the standard field N rate ($kg\ ha^{-1}$), respectively.

N management strategies incorporating a reliable mid-season predictor of Response Index for a harvested crop are anticipated to substantially enhance NUE in cereal production. To predict the crop response to additional fertilizer at mid-season, the NFOA algorithm employs NDVI readings to

Table 2 NUE indices and their corresponding formulas and references. Yield represents grain yield, measured in kg per hectare. Plant N denotes the total N in aboveground biomass, expressed in kg per hectare. Yield N denotes total N removed as grain, measured in kg

| NUE indicator | Acronym | Formula | Reference |
|---------------------------------|--------------|---|-------------------------|
| Nitrogen agronomic efficiency | AE | $\frac{Yield_{Nfert} - Yield_{N0}}{FertilizerN}$ | Cassman et al. (1998) |
| Recovery efficiency | RE | $\frac{PlantN_{Nfert} - PlantN_{N0}}{FertilizerN}$ | Cassman et al. (1998) |
| Partial factor productivity | PFP | $\frac{Yield_{Nfert}}{FertilizerN}$ | Cassman et al. (1998) |
| Nitrogen balance intensity | NBI | $YieldN - FertilizerN$ | Congreves et al. (2021) |
| Partial N balance | PNB | $\frac{PlantN}{FertilizerN}$ | Dobermann et al. (2007) |
| Crop nitrogen use efficiency | NUE_{crop} | $\frac{YieldN}{FertilizerN}$ | Congreves et al. (2021) |
| Physiological efficiency | PE | $\frac{Yield_{Nfert} - Yield_{N0}}{PlantN_{Nfert} - PlantN_{N0}}$ | Cassman et al. (1998) |
| Nitrogen utilization efficiency | NUtE | $\frac{Yield}{PlantN}$ | Moll et al. (1982) |
| Internal efficiency | IE | $\frac{YieldN}{PlantN}$ | Dobermann et al. (2007) |

per hectare. Fertilizer N accounts for the inorganic N originating from fertilizer inputs, measured in kg per hectare. Parameters followed by subscript Nfert pertain to fertilized conditions, whereas those with subscript N0 correspond to non-fertilized conditions

compute the NDVI-based Response Index (RI_{NDVI}), thus estimating Response Index for a harvested crop through Eq. 3.

$$RI_{NDVI} = \frac{NDVI_{NRich}}{NDVI_{Field}} \quad (3)$$

where $NDVI_{NRich}$ represents the NDVI of the plot subjected to non-limiting conditions of N and $NDVI_{Field}$ corresponds to the NDVI of the adjacent plot fertilized under the fixed-standard N rate. NDVI-based Response Index has been demonstrated to be a reliable and conservative predictor of grain yield in response to additional fertilizer across several cereal crops (Johnson and Raun 2003; Raun et al. 2005; Tubaña et al. 2008, 2012; Yang et al. 2022). In-season yield potential and NDVI-based Response Index were subsequently used to compute the potential yield with additional N fertilizer (YP_N) following Eq. 4.

$$YP_N = YP_0 * RI_{NDVI} \quad (4)$$

The topdress N requirement (R) can then be calculated by Eq. 5.

$$R = N\% * \frac{YP_N - YP_0}{\eta} \quad (5)$$

where $N\%$ denotes the average of grain N content and η the efficiency factor representing mid-season N fertilizer utilization rate (Recovery Efficiency, Table 2). In this study, we adopted values of 1.24% for grain N content and 40% for the N fertilizer utilization rate. These values were derived from previous field measurements conducted within the same region for the JSendra variety and align with findings reported in other studies on rice (Yang et al. 2022; Mondal et al. 2023).

2.4 Data analysis

The difference between the various N fertilization strategies in NUE indices and agronomic parameters in the NFOA algorithm performance experiment (2023) were evaluated through analysis of variance (one-way ANOVA) employing a mixed model. In this model, the N rate was treated as a fixed effect, while block was considered a random effect. Subsequently, a Tukey's test (HSD) was performed for a comprehensive mean comparison analysis on the dataset, as the ANOVA identified a significant response to the N rate ($p < 0.05$). The effects of year and the interaction between year and treatment were incorporated into the model for the analysis of variance of yield data from Trial 1 and Trial 2, which were used for deriving the algorithm, using the general linear model procedure (GLM). A regression analysis was conducted to assess the relationship between absolute yield and INSEY across various treatments (Trial 1 and Trial 2) and sensor dates. Exponential models were derived to predict yield potentials, and prediction equations were obtained. Data from commercial fields was

gathered from a total area of approximately 124 hectares, corresponding to 12,435 pixels (100 m² per pixel). Spectral data was extracted from these pixels to compute the site-specific recommendation prescription maps using the open-source software QGIS ver. 3.28.2 (QGIS Development Team 2022). The efficiency of the prediction equation in estimating rice yield under diverse crop conditions was evaluated. The linear relationships between Response Index for a harvested crop and the NDVI-based Response Index, as well as between predicted and actual measured yield values, were analyzed using data from the NFOA performance experiment, commercial fields and data from 2017 to 2020 from Trial 2. We compared the performance of the yield prediction regression model to an identity line ($y=x$) to evaluate the model's reliability by analyzing the alignment of predicted yield regression with the identity line. The strength of the relationships was determined by the coefficient of determination (R^2), and prediction error was assessed using the root mean squared error (RMSE). All statistical analyses and graph designs were conducted using the JMP 16 Statistical Software (SAS Institute Inc. 1989–2023) and R Statistical Software (R Core Team 2023).

3 Results and discussion

3.1 Innovative approaches to organic fertilizer management in rice fields: harnessing remote optical sensors and NFOA models

To assess the yield prediction capability of the exponential curve derived from in-season estimates of yield (INSEY) using NDVI and growing degree days, data collected over two years from mineral and organic fertilized fields were analyzed both separately and in combination. The analysis of variance revealed a significant effect of treatment and year on yield, with no significant interaction between these factors. Regression models of the exponential function to predict in-season yield potential were developed based on INSEY obtained from NDVI and days after sowing (Fig. 3a). The correlation analysis ($R^2 = 0.73$, $p < 0.0001$, see Fig. 3) demonstrated that the exponential curve strongly supports that INSEY can predict potential yield when accounting for the ratio of NDVI to the accumulated growing degree days from sowing to the sensing date, applicable to both mineral and organic fertilizer strategies.

3.2 Improving precision N recommendations in rice production based on phenological stages and fertilizer dynamics

Prediction equations were developed based on the data obtained from the handheld sensor at two key phenological stages, panicle initiation and maximum tillering, known

a)

| Experiment | Year | YP ₀ equations | | R ² | |
|--------------------------------|-----------|---|---|-------------------|--------------------|
| | | Maximum tillering | Panicle initiation | Maximum tillering | Panicle initiation |
| Organic + Mineral (Trial 2) | 2021 | YP ₀ = 1886e ^{166.03*INSEY} | YP ₀ = 1866.8e ^{172.4*INSEY} | 0.70 | 0.66 |
| | 2022 | YP ₀ = 699.91e ^{260.69*INSEY} | YP ₀ = 573.67e ^{273.49*INSEY} | 0.51 | 0.65 |
| | Avg | YP ₀ = 1271.6e ^{199.03*INSEY} | YP ₀ = 1338.9e ^{188.5*INSEY} | 0.51 | 0.38 |
| Mineral (Trial 1) | 2021 | YP ₀ = 2151.2e ^{114.35*INSEY} | YP ₀ = 1458.1e ^{159.87*INSEY} | 0.75 | 0.67 |
| | 2022 | YP ₀ = 3432.4e ^{69.317*INSEY} | YP ₀ = 2360.1e ^{107.97*INSEY} | 0.64 | 0.51 |
| | Avg | YP ₀ = 3278.8e ^{75.149*INSEY} | YP ₀ = 2493.6e ^{106.49*INSEY} | 0.61 | 0.52 |
| Overall | 2021-2022 | YP ₀ = 2586.5e ^{93.916*INSEY} | YP ₀ = 2071e ^{123.05*INSEY} | 0.73 | 0.71 |

b)

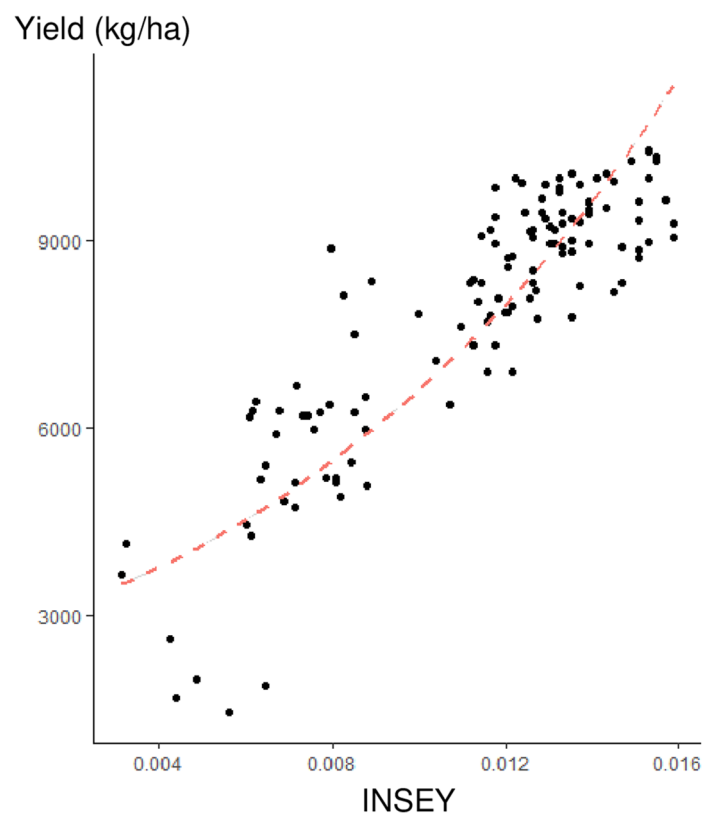


Fig. 3 a Prediction equations for yield potential and their corresponding correlation coefficient at two phenological stages across different years and fertilization management practices. **b** Relationship between

observed rice grain yield and in-season estimate of yield (INSEY) at several fertilization management strategies from 2021 to 2022 (Equation: $YP_0 = 2586.5e^{93.916*INSEY}$; $R^2 = 0.73$; $p < 0.0001$).

for their high N requirements and suitability for top-dressing applications (Dobermann and Fairhurst 2000; Tubaña et al. 2012; Bashir et al. 2023). Particularly, panicle initiation stage is critical for N application due to its substantial

impact on yield (Marti-Jerez et al. 2023). However, in organically fertilized fields, topdressing at panicle initiation may not adequately cover N needs, leading to reduced N use efficiency and yield (Kögel-Knabner et al. 2010; Kumar

et al. 2023; Mondal et al. 2023). The unpredictability of environmental factors and agronomic practices affects mineralization rates and soil N-supplying capacity (Mohanty et al. 2013; Tang et al. 2023). Variations in organic fertilizer composition and seasonal differences further complicate N dynamics prediction (Huang et al. 2018; Tang et al. 2023). Additionally, rhizosphere variations influenced by microorganisms and root exudates affect N availability (Huang et al. 2018; Tang et al. 2023). Accurately estimating rice yield response to N fertilizer in-season is crucial for deriving precise recommendation models (Huang et al. 2018; Tang et al. 2023).

The regression coefficients varied greatly across the different datasets (Fig. 3a). In general, a better fit was obtained at maximum tillering stage and slightly stronger fit observed for equations derived from mineral trials. We found that the accuracy of the model of in-season yield potential established by INSEY at the maximum tillering stage involving all data from both fertilization conditions was significantly high, with its $R^2 = 0.73$ (see Fig. 3). The accuracy of the potential yield prediction model for rice based on INSEY developed herein exceeded slightly those obtained in previous research on wheat (Lukina et al. 2001; Raun et al. 2005) and rice (Yao et al. 2012; Yang et al. 2022) under mineral fertilization. Therefore, we considered the equation derived from data involving both fertilization practices at the maximum tillering stage the most adequate for the construction of our prescription model.

The ability of maximum tillering canopy reflectance handheld sensor readings to predict the rice grain yield response to applied N exhibited certain trade-offs. A substantial correlation between Response Index for a harvested crop and NDVI-based Response Index ($R^2 = 0.63$, see Supplementary Figure 2) was established, supporting that NDVI-based Response Index generally provided reliable estimates of the actual crop response to N fertilizer, aligning with findings from prior studies (Tubaña et al. 2012). Nevertheless, a notable dispersion with significant instances of both overestimation and underestimation was observed in plots deviating from the common mean within the studied population, particularly those exceeding 2 in the Response Index for a harvested crop. Slight deviations in predictions are anticipated due to unforeseen events occurring between sensing and harvest, which may adversely affect yield outcomes. The underestimations were of a greater magnitude and observed predominantly in organic fertilized plots, whereas the overestimations were smaller and more frequent in certain mineral fertilized plots. In addition, there was a significant variation in the yield response to applied N across years, locations, and fertilization practices, likely due to the variability in N soil dynamics. This variability in N supply and availability is notably pronounced in organically fertilized fields, which exhibit greater heterogeneity. These findings

underscore the increased challenges associated with assessing N status in organically fertilized fields. They suggested that the ability of NDVI-based Response Index to predict the Response Index for a harvested crop is one of the principal weaknesses of the methods employed, particularly in fields employing organic fertilization. Moreover, it is important to recognize that the reliability of NDVI in assessing crop N requirements can be limited due to its sensitivity to factors unrelated to N that affect crop spectral response. Consistent field observations are essential to ensure the implementation of appropriate agronomic strategies.

3.3 Overcoming limitations in yield prediction under organic fertilization using NFOA and remote sensing techniques

Another crucial consideration for the prescription model involves obtaining precise estimates of in-season yield potential. The relationship between the predicted potential yield derived from NFOA and the actual yield was statistically significant, with an R^2 value of 0.74 (see Fig. 4). It is noteworthy that this value is consistent with those reported in previous studies conducted by Yao et al. (2012) and Yang et al. (2022) using mineral fertilization. It is essential to recognize that the accuracy of the model is contingent upon fitting a model that remains robust despite variations in growing conditions; otherwise, in-season yield potential predictions may lead to overestimations or underestimations. Certain predicted values deviated from the measured yield due to subsequent events occurring after the sensing date that had adverse effects on the actual yield. Despite the model's robust capability to estimate in-season yield potential, a saturation effect may occur in fields characterized by high canopy density (exceeding approximately 8 tons per hectare). This effect leads to deviations from the identity line, primarily due to the saturation phenomenon in NDVI at dense canopy densities (Yao et al. 2012; Garcia-Romero et al. 2023). This underscores the necessity of enhancing N status assessment through the evaluation of more reliable and sensitive spectral indices. It is important to acknowledge that, despite the advantageous large-scale data provided by Sentinel-2, satellite spectral information is subjected to problems related to atmospheric corrections, reflectance calibration, and view angle effects (Romero et al. 2020; Brinkhoff et al. 2021; Benami et al. 2021). Furthermore, additional factors such as image acquisition time, precise phenological stage assessment, and crop variety can introduce disturbances to spectral reflectance (Brinkhoff et al. 2021). Therefore, the remote sensing tools employed in the present study show certain limitations that should be considered, as they can lead to misleading estimates. Nevertheless, a prominent linear correlation is evident, emphasizing the appropriateness of our model in providing precise

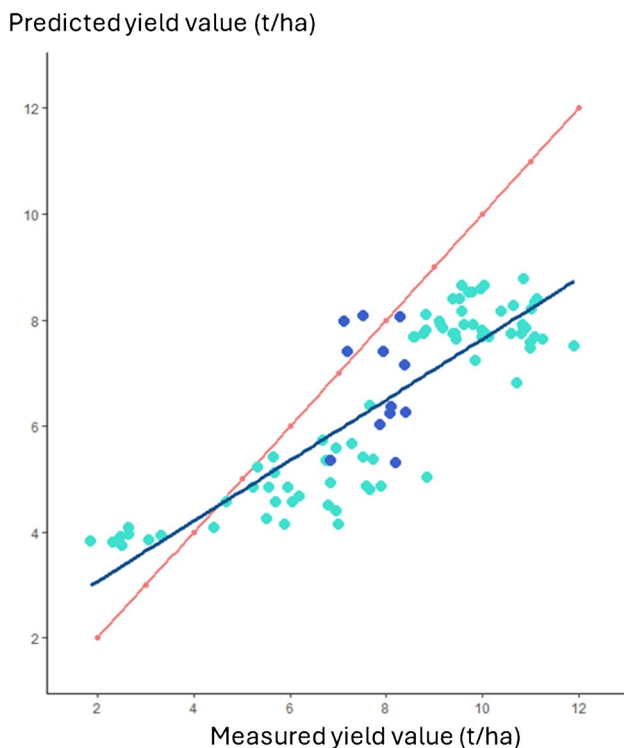


Fig. 4 Relationship between NFOA-predicted yield and measured yield for mineral and organic fertilized fields from 2017 to 2020 and 2023, including experimental plots (light blue) and commercial fields (dark blue) (Equation: $YP_0 = 1.925 + 0.5716 \cdot \text{Yield}$; $R^2 = 0.74$; $p < 0.0001$; $RMSE = 0.84$). The identity line ($y=x$) is depicted in orange.

N recommendations when an accurate in-season Response Index for a harvested crop estimation is available (Supplementary Figure 2). N management strategies incorporating a dependable mid-season predictor of Response Index for a harvested crop have the potential to substantially enhance NUE in cereal production (Johnson and Raun 2003; Raun et al. 2005). This holds true for both organically and minerally fertilized fields, even when accounting for distinct agronomic management practices and varying durations from sowing to sensing date.

3.4 Enhancing profitability and sustainability in rice farming: lessons from NFOA implementation in organic and mineral farming systems

According to the described NFOA method, the recommended fertilizer rate was calculated for each test plot in the NFOA algorithm's performance experiment using handheld NDVI data. The recommended prescription rates ranged between 17.9 and 22.8 kg N per hectare. We evaluated the performance of the variable-rate N application system using NFOA algorithm compared to uniform N

application rates. A summary of the observed NUE indices is presented in Table 3. Yields did not exhibit a significant increase beyond the total application of 110 kg N per hectare. The NFOA strategy achieved yields comparable to those observed under non-limiting N conditions. Statistically significant differences were observed among strategies in several NUE indices, including N agronomic efficiency, partial factor productivity, N balance intensity, partial N balance, crop N use efficiency, and N utilization efficiency. In general, the values of all N use efficiency indices exhibited a gradual decline with increasing doses of N fertilizer application. The NFOA strategy was positioned among the most efficient strategies (Table 3). The implementation of the developed prescription model under controlled experimental conditions entailed a reduction in fertilizer input while maintaining yield output. The maximum profitable fertilizer N rate was within the range of 110 to 140 kg N ha⁻¹ (Table 3). The incremental rise in N supply did not efficiently translate into increased yield output, suggesting that many strategies reached saturation situations, indicative of poor resource use efficiency. Despite observing a trend of lower yields in a lower dose of 110 kg N ha⁻¹, these differences did not reach statistical significance (Table 3).

High N doses (260 and 300 kg N ha⁻¹) resulted in poor resource use efficiency, producing the highest yields only under conditions where N was not limiting. Treatments 7 and 8, which involve fixed rates of 200 kg N ha⁻¹, are currently the predominant N application rates in the local area. The implementation of the NFOA approach with appropriate N application rates led to substantial N savings of up to 40% and a 28% increase in N agronomic efficiency compared to Treatments 7 and 8 (Table 3). This increase in N agronomic efficiency was directly proportional to the benefit-cost ratio from purchased N inputs (Cassman et al. 1998; Xue and Yang 2008). Furthermore, the NFOA approach achieved a 29% increase in the partial factor productivity, indicating higher yield per unit of applied fertilizer N compared to the fixed schedules of 200 kg N ha⁻¹ (Ali et al. 2015; Congreves et al. 2021). Partial N balance, crop N use efficiency, and N utilization efficiency exhibited increases of 28%, 26%, and 2%, respectively, in the NFOA approach compared to Treatments 7 and 8 (Table 3). Hence, there was a higher N content per unit of fertilizer N applied, a higher fraction of fertilizer N used and allocated in yield, and greater contribution of fertilizer N from the plant tissues towards the yield component was attained (Huang et al. 2018; Congreves et al. 2021). However, no discernible distinctions were noted in recovery efficiency, physiological efficiency, and internal efficiency among the various fertilization treatments (Table 3). These indices are more closely associated

Table 3 Yield and NUE indices in response to fixed and midseason-NFOA-based (bold and asterisk) nitrogen rates in 2023. Measurements are shown as means and *p*-values are provided at the bottom of the table. Means followed by different lowercase letters indicate significant differences at a significance level of *p* < 0.05 between treatments, as determined by Tukey's test (HSD)

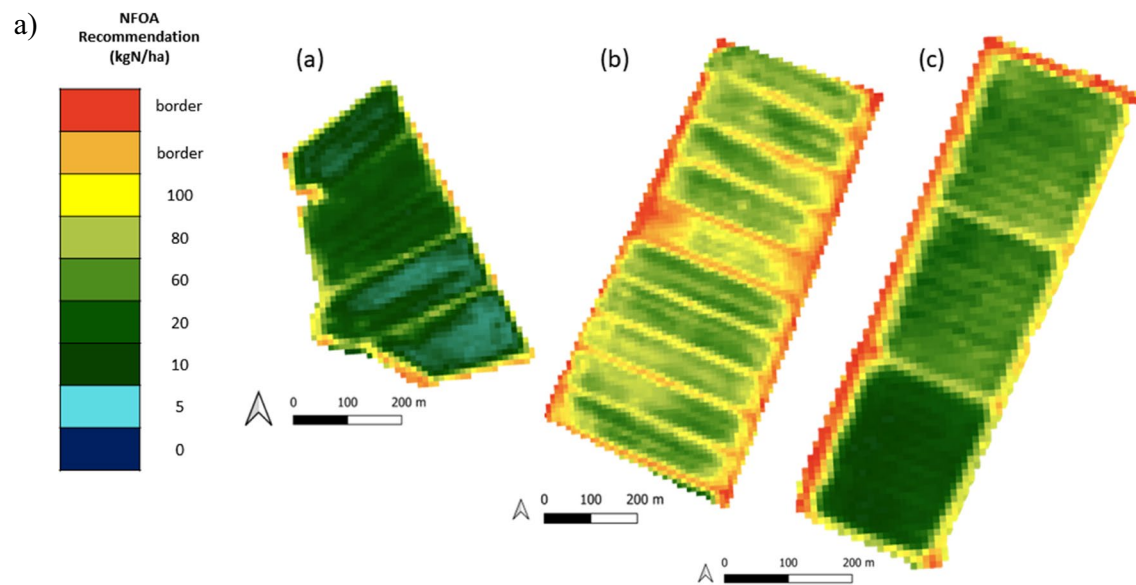
| Treatment | N total | Yield (Mgha ⁻¹) | AE | RE | PPP | NBI | PNB | NUE _{crop} | PE | NUtE | IE |
|-----------|-----------------|-----------------------------|--------------|--------------|--------------|----------------|---------------|---------------------|--------------|----------------|--------------|
| 1 | 0 | 7.8b | | | | | | | | | |
| 2 | 110 | 9.4a | 14.1 ab | 50.8a | 85.1a | -0.3a | 1.73a | 1.00a | 45.4a | 50.2abc | 0.58a |
| 3 | 140 | 9.3a | 10.5 b | 24.1a | 66.2bc | -39.3abc | 1.20bc | 0.72bc | 51.3a | 57.1a | 0.62a |
| 4 | 139.6* | 10.3a | 18.0a | 50.4a | 73.9b | -20.0ab | 1.51ab | 0.85ab | 33.5a | 49.1abc | 0.57a |
| 5 | 170 | 9.5a | 10.3ab | 54.1a | 56.2d | -65.7bc | 1.08cd | 0.61cde | 37.5a | 53.0ab | 0.57a |
| 6 | 170 | 10.2a | 14.1 ab | 28.6a | 60.0cd | -49.5abc | 1.21bc | 0.71bcd | 34.8a | 49.8abc | 0.59a |
| 7 | 200 | 10.4a | 13.0ab | 41.6a | 52.0de | -78.1abc | 1.09cd | 0.61cde | 33.3a | 48.0abc | 0.56a |
| 8 | 200 | 10.4a | 12.9ab | 39.6a | 51.9de | -69.2bc | 1.07cd | 0.65cde | 36.7a | 48.5abc | 0.61a |
| 9 | 230 | 10.3a | 10.7ab | 30.3a | 44.6ef | -103.6cd | 0.89cd | 0.55def | 35.3a | 50.5abc | 0.62a |
| 10 | 230 | 10.5a | 11.7ab | 45.4a | 45.6ef | -98.9bc | 1.04cd | 0.57cdef | 26.7a | 43.9abc | 0.55a |
| 11 | 260 | 10.1a | 8.9b | 50.4a | 38.9f | -130.5bc | 1.02cd | 0.50ef | 20.1a | 38.7c | 0.50a |
| 12 | 300 | 10.5a | 7.8b | 38.5a | 30.1g | -206.1d | 0.77d | 0.41f | 22.2a | 39.7bc | 0.54a |
| | <i>p</i> -value | <0.0001 | 0.023 | 0.192 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.17 | 0.003 | 0.2 |
| | <i>Std Dev</i> | 1.04 | 4.4 | 19.1 | 15.8 | 70.4 | 0.3 | 0.2 | 16.9 | 8.0 | 0.1 |

with genotype performance compared to the previously mentioned ones, which are more useful for assessing N management and optimal input rates. Therefore, the notable consistency and uniformity observed across the tested treatments can be attributed to the utilization of the same rice variety in all experimental conditions (Dobermann et al. 2007; Congreves et al. 2021).

In summary, these observations suggest that rice plants were unable to absorb or assimilate N at higher rates than those recommended by NFOA, leading to significant losses of N input from the soil-plant system when general fixed schedules were followed (Xue and Yang 2008; Congreves et al. 2021). This was supported by the higher N surplus for all strategies compared to NFOA-based strategy, as indicated by the N balance intensity index (Table 3). It reflects a more balanced N input-output equilibrium in fields, contributing to reduced environmental risk and enhanced income (Naser et al. 2020; Ren et al. 2022). The comprehensive assessment of NUE revealed that the treatment guided by NFOA exhibited higher resource use efficiency and a more profitable cost-benefit balance when compared to the fixed treatments. This approach prescribed the minimum necessary dose of N to apply, ensuring high yields based on an in-season accurate assessment of nutritional requirements. This placement positions the NFOA-based strategy as the most economical. These findings hold high reliability, as the experiment was conducted in the same year and location, mitigating variations in soil N supply and conditions to better capture the N use efficiency of the strategies.

The developed NFOA method was employed to generate spatial N recommendation maps for the commercial sites assessed in 2023 utilizing Sentinel-2 imagery data (examples shown in Fig. 5). The recommended fertilizer prescriptions recommended to apply N fertilizer within a range of 6 to 80 kg N ha⁻¹ for most sites (Fig. 5). Fields subjected to lower doses at earlier stages reached recommended rates of up to 100 kg N ha⁻¹. The total N applied ranged from 150 to 260 kg N ha⁻¹, while yields varied between 6.8 and 8.3 Mg grain ha⁻¹ at 14% humidity, depending on the location. It is important to acknowledge that, in this case, the mean recommendation rates did not drastically diverge from the uniform doses applied by farmers but were more site-specific and precise.

The assessment on real-farm approaches indicates that the uniform application within the same farm is not an optimal procedure. The observed non-uniform rates within the same farm, particularly in organic-fertilized fields, may be attributed to the uneven distribution of available N (Tubaña et al. 2008). The variability in N sources and dynamics influenced by site-specific



b)

| Site | Treatment | N dose criteria | Base N (kg ha ⁻¹) | Topdressing tillering stage (kg N ha ⁻¹) | Topdressing before PI (kg N ha ⁻¹) | Total N (kg ha ⁻¹) | Yield (kg ha ⁻¹) |
|------|-----------|-----------------|----------------------------------|--|--|-----------------------------------|---------------------------------|
| 1 | MIN | FM | 40 | 80 | 80 | 200 | 6845 |
| | | NFOA | | | 149 | 269 | |
| 2 | MIN | FM | 100 | | 90 | 190 | 7206 |
| | | NFOA | | | 62 | 162 | |
| 3 | MIN + DS | FM | | 86 | 120 | 206 | 8093 |
| | | NFOA | | | 107 | 193 | |
| 4 | MIN | FM | 50 | 84 | 67 | 201 | 8115 |
| | | NFOA | | | 52 | 186 | |
| 5 | MIN | FM | 120 | | 80 | 200 | 8208 |
| | | NFOA | | | 77 | 197 | |
| 6 | MIN | FM | 120 | | 80 | 200 | 7866 |
| | | NFOA | | | 45 | 165 | |
| 7 | MIN | FM | 81 | 63 | 18 | 162 | 8304 |
| | | NFOA | | | 36 | 180 | |
| 8 | CM+ MIN | FM | 184 _{CM} | | 91 | 275 | 7134 |
| | | NFOA | | | 52 | 236 | |
| 9 | CM+ MIN | FM | 116 _{CM} | 24 | 23 | 163 | 8390 |
| | | NFOA | | | 61 | 201 | |
| 10 | PS+MIN | FM | 40 _{PS} | 94 | 50 | 184 | 7934 |
| | | NFOA | | | 14 | 148 | |
| 11 | PS+MIN | FM | 90 _{PS} | 99 | 53 | 242 | 7517 |
| | | NFOA | | | 10 | 199 | |
| 12 | PS+MIN | FM | 120 _{PS} | 66 | 66 | 252 | 8400 |
| | | NFOA | | | 45 | 231 | |

Fig. 5 a Prescription maps derived from the NFOA model and Sentinel-2 imagery for (a) commercial plot fertilized with pig slurry and supplemented with mineral fertilizer (site 11), (b) commercial plot fertilized with chicken manure and supplemented with mineral fertilizer (site 9), and (c) commercial plot exclusively fertilized with min-

eral fertilizer (site 7) in 2023; **b** Nitrogen rates and yields for commercial sites in 2023, comparing fixed and midseason-NFOA-based (bold) approaches (PI: panicle initiation; PS: pig slurry; CM: chicken manure; FM: farmers N management with fixed N rates; DS: dry-direct seeding).

characteristics illustrated by the nutritional status maps, underscores the need for targeted fertilization strategies. Moreover, year-to-year variability highlights distinct field requirements across growing seasons, necessitating more precise approaches accounting the actual dynamics of N nutrition during the growing season. This study underscores the capability of the NFOA approach to provide recommendation rates while considering spatial and temporal variations in crop growth. However, it remarks the limitations of the current methods that must be addressed to facilitate the adoption of these strategies within the commercial rice sector. Sentinel-2 data has demonstrated promising capabilities to scale up methodologies, offering valuable support for farmers providing accessible, time-saving, and cost-effective tools for monitoring crop status and nutritional requirements. Despite the necessity for refining the prescription model to mitigate inconsistent results arising from inaccurate estimates of the response index and yield predictions, attributable to variations in soil inorganic N supply and NDVI saturation, this study underscores the advantages of applying N fertilizer on a need-basis over uniform fixed rate application. Following a uniform fertilizer application approach may result in instances of both over and under-application, with a tendency toward over-application (Cui et al. 2018). This not only fails to enhance crop yield and profitability but also exacerbates environmental pollution (Mekonnen and Hoekstra 2011; Eckardt et al. 2023). The NFOA methodology offers an improvement in fertilizer prescriptions, ensuring that N topdressing is dynamically adjusted based on the real-time growth status of the crop.

3.5 Remarks for advancing NFOA methods: future perspectives for enhanced prediction of crop response to organic nitrogen application

The findings presented in this study suggest that the NFOA approach is suitable for calculating N fertilizer application rates in both mineral and organic fertilized fields. The NFOA method can be adapted for calculating the amount of fertilizer to apply, though it might require some modifications and considerations specific to organic fertilizers. When working with organic fertilizers, the key is to understand their nutrient content, especially N, and how this translates into the needs of the rice crop (Wei et al. 2016). Organic fertilizers not only contribute N but also improve soil health by enhancing nutrient holding capacity, water retention, and soil structure (Wei et al. 2016). However, the application rates can vary significantly based on the type of organic material, its nutrient content, and the specific crop requirements. Tools like the organic fertilizer and cover crop calculators provided by institutions such as Oregon State University's College of Agricultural Sciences

offer a way to estimate the N supplied by cover crops and organic fertilizers. These calculators can help develop balanced and cost-effective nutrient management programs by comparing the nutrient value and cost of different organic and synthetic fertilizers and composts. Despite ongoing efforts, the development of accessible tools that utilize satellite data across extensive regions for numerous farmers could markedly improve rice production efficiency and lessen environmental impacts by reducing N losses on a broader scale. The developed tool presented herein may support the creation of timely and accurate variable rate N prescription maps, enabling the assessment of in-field variability through a user-friendly tool for farmers, eliminating the need for extensive and destructive field sampling, and delivering prompt results. Additionally, the complementary use of handheld tools for assessing crop nitrogen status can be advantageous for monitoring nitrogen levels and anticipate N deficiencies (Ravier et al. 2018; Paut et al. 2024). This approach is particularly useful when climatic conditions, such as high and persistent cloudiness, impede the acquisition of remote sensing data or interfere with readings. Managing manure involves understanding the nutrient content, particularly total N, to determine suitable application rates for crops. Factors such as N forms (organic vs. ammonium), availability to crops, and N loss based on the manure's carbon-to-N ratio must be considered. While the NFOA method offers guidance, adjustments are necessary for organic materials' unique traits. Utilizing tools for organic fertilizer calculation can support efficient and sustainable fertilization practices (Verma et al. 2020). Overall, while the NFOA methods developed in this study exhibited satisfactory performance, further enhancement is necessary. This improvement involves addressing the integration of a more reliable spectral index or estimation parameter that can more effectively capture the response of crop to applied N, thus increasing the predictive accuracy. The incorporation of more detailed information about weather conditions, soil characteristics, and N dynamics for each fertilization source and soil type should be considered in the model. Thus, additional research is warranted to assess different rice varieties, locations, management practices, years, and environmental conditions. This comprehensive approach will contribute to the refinement of the algorithm parameters established in this study and enhance the validation of the methods on a commercial-field scale.

4 Conclusions

Our study demonstrates the effectiveness of the novel NFOA-based methodology for guiding variable-N rate applications in rice based on canopy reflectance readings. This approach

successfully addresses the gaps in precision fertilization, particularly in fields utilizing a combination of organic and mineral fertilizers. The model provides precise, data-driven fertilizer application plans tailored for real-farm conditions, demonstrating its practical applicability across diverse farming scenarios. Our results show that the NFOA decision-making tool optimizes nitrogen management in commercial rice fields, regardless of fertilizer type, contributing to improved net income and enhanced sustainability. This methodology proves to be a valuable tool for farmers, helping optimize their fertilization practices. To successfully accomplish the transition to precise nutrient management in sustainable rice crops, it is imperative to conduct further testing and refinement of the algorithm and the remote sensing tools. Future research should encompass diverse varieties, environmental conditions, locations, and seasons to ensure its adaptability and reliability across a wide spectrum of scenarios.

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Authors' contributions Conceptualization: M.J.K., S.L.M., and C.F.M.; methodology: M.J.K. and S.L.M.; software: M.J.K.; formal analysis: M.J.K. and T.N.; investigation: M.J.K. and T.N.; data curation: M.J.K. and T.N.; resources: T.N., M.G., O.C., and C.F.M.; writing—original draft: M.J.K.; funding acquisition: M.G., O.C., S.L.M., and C.F.M.; validation: S.L.M. and C.F.M.; writing—review and editing: S.L.M.; visualization: C.F.M.; supervision: S.L.M. and C.F.M.; project administration: S.L.M. and C.F.M.

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Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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