Title: Chlorophyll Meter–based Nitrogen Fertilizer Optimization Algorithm and Nitrogen Nutrition Index for In-season Fertilization of Paddy Rice

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Abbreviations: NNI, Nitrogen Nutrition Index; LNC, Leaf Nitrogen concentration; SSNM, Site Specific Nutrient Management; NUE, Nitrogen Use Efficiency, NFOA, Nitrogen fertilization optimization algorithm; NTE, Nitrogen transportation efficiency; PFP, Partial factor productivity; AE, Agronomy efficiency; HI, Harvest index.

ABSTRACT

Nitrogen fertilizer optimization algorithm (NFOA) and nitrogen nutrition index (NNI) have been developed to achieve higher yield and N use efficiency. This study was to improve NFOA and NNI strategies for managing rice N nutrition based on portable Soil and Plant Analyzer Development (SPAD) meter. Four field experiments were conducted in 2013-2014 to generate diverse N fertilizer rates in rice cultivars at three eco-sites. SPAD readings and N indicators were measured to establish SPAD-based management strategies. Two experiments were conducted to assess the effectiveness of developed NFOA and NNI algorithm for upward and downward adjustment of N fertilizer doses twice within the growing season in 2015. Newly N adjustment strategies optimized N topdressing by upward-, fine-, and downward- adjustment with an average N application rate of 264-272 kg·N·ha⁻¹ in Eastern China. Maximum grain yield (10.5 t·ha⁻¹) was obtained when 264 kg·N·ha⁻¹ was applied. The recovery efficiency of N fertilizer was higher for NFOA and NNI (51-57 %) than fixed-time application of 270 kg·N·ha⁻¹ (48 %). And the comparable high net profit (>$1080·ha⁻¹) was achieved with lower N adjustment fertilizer input in 270 and 360 kg·N·ha⁻¹.
treatments. SPAD-based NFOA and NNI methods are practical approaches for reducing excessive use of N fertilizer, and achieving slight increase in yield and net profit was decreased (360 kg·N·ha⁻¹). More refinements are required to ensure that these strategies can be used for yield- and income-enhancing production for farmers.

INTRODUCTION

Rice (Oryza sativa L.) is a major source of calories for more than half of the world’s population (Erisman, Sutton, et al., 2008). Nitrogen (N) is one of the most significant yield-limiting factors in rice production (Ata-Ul-Karim, Liu, et al., 2017). An appropriate N management strategy is imperative to optimize the application of N fertilizer and maximize grain yield. Generally, two steps are needed to establish the appropriate plant-based N management strategy: the in-season determination of plant N nutrition status, and the subsequent application of N fertilizer (Yuan et al., 2016). Despite many investigations into the diagnosis of in-season crop N status, only four N regulation methods have been extensively reported: site-specific nutrient management (SSNM) (Peng, Garcia, et al., 1996), the N fertilization optimization algorithm (NFOA) (Lukina, Freeman, et al., 2001), the N nutrition index (NNI) method (Ata-Ul-Karim, Liu, et al., 2017), and the leaf area index (LAI) (Wood, Welsh, et al., 2003) etc. These methods are generally associated with a special indicator or apparatus. For example, SSNM provides an option to use the leaf chlorophyll meter (Minolta Camera Co., Osaka, Japan) or a leaf color chart, and NFOA employs a canopy spectral meter,
while NNI and LAI use agronomic indicators (NNI and LAI) as the input parameters, respectively, even though these are more time-consuming.

Chlorophyll meters have been widely used as rapid, non-destructive, convenient, and reliable diagnostic tools by farmers and agronomic consultants to help determine appropriate levels of N fertilizer in crop production (Ata-Ul-Karim, Cao, et al., 2016, Peng, Buresh, et al., 2010). SSNM also employs a chlorophyll meter to monitor leaf N status for regulating N dressing rates (Peng, Buresh, et al., 2010, Peng, Garcia, et al., 1996). Previous studies on SSNM showed a 5 % increase in rice grain yield and N use efficiency (NUE) compared to traditional fertilization methods, with a 32 % decrease in N fertilizer application. However, cultivars, eco-site, environment, growing season, and crop growth stage can significantly influence Soil and Plant Analyzer Development (SPAD) readings (Yuan et al., 2016). Consequently, SSNM strategies needed to be modified with the aforementioned factors in mind (Peng, Buresh, et al., 2006).

Several attempts have been made to eliminate the influence of factors that affect SPAD readings by normalizing the SPAD reading (Liu, Ferguson, et al., 2017), which can overcome the negative influences of cultivars, locations, years, and growing stages (Wang et al., 2006). However, N regulation strategies based on normalized SPAD values have been rarely reported. A previous study on rice indicated that a normalized SPAD value of the fourth uppermost fully expanded leaf from the top (NSI4) is a reliable indicator for N diagnosis from the stem elongation (SE) to the
booting (BT) stages (Yuan, Ata-Ul-Karim, et al., 2016). Moreover, NSI4 showed a strong relationship with shoot N accumulation (NA) and NNI. Accurate estimations of NA and final grain yield are the key variables for applying spectral indices in the NFOA (Yuan, Ata-Ul-Karim, et al., 2016). This implies that SPAD-value-based NFOA management strategy can also be set up to facilitate the appropriate N management in crop production. Despite being a reliable N indicator for diagnosing the crop N nutrition status, NNI-based N regulation has been rarely reported (Ata-Ul-Karim, Liu, et al., 2017, Lemaire and Meynard, 1997). Real-time estimation of NNI in the field is the main constraint for widespread application of an NNI-based N fertilizer regulation strategy. The robust and stable relationship between normalized SPAD and NNI in a previous study on rice shows the opportunity for to apply the NNI-based N fertilizer regulation strategy in crop production (Ata-Ul-Karim, Zhu, et al., 2017).

Therefore, studies on N regulation are now required. The objectives of this research were to develop the SPAD-values-based NFOA and NNI regulation strategies, as well as to validate the performance of the newly established strategies in rice under different N conditions (including deficient, sufficient, and excessive N). The results provide practical guidance to rice growers for precision N fertilizer management.
MATERIALS AND METHODS

2.1 Experimental design

Six field experiments involving multiple N rates and varieties were conducted in Jiangsu province in Eastern China from 2013 to 2015 (Table 1). N application rates (0-375 kg·N·ha\(^{-1}\)) with three Japonica rice varieties [Wuyunjing-19 (WYJ-19), Yongyou-8 (YY-8), Wuyunjing-24 (WYJ-24)] and one Indica variety [Yliangyou-1 (YLY-1)] were used to generate various N availability and growth indices from 2013 to 2014. N regulation experiments were conducted in 2015 using two Japonica rice varieties, WYJ-19 and Wuyunjing-30 (WYJ-30). Three N nutrition conditions (deficient, sufficient, and excessive N nutrition) were created. In all six experiments, similar N application rates and N application strategies were achieved. SPAD-based N regulation was employed at the panicle initiation (PI) and booting (BT) stages, where pre-transplanting N applications treatments were denoted N1 (180 kg·N·ha\(^{-1}\)), N2 (270 kg·N·ha\(^{-1}\)), and N3 (360 kg·N·ha\(^{-1}\)).
Table 1. Basic information about six rice field experiments used in the study.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Transplanting date</th>
<th>Location</th>
<th>Cultivar</th>
<th>Treatment</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>25-June 2013</td>
<td>Wujiang</td>
<td>Wuyungjing-19</td>
<td>N rates (0, 90, 180, 270, 360 kg·N·ha⁻¹)</td>
<td>Loam soil</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>16-June 2013</td>
<td>Zhangjiagang</td>
<td>Wuyunjing-19</td>
<td>N rates (0, 90, 180, 270, 360 kg·N·ha⁻¹)</td>
<td>Clay soil</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>15-June 2014</td>
<td>Rugao</td>
<td>Wuyunjing-24</td>
<td>N rates (0, 150, 225, 300, 375 kg·N·ha⁻¹)</td>
<td>Loam soil</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>20-June 2014</td>
<td>Zhangjiagang</td>
<td>Wuyunjing-19</td>
<td>N rates (0, 90, 180, 270, 360 kg·N·ha⁻¹)</td>
<td>Loam soil</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>20-June 2015</td>
<td>Wujiang</td>
<td>Wuyunjing-30</td>
<td>N regulation treatments†</td>
<td>Loam soil</td>
</tr>
<tr>
<td>Experiment 6</td>
<td>25-June 2015</td>
<td>Zhangjiagang</td>
<td>Wuyunjing-19</td>
<td>N regulation treatments†</td>
<td>Loam soil</td>
</tr>
</tbody>
</table>

† N regulation treatments includes 10 types: zero nitrogen (N) treatment or the check treatment (N0); N deficiency treatment (N1), sufficient N treatment (N2), excessive N treatment or the farmer method (N3). N1M1: NFOA regulation for N1, N2M1: NFOA regulation for N2, N3M1: NFOA regulation for N3; N1M2: NNI method for N1, N2M2: NNI method for N2; N3M2: NNI method for N3. More detailed information are showed in Table 2.

A randomized complete design with three replicates was used in all experiments. Hill spacing of 0.25 m×0.15 m with three seedlings per hill was used. The area of each plot was 5 m×6 m. N fertilizer (urea) was applied in three split forms: pre-transplanting (basal, 30 %), tillering (TI, 20 %), and spikelet (50 %) fertilizers. Phosphorus and potassium fertilizers were added to the soil before transplanting, as monasticism phosphate Ca(H₂PO₄)₂ and potassium chloride (K₂O, K) at the rate of 135 kg·ha⁻¹ (P₂O₅, P) and 170 kg·ha⁻¹ (K₂O).
2.2 Plant measurements

Five hills from each plot were sampled during 2013-2014. Rice plants were manually uprooted and cut at ground level to determine shoot biomass and N concentration. Fresh plants were segregated into green leaf blade (leaf) and culm plus sheath (stem). The samples were heated at 105 °C for 30 min to stop metabolism and then oven-dried at 80 °C until they reached a constant weight. Plant dry matter (PDM) was measured. The dried samples were milled to pass a 1 mm sieve and stored in plastic bags at room temperature before chemical analyses. N concentration was identified using a continuous-flow Auto-Analyzer (BRAN + LUEBBE AA3; Norderstedt, Germany). Grain yield was determined from an area of 2 m² in each plot and adjusted to the standard moisture content of 14 %.

The chlorophyll meter is a spectral instrument, as it measures the difference between the transmittance of a red (650 nm) and an infrared (940 nm) light through the leaf, generating a 3-digit SPAD value (Uddling, Gelangalfredsson, et al., 2007), which was used to take SPAD readings from the four uppermost fully expanded leaves of 10 randomly selected plants from each plot. Three SPAD values per leaf, including one value around the midpoint of the leaf blade and two values 3 cm apart from the midpoint were averaged to give the mean SPAD value of the leaf. SPAD measurements were taken at the tillering (TI), stem elongation (SE), panicle initiation (PI), booting (BT), and heading (HD) stages during 2013-2014, while in 2015 SPAD values were measured at critical growth stages (the PI and BT stages) according to the findings of Yuan et al. (2016).
The SPAD value of the excessive N (N3, 360 kg·N·ha$^{-1}$) was used to determine the normalized SPAD index (NSI, NSII = $L_i / L_{ie}$, where $L_i$ is the SPAD value of the $i^{th}$ fully expanded leaf from top, and $L_{ie}$ is the SPAD value of the $i^{th}$ fully expanded leaf from top measured in the N excessive plot) (Yuan et al., 2016) of each fertilizer rate [$N1M1$, $N2M1$, $N3M1$ (M1, NFOA method); $N1M2$, $N2M2$, $N3M2$ (M2, NNI method)]. The NSI was measured as the input parameters of SPAD-based NFOA and NNI methods, and the results were further used to guide the N top-dressing to the corresponding plot.

Fig. 1. Exponential regressions fitted between NSI4 and N accumulation (a) and between NSI4 and grain yield in rice under varied N rates from SE to BT stages (b) using data from experiments 1 to 3. The dashed line is “95% prediction band”. Adapted from Yuan, et al. 2016. Field Crops Research 185, 12-20.

2.3 Overview of site-specific N topdressing recommendation approaches

2.3.1 SPAD-values-based NFOA method

Our previous study of in-season N management in rice showed NSI4 (Eq. 1) can be used to assess plant N nutrition status during the PI and BT growth stages (Figure
Eq. 2). Eq. 3 was used to predict the final grain yield (Figure 1b, Eq. 3). The predicted grain N uptake (GNU, kg·ha⁻¹, Eq. 4) was calculated based on the N uptake per 100 kg grains. According to the rice cultivation practices, N uptake per 100 kg grain for Japonica rice cultivars with 16-18 leaves in Jiangsu Province of China is 1.9 kg in the yield level of 9 t·ha⁻¹ (Ling, Zhang, et al., 2005). Finally, the N fertilizer requirement (Nr, kg·N·ha⁻¹) is given in Eq. 5. Through Eq. 2-5, a SPAD-values-based NFOA regulation method was established.

\[
\text{NSI}_4 = \frac{L_4}{L_4} \quad (1)
\]

\[
\text{NA} = 0.0279 \times e^{8.6957} \times \text{NSI}_4 \quad (2)
\]

\[
\text{PGY} = 1.137 \times e^{2.1153} \times \text{NSI}_4 \quad (3)
\]

\[
\text{GNU} = \frac{1.9 \times \text{PGY}}{100} \quad (4)
\]

\[
\text{Nr} = \frac{(\text{GNU} - \text{NA})}{\text{NUE}} \quad (5)
\]

where NSI₄ is the normalized SPAD value of the fourth uppermost fully expanded leaf from the top, L₄ is the SPAD value of the fourth fully expanded leaf from top, and L₄ₑ is the L₄ value measured in the N excessive plot (N₃, 360 kg·N·ha⁻¹); NA is nitrogen accumulation; PGY is the potential grain yield; and NUE was set to 0.7 (Chen, Tian, et al., 2014).

### 2.3.2 SPAD-values-based NNI method

The NNI can be also estimated by the NSI₄ from the SE to BT stages in rice (Yuan et al., 2016) (Figure 2, Eq. 6), while the N deficit or excess (accumulated N deficit, ΔAND) was calculated based on the relationship between ΔAND and NNI.
The N fertilizer requirement \( (N_r, \text{kg} \cdot \text{N} \cdot \text{ha}^{-1}) \), Eq. 8) was determined by Eq. 8. Through Eq. 6-8, a SPAD-values-based NNI regulation method could be established.

\[
\text{NNI} = 0.0163e^{4.13 \times NSI4} \tag{6}
\]

\[
\Delta \text{AND} = 229.06 \times \text{NNI} - 272.43 \tag{7}
\]

\[
N_r = \frac{\Delta \text{AND}}{\text{NUE}} \tag{8}
\]

Where NUE was also set to 0.7 (Chen, Tian, et al., 2014).

Fig. 2. Exponential regressions fitted between NSI4 and NNI (a), and between NNI and accumulation N deficit (AND) from SE to BT stages (b) using data from experiments 1 to 3. The dashed line is “95% prediction band”. Adapted from Yuan, et al. 2016. Field Crops Research 185, 12-20.

2.4 Data analysis

Data collected from experiments 1 to 4 (2013-2014) were used to construct Eq. 1 to 8, while data from experiments 5 and 6 (2015) were used to validate the newly established SPAD-based NFOA (Eq. 2 to 5) and NNI (Eq. 6 to 8) regulation methods.
Data-fitting processes were performed using Origin 8.0 (Origin 8.0, Origin Lab, Northampton, USA) by choosing different equations based on convergence. Linear, quadratic, logarithmic, exponential, and rational models were evaluated and the model with the highest coefficient of determination value ($R^2$) was used. Analysis of variance and multiple comparisons were carried out to evaluate the performance of different N dressing rates on grain yield using SPSS.13 software packages (SPSS Inc., Chicago, USA). Six indices of N utilization efficiency was calculated, including NUE (Eq. 9) (Raun and Johnson, 1999), agronomic efficiency (AE, Eq. 10), partial factor productivity (PFP, Eq. 11), grain production efficiency (GPE, Eq. 12), N transportation efficiency (NTE, Eq. 13), grain harvest index (HI, Eq. 14), recovery efficiency (RE, Eq. 15), and physiological efficiency (PE, Eq. 16). A modified benefit-fertilizer cost ratio was used to assess the profit of the paddy rice (Eq. 17). The major economic benefit in field production was the income derived from grain yield, while the many production costs included fertilizers (N, P, and K), seed, transplanting, pesticides, ploughing, and management expenditures. The net profit (Eq. 19) was calculated by subtracting production costs from the income gained when rice grain yield was sold (Eq. 18). All other costs, except that of N fertilizer, were same for different N treatments in this study.

\[
\text{NUE} = \frac{\text{HTNH}}{(\text{N fertilizer rates} - \text{N}_{\text{soil}})} \quad (9)
\]

\[
\text{AE} = \frac{(\text{GY} - \text{GY0})}{\text{NRt}} \quad (10)
\]

\[
\text{PFP} = \frac{\text{GY}}{\text{NRt}} \quad (11)
\]
\[
\text{NTE} = \frac{(\text{HTNH} - \text{HTNM})}{\text{HTNH}} \tag{12}
\]

\[
\text{GPE} = \frac{\text{GY}}{\text{NA}} \tag{13}
\]

\[
\text{HI} = \frac{\text{GY}}{\text{PT}} \tag{14}
\]

\[
\text{RE} = \frac{(\text{PTN} - \text{PTN0})}{\text{NRt}} \tag{15}
\]

\[
\text{PE} = \frac{(\text{GY} - \text{GY0})}{(\text{PTN} - \text{PTN0})} \tag{16}
\]

Benefit-fertilizer cost ratio = net profile / cost of N fertilizer. \tag{17}

Return from grain = grain yield \times grain price \tag{18}

Net profit = return from grain – cost of nitrogen fertilizer – additional labor cost – other cost \tag{19}

where \( \text{N}_{\text{soil}} \) is the N supply of soil (plant N accumulation in N0 plot), \( \text{GY} \) is the grain yield, \( \text{GY0} \) is the grain yield in N0 plot, \( \text{NRt} \) is the total N fertilizer rates, \( \text{HTNH} \) is the shoot N accumulation (kg·N·ha\(^{-1}\)) at full HD stage, \( \text{HTNM} \) is the shoot N accumulation (kg·N·ha\(^{-1}\)) at maturity, \( \text{PT} \) is the shoot dry matter at maturity.

Moreover, the price was $309·t\(^{-1}\), other cost includes K and P fertilizers ($180 and $105·ha\(^{-1}\), respectively), seeding ($186·ha\(^{-1}\)), pesticides ($185·ha\(^{-1}\)), ploughing ($130·ha\(^{-1}\)), and management expenditures ($986·ha\(^{-1}\) ).
Table 2. Nitrogen fertilizer management treatments for the ten treatments in experiment 5 and 6 conducted in 2015 (N fertilizer rate, kg·N·ha⁻¹)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Basal fertilizer</th>
<th>Tillering fertilizer</th>
<th>Spikelet-promoting in PI stage</th>
<th>Spikelet-protecting in BT stage</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>N0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N1</td>
<td>54</td>
<td>36</td>
<td>54 (±2.6)</td>
<td>36 (±1.7)</td>
<td>180</td>
</tr>
<tr>
<td>N1M1</td>
<td>54</td>
<td>36</td>
<td>116 (±2.6)</td>
<td>58 (±1.7)</td>
<td>264 (±1.5)</td>
</tr>
<tr>
<td>N1M2</td>
<td>54</td>
<td>36</td>
<td>113 (±2.2)</td>
<td>57 (±1.5)</td>
<td>260 (±1.3)</td>
</tr>
<tr>
<td>N2</td>
<td>81</td>
<td>54</td>
<td>81</td>
<td>54</td>
<td>270</td>
</tr>
<tr>
<td>N2M1</td>
<td>81</td>
<td>54</td>
<td>88 (±1.8)</td>
<td>55 (±2.0)</td>
<td>278 (±0.9)</td>
</tr>
<tr>
<td>N2M2</td>
<td>81</td>
<td>54</td>
<td>85 (±1.4)</td>
<td>51 (±3.1)</td>
<td>271 (±0.7)</td>
</tr>
<tr>
<td>N3</td>
<td>108</td>
<td>72</td>
<td>108</td>
<td>72</td>
<td>360</td>
</tr>
<tr>
<td>N3M1</td>
<td>108</td>
<td>72</td>
<td>67 (±4.6)</td>
<td>73 (±4.1)</td>
<td>320 (±2.1)</td>
</tr>
<tr>
<td>N3M2</td>
<td>108</td>
<td>72</td>
<td>55 (±3.8)</td>
<td>71 (±4.4)</td>
<td>306 (±2.0)</td>
</tr>
</tbody>
</table>

Note: Values in the brackets are coefficient of variation (CV, %).
N0: zero N treatment or the check treatment; N1: N deficiency treatment, N2: sufficient N treatment, N3: excessive N treatment or the farmer method; N1M1: NFOA regulation for N1, N2M1: NFOA regulation for N2, N3M1: NFOA regulation for N3; N1M2: NNI method for N1, N2M2: NNI method for N2; N3M2: NNI method for N3.
‘PI’ means panicle initiation stage, ‘BT’ indicates booting stage.

RESULTS

3.1 Nitrogen application rates under different N conditions

Fixed-time management included N0, N1, N2 and N3, while the SPAD-values-based NFOA and NNI regulation methods involved N1, N2, and N3. For all treatments, half of the N fertilizer was applied as basal (30 %) and tillering fertilizers (20 %) (Table 2). N topdressing in the fixed-time management was applied as
spikelet-promoting and spikelet-protecting fertilizers at the PI and BT growth stages (30 and 20 %), respectively. Similarly, N regulation was also always performed at the PI and BT stages.

The NSI4 in the N adjustment plots were identified at the PI and BT stages for N topdressing in the regulation treatments. NSI4 served as the input in the SPAD-values-based NFOA (Eq. 2 to 5), and NNI (Eq. 6 to 8) models. N application rates used in the regulation experiment during 2015 were shown in Table 2. Under slightly deficient N conditions (N1 treatment), the higher topdressing rate of N fertilizer was applied in SPAD-values-based NFOA (116 + 58 kg·N·ha⁻¹) and NNI (113 + 57 kg·N·ha⁻¹) methods as compared to fixed-time management (54 + 36 kg·N·ha⁻¹). Both regulation methods mainly affected the spikelet promoting fertilizer. Two regulation methods only adjusted the N topdressing slightly under the sufficient N condition treatment (N2), and no significant difference occurred between fixed-time management (81 + 54 kg·N·ha⁻¹) and the SPAD-values-based NFOA (88 + 55 kg·N·ha⁻¹) and NNI (85 + 51 kg·N·ha⁻¹) methods. As far as the excessive N treatment (N3) is concerned, both NFOA (total N 320 vs. 360 kg·N·ha⁻¹) and NNI (306 vs. 360 kg·N·ha⁻¹) methods suggested a reduction of the N application rate (a downward adjustment of the corresponding N topdressing). Additionally, newly developed methods resulted in a reduction (67 and 55 vs. 108 kg·N·ha⁻¹) on spikelet promoting fertilizer, while a fine-adjustment (73 and 71 vs. 72 kg·N·ha⁻¹) occurred for spikelet-protecting period (Table 2).
Grain yield in fixed-time and SPAD-values-based regulation management are provided in Table 3. In spite of a relatively low yield level under the N0 (6.1 t·ha\(^{-1}\)) and N1 (8.1 t·ha\(^{-1}\)) treatments, relatively high grain production (> 10 t·ha\(^{-1}\)) was achieved under other treatments. Meanwhile, the newly established SPAD-values-based NFOA and NNI methods were needed to be able to perform upward-, fine-, and downward-regulation of N under slightly deficient, sufficient, and excessive N conditions (Table 2).

Table 3. Yield, Partial factor productivity (PFP), Recovery efficiency (RE), Nitrogen use efficiency (NUE), Physiological efficiency (PE), Agronomy efficiency (AE) and Harvest index (HI) under different N treatments.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Yield, t · ha(^{-1})</th>
<th>PFP, kg · kg(^{-1})</th>
<th>RE, %</th>
<th>NUE, %</th>
<th>PE, kg · kg(^{-1})</th>
<th>AE, kg · kg(^{-1})</th>
<th>HI, kg · kg(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>N0</td>
<td>6.1c</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.56a</td>
</tr>
<tr>
<td>N1</td>
<td>8.1b</td>
<td>45.0a</td>
<td>54.9c</td>
<td>0.41a</td>
<td>0.20d</td>
<td>11.2c</td>
<td>0.41ab</td>
</tr>
<tr>
<td>N1M1</td>
<td>10.4a</td>
<td>39.7b</td>
<td>56.6a</td>
<td>0.42ab</td>
<td>0.29ab</td>
<td>16.6a</td>
<td>0.41ab</td>
</tr>
<tr>
<td>N1M2</td>
<td>9.8a</td>
<td>38.4b</td>
<td>55.4b</td>
<td>0.41ab</td>
<td>0.27c</td>
<td>14.9ab</td>
<td>0.53b</td>
</tr>
<tr>
<td>N2</td>
<td>10.5a</td>
<td>37.7b</td>
<td>48.3f</td>
<td>0.38b</td>
<td>0.32a</td>
<td>15.3ab</td>
<td>0.55a</td>
</tr>
<tr>
<td>N2M1</td>
<td>10.1a</td>
<td>37.1b</td>
<td>51.3d</td>
<td>0.41ab</td>
<td>0.31a</td>
<td>16.1a</td>
<td>0.53b</td>
</tr>
<tr>
<td>N2M2</td>
<td>10.4a</td>
<td>38.2b</td>
<td>50.6e</td>
<td>0.40ab</td>
<td>0.30ab</td>
<td>15.3ab</td>
<td>0.41ab</td>
</tr>
<tr>
<td>N3</td>
<td>10.4a</td>
<td>28.2d</td>
<td>36.7h</td>
<td>0.30c</td>
<td>0.31a</td>
<td>11.2c</td>
<td>0.41ab</td>
</tr>
<tr>
<td>N3M1</td>
<td>10.2a</td>
<td>32.0c</td>
<td>43.5g</td>
<td>0.37b</td>
<td>0.30ab</td>
<td>12.9b</td>
<td>0.53b</td>
</tr>
<tr>
<td>N3M2</td>
<td>10.2a</td>
<td>33.4c</td>
<td>43.8g</td>
<td>0.36b</td>
<td>0.31a</td>
<td>13.4b</td>
<td>0.53b</td>
</tr>
<tr>
<td>SD</td>
<td>1.35</td>
<td>4.59</td>
<td>6.24</td>
<td>0.13</td>
<td>0.03</td>
<td>1.90</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Note: Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by Duncan's multiple comparison tests.

N0: zero N treatment or the check treatment; N1: N deficiency treatment, N2: sufficient N treatment, N3: excessive N treatment or the farmer method to ‘M1’: in-season N management using N fertilizer optimization algorithm (NFOA).

3.2 SPAD values of different N management strategies

SPAD values of the fourth fully expanded leaf (L4) from the top were greatly influenced by different N fertilizer rates (Figure 3A). The L4 value of N1 was 4.0 \( \frac{100 \text{ kg·N·ha}^{-1}}{} \) higher than that of N0 plot, and the L4 value of N3 was 2.4 \( \frac{100 \text{ kg·N·ha}^{-1}}{} \) higher than that of the sufficient N rate (N2). These results show the value of L4 was responsive to N application.

Fig. 3. SPAD readings of the fourth fully expanded leaf from top before the N regulation (Stem elongation stage, A) After the N regulation (Panicle initiation stage, B) under different N treatments (N0: zero N treatment; N1: light N deficiency treatment; N2: sufficient N treatment; N3: excessive N treatment; NiM1 and NiM2 represent the NFOA and NNI N regulation for the corresponding N treatment).
The SPAD values of L4 under N0, slightly deficient (N1), sufficient (N2) and excessive (N3) N conditions after the fixed-time N topdressing, were 36.3 ± 1.1, 42.6 ± 0.8, 43.0 ± 0.8, and 43.3 ± 0.6, respectively (Figure 3B). In contrast, SPAD values of L4 under the N fertilizer management strategies (N1M1, N2M1, N1M2, N3M1, N2M2, N3M2) were all greater than that of the excessive fixed-time plot (N3). Therefore, the newly established SPAD-based N fertilizer management strategies could be used to manage N nutrition in rice cultivation accurately.

3.3 Shoot biomass, N uptake, and N transportation efficiency under different N management strategies

Nitrogen topdressing in rice is generally performed during the PI and BT stages, since rice plants have well-developed root systems and can uptake N more efficiently at these stages. Shoot biomass, NA, and N transportation efficiency (NTE) under different N treatments at the SE and harvest stages (HS) were calculated to compare discrete N topdressing strategies (Table 4).

Shoot biomass at the SE stage increased with increasing N rates. Different N treatments showed a significant difference of 26 % between plots with and without N fertilizer input (Table 4). Different N treatments resulted in a 42 % increase in shoot biomass at the harvest stage after N topdressing at the PI and BT stages. Moreover, shoot biomass in different plots followed the same pattern as that of grain yield (Table 3, Table 4): despite N0 (12 t·ha⁻¹) and N1 (17 t·ha⁻¹), a relatively high shoot biomass (20 t·ha⁻¹) was seen in other treatments. Since shoot biomass increases mainly after the SE stage, the difference between the SE and HS stages under different treatments
showed the same pattern as shoot biomass at the HS stage, while a larger difference (47%) was observed among different treatments (Table 4).

Table 4. Shoot dry matter, N accumulation and N transportation efficiency under different N treatments at stem elongation and harvest stages

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Shoot dry matter(t·ha⁻¹)</th>
<th>Shoot N accumulation(kg·ha⁻¹)</th>
<th>NTE %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SE</td>
<td>HS</td>
<td>SE+HS</td>
</tr>
<tr>
<td>N0</td>
<td>2.22d</td>
<td>11.66c</td>
<td>9.45c</td>
</tr>
<tr>
<td>N1</td>
<td>2.61abc</td>
<td>17.20b</td>
<td>14.58b</td>
</tr>
<tr>
<td>N1M1</td>
<td>2.57bc</td>
<td>20.17a</td>
<td>17.60a</td>
</tr>
<tr>
<td>N1M2</td>
<td>2.54abc</td>
<td>19.73a</td>
<td>17.19a</td>
</tr>
<tr>
<td>N2</td>
<td>2.82abc</td>
<td>20.21a</td>
<td>17.38a</td>
</tr>
<tr>
<td>N2M1</td>
<td>2.86ab</td>
<td>19.25a</td>
<td>16.39ab</td>
</tr>
<tr>
<td>N2M2</td>
<td>2.47c</td>
<td>20.13a</td>
<td>17.65a</td>
</tr>
<tr>
<td>N3</td>
<td>2.95a</td>
<td>19.08a</td>
<td>16.13ab</td>
</tr>
<tr>
<td>N3M1</td>
<td>2.94a</td>
<td>19.63a</td>
<td>16.68ab</td>
</tr>
<tr>
<td>N3M2</td>
<td>2.98a</td>
<td>19.48a</td>
<td>16.50ab</td>
</tr>
<tr>
<td>SD</td>
<td>0.24</td>
<td>2.48</td>
<td>2.34</td>
</tr>
</tbody>
</table>

Note: SE and HS are stem elongation and harvest stages respectively, SE+HS means SE stage and HS stage; NTE is N transportation efficiency. ‘SD’ means standard deviation values.

Values followed by a different letter are significant at 5% probability level using LSD method.

- N0: zero N treatment or the check treatment; N1: N deficiency treatment, N2: sufficient N treatment, N3: excessive N treatment or the farmer method to ‘M1’: in-season N management using N fertilizer optimization algorithm (NFOA)
- N1M1: NFOA regulation for N1, N2M1: NFOA regulation for N2, N3M1: NFOA regulation for N3;
- N1M2: NNI method for N1; N2M2: NNI method for N2; N3M2: NNI method for N3 to ‘M2’: in-season N management using N nutrition index (NNI)

Nitrogen uptake also increased with increasing N rates. However, a highly significant difference (59%) in plant NA was observed under different treatments at the SE stage. In contrast, no significant difference between N treatments was observed
at the HS stage, except in the N0 and N1 treatments, and the difference in NA among different N rates reached up to 63%. However, there was no significant in the N2 and N3 treatments. The difference of NA between the SE and HS stages followed the same pattern with their corresponding shoot biomass, and a larger difference (70%) was also observed among different treatments.

Nitrogen transportation efficiency (NTE) of different N treatments was compared (Table 4). NTE increased from 51% in N0 plot to 72% in N1 plot and then decreased to 57% under excessive N condition (N3). A relatively high NTE (66%) and grain yield (10 t·ha⁻¹) observed in the N1M1, N1M2, N2, N2M1, N2M2 plots indicated that both new methods could be used to regulate deficient and sufficient N conditions appropriately in rice.

3.4 Comparison of N-fertilizer use efficiency

An effective N management strategy requires a high grain yield with relatively low N-fertilizer input to optimize crops N efficiently. Multiple N fertilizer-use efficiency indicators, such as PFP, NUE, AE, and HI, were used to assess plant uptake efficiency.

Partial factor productivity (PFP) gradually decreased with increasing N application rates (Table 3). The highest PFP (45 kg·kg⁻¹) was observed in the N1 treatment, while the lowest (28 kg·kg⁻¹) was observed in N3. The two newly developed regulation methods showed a higher PFP (32, 33 kg·kg⁻¹) than that under N3. At the same time, a relatively stable PFP (37 kg·kg⁻¹) and grain yield was
observed under the N1M1, N1M2, N2, N2M1, and N2M2 treatments. A PFP value of 38 kg·kg⁻¹ could be used as an indicator for ensuring high yield (≈ 10 t·ha⁻¹) and N use efficiency in rice. NUE also followed a similar pattern as that of PFP under different N treatments (Table 3). A significant (p < 0.05) difference was observed between deficient (N1) and excessive (N3, N3M1, N3M2) N treatments, while a relatively stable NUE (≥ 0.41) was achieved in the N1M1, N1M2, N2M1, and N2M2 plots. AE first increased (16.6 kg·kg⁻¹) and then decreased with increasing N application rates (Table 3). In contrast, HI was not significantly different between the N treatments (Table 3), with an average value of 0.55. These results showed that PFP (38 kg·kg⁻¹), NUE (0.41), and AE (16.6 kg·kg⁻¹) could be used to assess N fertilizer use efficiency in rice.

The RE is another indicator of NUE. The present study revealed the RE of the fixed-time N fertilizer application treatments were less than that of the in-season N fertilizer management plots under the same basal N fertilizer level (Table 3). The contribution of N topdressing under deficient or sufficient N conditions performed better than under excessive N application. The RE of in-season N fertilizer-adjustment management was greater than that of the fixed-time N fertilizer application under deficient N basal fertilizer conditions. Based on these findings, our preliminary conclusion is that the newly modified regulation methods not only ensure a high grain yield under deficient and sufficient N conditions, but also sustain a relatively high N-fertilizer use efficiency.
3.5 Cost-benefit analysis of different N regulation methods

Crop production not only aims to guarantee food security but also to maximize a farmer’s net profit. Net profit in the present study ranged from $411 to $1250·ha\(^{-1}\). The relatively high net profit values (> $1080·ha\(^{-1}\)) were observed in the treatments of NFOA and NNI regulations for N2 and N3 (N2M1, N2M2, N3M1, N3M2) (Table 5). High net profit ($1159·ha\(^{-1}\)) for plots where excessive N was applied was attributed to the low price of N fertilizer (5.43 kg·ha\(^{-1}\)). However, the benefit-fertilizer cost ratio (3.8) of N3 was the lowest, and similar to that of the N1 treatment. In contrast, two newly established regulation methods showed the optimal benefit-fertilizer cost ratio (4.1 ~ 5.3) under all N conditions, especially for the deficient N plots (N1M1, N1M2) (Table 5).

Fig. 4. Statistical analysis of Economic benefit under different N treatments (A), and the trends of benefit-fertilizer cost under different N treatments (B).

The optimum N fertilizer recommendation is an effective way to improve NUE. Therefore, this study determined the relationship between the return from grain, net profit, and N fertilizer rates by nonlinear-plateau regression analysis (Return from grain, \(R^2=0.98\); Net profit, \(R^2=0.94\); Figure 4A). The plateau value was $3165·ha\(^{-1}\)
(Return from grain) and $1109·\text{ha}^{-1}$ (Net profit), and the range of critical N treatment was 264 ~ 272 kg·N·ha$^{-1}$. The benefit-fertilizer cost ratio increased quickly to the maximum benefit-fertilizer cost-ratio (5.5) under N treatment of 260 kg·N·ha$^{-1}$, then decreased to 3.8 (Figure 4B). Therefore, we considered benefit-fertilizer cost ration of 5.5 as a special threshold for paddy rice production.

Table 5. Economic benefit under different N treatments ($\cdot\text{ha}^{-1}$)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Return from grain</th>
<th>Cost of nitrogen fertilizer</th>
<th>Other cost †</th>
<th>Additional Labor cost</th>
<th>Net profit</th>
<th>benefit-fertilizer cost ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>N0</td>
<td>1888</td>
<td>0</td>
<td>1477</td>
<td>-</td>
<td>411i</td>
<td>-</td>
</tr>
<tr>
<td>N1</td>
<td>2507</td>
<td>151</td>
<td>1773</td>
<td>23</td>
<td>583h</td>
<td>3.8d</td>
</tr>
<tr>
<td>N1M1</td>
<td>3204</td>
<td>222</td>
<td>1773</td>
<td>23</td>
<td>1185c</td>
<td>5.3a</td>
</tr>
<tr>
<td>N1M2</td>
<td>3034</td>
<td>219</td>
<td>1773</td>
<td>23</td>
<td>1019g</td>
<td>4.7b</td>
</tr>
<tr>
<td>N2</td>
<td>3250</td>
<td>227</td>
<td>1773</td>
<td>23</td>
<td>1250a</td>
<td>5.5a</td>
</tr>
<tr>
<td>N2M1</td>
<td>3111</td>
<td>234</td>
<td>1773</td>
<td>23</td>
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<tr>
<td>N2M2</td>
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<td>227</td>
<td>1773</td>
<td>23</td>
<td>1211b</td>
<td>5.3a</td>
</tr>
<tr>
<td>N3</td>
<td>3235</td>
<td>303</td>
<td>1773</td>
<td>-</td>
<td>1159d</td>
<td>3.8d</td>
</tr>
<tr>
<td>N3M1</td>
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<td>23</td>
<td>1092f</td>
<td>4.1c</td>
</tr>
<tr>
<td>N3M2</td>
<td>3158</td>
<td>258</td>
<td>1773</td>
<td>23</td>
<td>1104e</td>
<td>4.3c</td>
</tr>
</tbody>
</table>

† Other cost includes cost of K and P fertilizers (180 and 105 $\cdot\text{ha}^{-1}$, respectively), seeding (186 $\cdot\text{ha}^{-1}$), pesticides (185 $\cdot\text{ha}^{-1}$), ploughing (130 $\cdot\text{ha}^{-1}$), and management expenditure (987 $\cdot\text{ha}^{-1}$); additional labor cost was the highest daily salary of workers in Jiangsu province (2.86 $\cdot\text{h}^{-1} \times 8$ h), China.

Values (a-i) followed by a different letter are significant at 5 % probability level using LSD method.

DISCUSSION

4.1 Enrich N regulation strategies

In this study, we developed two rice N regulation methods by using SPAD values to replace the spectral index and NNI as the input parameters for both NFOA and NNI regulation algorithms. NFOA or NNI regulation algorithms was modified using the
SPAD values, and the in-situ validation indicated both management strategies could be used to regulate N topdressing of paddy rice under slightly deficient, sufficient, and excessive N nutrition conditions.

Yuan et al. (2016) indicated that NSI4 could be used to predict NA, grain yield and NNI in previous studies. By analyzing those quantitative relationships (Figures 1 & 2, Eq. 1-8), SPAD-values-based NFOA and NNI regulation methods were built. Previous studies had also indicated the normalized SPAD readings exhibited more stable relationships with shoot NA, NNI, and relative grain yield than absolute SPAD values (Ata-Ul-Karim, Liu, et al., 2016, Ravier, Quemada, et al., 2017, Ziadi, Brassard, et al., 2008). These results supported our hypothesis for establishing SPAD-values-based NFOA and NNI regulation methods. This integration took full advantage of chlorophyll meters, as well as NFOA and NNI regulation methodologies. Built on the in-situ validation, SPAD measurements and N fertilizer topdressing at SE and PI stages resulted in a higher yield (Yuan et al., 2016).

However, SSNMs, such as real-time N management (RTNM) and fixed-time adjustable-dose N management (FTNM), were developed to increase the NUE of the irrigated rice based on SPAD or LCC readings (Dobermann, Witt, et al., 2002, Peng, Garcia, et al., 1996). SSNM provides an option for real-time N management (RTNM) and fixed-time adjustable-dose N management (FTNM) to regulate N fertilizer dose using the LCC or SPAD (Witt et al., 2007). For RTNM, plant N status indicates a deficit, and additional top-dressing N fertilizer will be applied when the SPAD or
LCC readings of rice leaves falls below a critical threshold at critical growth stages.

For FTNM, N doses and times for N application are predetermined based on the cropping season, crop growth stage, variety, and crop establishment method. (Peng et al., 2006).

### 4.2 SPAD-value-based N regulation

Accurate regulation of N fertilizer topdressing is the key technical procedure for crop N nutrition management. The multiple or dynamic critical SPAD thresholds could lead to confusion among farmers, which would restrict the widespread application of SPAD-values-based SSNM regulation strategy. Moreover, SPAD readings are affected by such factors as irradiance, leaf thickness, growth stage, and genotype (Martinez and Guiamet, 2004, Peng, Garcia, et al., 1996, Zhang, Ge, et al., 2017), which posed a great challenge for the reliability of the SPAD-values-based SSNM method. In contrast, normalized SPAD readings are more reliable than the absolute SPAD readings, mainly because the former can overcome the negative influence of year, eco-site, cultivar, growing stages, etc. (Noura, Gilles, et al., 2010, Yuan, Ata-Ul-Karim, et al., 2016, Ziadi, Brassard, et al., 2008). Excessive N treatment is needed to normalize the SPAD-values-based N regulation, yet a more reliable N diagnosis and regulation can be achieved. Therefore, normalized SPAD-values-based N regulation would be promising for crop N management in the future.

### 4.3 The performance of NSI4 based NFOA and NNI methods

Among the N fertilizer regulation methods, NFOA and NNI were widely used in the NDVI or RVI optical index as the input variables (Ata-Ul-Karim, Liu, et al., 2017,
Xue and Yang, 2008). Until now, the SPAD-values-based NFOA and NNI methods have rarely been recorded. Therefore, performance of NSI4-based NFOA and NNI methods were explored in this study. The results showed that the two newly modified methods could be utilized to manage N nutrition in rice under deficient, sufficient, and excessive N conditions through upward-, fine-, and downward-adjustment of N fertilizer topdressing respectively (Table 2, Figure 3). As for the NUE, low AE (~12 kg·kg⁻¹) and NUE (~0.3) were observed in the excessive N plot treatment, which was consistent with Hussain, Bronson, et al. (2000). Since PFP and NUE are more sensitive to different N statuses than AE and HI (Guarda, Padovan, et al., 2004, Sun, Ma, et al., 2012), the optimum N fertilizer based on the intersection of yield line and N efficiency line was used to test our regulation methods (Figure 5). The cross-validation showed that the optimal N rates, PFP and NUE in this study were 257~270 kg·N·ha⁻¹, 39 kg·kg⁻¹ and 0.40, respectively. Those parameters could be used to improve the local rice production. And we are also conducting further study to explore the optimal equilibrium point between high grain yield and N fertilizer efficient application.
This study also provided more detail on cost-benefit analyses than previous ones (Chen, Tian, et al., 2014), incorporating the costs of N, K, and P fertilizers, seeding, pesticides, ploughing, and field management fees. The net profit includes all costs and the net benefit reflects the actual financial gain or loss for a farmer, so it is a more appropriate indicator of financial performance than benefit fertilizer cost ratio (Li et al., 2012). Furthermore, the coefficient of determination and the plateau value reached a relatively high level (Figure 4B), suggesting that the optimal N fertilizer for rice production was 264 ~ 272 kg·N·ha⁻¹ in Eastern China. This result was consistent with our long-term field measurements and the validation experiment. Guo et al. (2017) reported that a very small number of farmers achieved a high yield (8.9 t·ha⁻¹) and high N utilize efficiency (PFP=32 kg·kg⁻¹) in rice with 278 kg·N·ha⁻¹ applications. Therefore, two newly established N fertilizer management strategies were (264 ~ 272...
kg·N·ha\(^{-1}\)) effective in N fertilizer topdressing, which also can be used to guide N fertilizer application in Eastern China.

NTE is an index to evaluate nitrogen uptake and utilization efficiency (Jiang, Dai, et al., 2003). Shi et al. (2012) reported the NTE of N150 treatment (N fertilizer rate = 150 kg·N·ha\(^{-1}\)) was significantly higher than those of other N rates (N225, N300) in two winter wheats (Ningmai-9, Yumai-34) and for paddy rice. Moreover, Yan et al. (2010) showed that N100 (N fertilizer rate = 100 kg·N·ha\(^{-1}\)) was significantly higher than the other N fertilizer rates (N150, N200, N250). Wang et al. (2017) reported that NTE was mainly affected by N application rate. Particularly, the slightly deficient N fertilizer treatment showed a significantly higher NTE than the high N fertilizer treatment (Bailey, 2004). In this study, NTE of the N1 fertilizer rate was higher than the additional N fertilizer rates, which were consistent with previous studies.

We recommended a benefit-fertilizer cost ratio of 5.5 as an indicator to guide high production. The average rate of N fertilizer application for rice in Jiangsu province of Eastern China reached 387 kg·N·ha\(^{-1}\) during 2004-2008 (Chen, Huang, et al., 2011), which was the same nitrogen fertilizer rate as excessive N treatment we used in this study (N3, 360 kg·N·ha\(^{-1}\)). The conventional management of local farmers (N3) consumed the most N fertilizer, but resulted in an equivalent yield comparing with N2 (270 kg·N·ha\(^{-1}\)), lower N fertilizer utilization efficiency than other N treatments, and a lower benefit-fertilizer cost than the N regulation management treatment. The benefit-fertilizer cost ratio increased quickly to the maximum benefit-fertilizer cost ratio (5.5)
after an N treatment of 260 kg·N·ha\(^{-1}\), and then decreased to 3.8 (Figure 4B).

Therefore, the N2 treatment (270 kg·N·ha\(^{-1}\)) was the optimum range of N fertilizer cost, and it performed very well. However, N2 as a suitable N treatment based on long-term field experiment (Guo et al., 2017), is very hard to apply an exact proper N2 fertilizer rate (270 kg·N·ha\(^{-1}\)) for real-time crop production management in new eco-sites. Therefore, several new N regulation strategies were developed for site-specific crop nutrition management and sustainable agriculture (Wang et al., 2017; Raun et al., 1999).

Due to the fact that the N2 rate was set based on long-term field production at the experimental area, some measured parameters (yield, PFP, NUE, PE, AE, HI, net profit and benefit-fertilizer cost ratio) were not significantly improved by SPAD-based-NFOA and NNI methods when compared to the N2 treatment. Once the production area or varieties changed, this time-fixing N management method would not perform so well (Peng, Buresh, et al., 2006); in other words, it is hard to extend to other eco-sites. In this study, the validation data further showed the optimum N fertilizer rate (264 ~ 272 kg·N·ha\(^{-1}\)) was similar to N2 (270 kg·N·ha\(^{-1}\)). However, local rice farmers in our study area (Jiangsu province, PR, China) usually applied N fertilizer at levels (337 kg·N·ha\(^{-1}\)) closer to N3 (Peng et al., 2010; Guo et al., 2017). The NFOA and NNI approaches are not superior entirely in yield, N use efficiency, and financial outcomes comparing with the fixed-time N management under fewer N conditions, but those types of easily operated and reliable N regulation methods are critical for high-efficiency and sustainable agriculture.
In this work, two new N fertilizer management strategies were validated under three different N conditions. The N fertilizer topdressing of the NFOA strategy (M1) was greater than the NNI method (M2) in all N conditions, but M1 was not superior to M2 in PFP and yield except under the N1 condition (Table 2). The performance of N1M1 was preferable to that of the other NiMi management scenarios for almost all production indicators (PFP, RE, PE, etc.). The increment of shoot dry matter and N accumulation in the M1 strategy was fewer than M2 under the N2 treatments level, while N1M1 also performed better than most NiMi strategies in shoot dry matter and NTE (Table 4). In addition, the economic benefit of the M2 method was better than M1 under different N treatments levels, with the exception of N1M1. Therefore, the M1 strategy could be suitably used when the N nutrition status of paddy rice is slightly deficient, while the M2 method was more efficient to guide N fertilizer topdressing when the N nutrition status of paddy rice is sufficient or excessive. However, more experiments conducted in diverse eco-sites are needed to test the reliability of the two new in-season N fertilizer adjustment management methods, to further analyze environmental risk and provide more detailed cost estimates.

CONCLUSION

In this study, newly normalized SPAD values-based NFOA and NNI methods were established to accurately regulate N topdressing. The in-situ validation showed both new and improved methods could optimize N fertilizer topdressing under different N conditions (deficient, sufficient, and excessive) with upwards-, fine-, and
downward-adjustment of N application respectively. Meanwhile, both methods can achieve high yield, high efficiency as well as higher net profit under different N conditions, but less than the N2 (270 kg·N·ha\(^{-1}\)) treatment. Relatively high PFP, NUE and AE are essential to optimize fertilizer application for high-yield rice production. And the determined optimal N fertilizer was about 264 ~ 272 kg·N·ha\(^{-1}\) in Eastern China. Furthermore, more studies are still needed to optimize the algorithm and make it more robust for widespread application.

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agronj1999.00021962009100030001x


**Partially Factor Productivity (PFP)**

- **Equation:** $\text{PFP} = -0.0001853x^2 + 0.00228x + 50.79$
- **Equation:** $\text{Yield} = 0.0000259x^2 + 0.02048 + 5.963$

257 kg N ha$^{-1}$

---

**Nitrogen Use Efficiency (NUE)**

- **Equation:** $\text{NUE} = -0.000002719x^2 + 0.006926x + 0.4103$
- **Equation:** $\text{Yield} = 0.0000259x^2 + 0.02048 + 5.963$

270 kg N ha$^{-1}$