Comparison of Five Nitrogen Dressing Methods to Optimize Rice Growth

Qingchun Chen, Yongchao Tian, Xia Yao, Weixing Cao and Yan Zhu
(National Engineering and Technology Center for Information Agriculture, Jiangsu Key Laboratory for Information Agriculture, Nanjing Agricultural University, Nanjing, Jiangsu 210095, P. R. China)

Abstract: The applicability of five nitrogen (N) dressing methods to rice cultivation was examined using the canopy spectrum-based nitrogen optimization algorithm (CSNOA), leaf area index (LAI), site-specific N management (SSNM), N nutrition index (NNI), and N fertilizer optimization algorithm (NFOA). After base-tiller N dressing (basal dressing and top dressing at the tillering stage) at low and normal levels, rice plants were grown by the above five N dressing methods. The effects of different N dressing methods on plant dry weight, plant N accumulation, grain yield, N use efficiency, and economic benefit were analyzed. Compared with the standard method, under the low base-tiller N dressing level, the optimum N dressing rate was decreased, and the economic benefit was increased by adapting the N dressing methods of CSNOA and SSNM, whereas the optimum N dressing rate was increased, and the economic benefit was decreased by the other three N dressing methods. Under the general base-tiller N dressing level, the optimum N rate, N-use efficiency and economic benefit were increased by all N dressing methods except the NFOA. These results indicated that the CSNOA and SSNM were two good techniques for quantifying N dressing in rice, with higher economic benefit, less N input, and better applicability under different base-tiller N dressing levels.

Key words: CSNOA, Grain yield, Economic benefit, NUE, Nitrogen dressing approach, PNA, Rice, SSNM.

With the increase in the world population and the improvement of living standards, the demand for agricultural commodities continues to grow. In order to achieve higher yield, more and more fertilizer has been used, especially in China (Zhu and Chen, 2002). The current nitrogen (N) consumption in China is approximately twice of that in the 1980s (China Statistical Yearbook 1982 – 2008). N fertilizer consumption in China is higher than in other countries, while N use efficiency (NUE) is comparatively lower (Cassman et al., 2002; Zhang et al., 2008). Sufficient N input can improve crop yield and grain quality, but superfluous N reduces crop yield, and causes poor quality and soil acidification (Cassman et al., 2002; Guo, 2010). Therefore, optimization of N fertilization is important for both crop production and environmental protection.

Crop growth is affected by climate condition, soil fertility, cultivar characters, and management practices (Pan, 2008). Thus decision making on N fertilization should comprehensively consider the target grain yield, N uptake per day, LAI, leaf area index; DVI, differential vegetation index; NFOA, nitrogen fertilizer optimization algorithm; NHI, nitrogen harvest index; NNI, nitrogen nutrition index; NR, nitrogen requirement; NRT, nitrogen transport efficiency; NUE, nitrogen use efficiency; PDW, plant dry weight; PE, physiological efficiency; PFP, partial factor productivity of applied nitrogen; PNA, plant nitrogen accumulation; RVI, ratio vegetation index; SM, standard method; SSNM, site-specific nitrogen management; TNS, total soil nitrogen supply during whole growth cycle.

Abbreviations: AE, agronomic efficiency of nitrogen; CNR, canopy nitrogen requirement; CSNOA, canopy spectrum based nitrogen optimization algorithm; DAT, days after transplanting; DNF, dressing rate of fertilizer nitrogen; DVI, differential vegetation index; FAM, factor of nitrogen application mode; FAT, factor of nitrogen application time; FB, amount of base-tiller nitrogen; FBT, factor of base-tiller nitrogen fertilizer rate; FNT, factor of nitrogen fertilizer type; FTPM, fixed-time adjustable-dose nitrogen management; FVT, factor of rice variety type; GAI, green leaf area index; GtA, target green leaf area index; GPE, grain production efficiency; GTN, total nitrogen accumulation of grain at maturity; Gy, grain yield in nitrogen fertilized plot; Gy0, grain yield in zero-nitrogen plot; GyT, grain yield target; HTNH, total haulm nitrogen accumulation at full heading; HTNM, total haulm nitrogen accumulation at maturity; INSEY, in-season estimated grain yield, represents plant N uptake per day; LAI, leaf area index; NDFI, normalized differential vegetation index; NFOA, nitrogen fertilizer optimization algorithm; NHI, nitrogen harvest index; NNI, nitrogen nutrition index; NR, nitrogen requirement; NRT, total nitrogen requirement; NS, soil nitrogen supply after N dressing; NSI, nitrogen spectrum index; NSSt, total soil nitrogen supply during whole growth cycle; NTE, nitrogen transportation efficiency; NUE, nitrogen use efficiency; PDW, plant dry weight; PE, physiological efficiency; PFP, partial factor productivity of applied nitrogen; PNA, plant nitrogen accumulation; PTN, total aboveground plant nitrogen accumulation at maturity; PTN0, total aboveground plant nitrogen accumulation of zero-nitrogen treatment at maturity; RE, nitrogen recovery efficiency; RTNM, real-time nitrogen management; RVI, ratio vegetation index; SM, standard method; SSNM, site-specific nitrogen management; TNS, total soil nitrogen supply during whole growth cycle.
supply from soil (soil N supply), N uptake and utilization characters of cultivar, climate condition, and so on (Keating et al., 2003). N fertilization normally includes basal and top dressing of N. Many studies have been conducted to estimate the optimum N dressing rate in order to increase N use efficiency and reduce N loss (Lukina et al., 2001; Peng et al., 2006).

Since the 1990s, the leaf chlorophyll meter (SPAD-502, Minolta Camera Co., Ltd., Japan) and leaf color chart have been used to determine the dressing rate (Turner and Jund, 1994; Peng et al., 1996; Villeneuve et al., 2002). The site-specific N dressing management (SSNM), developed by the International Rice Research Institute, used a chlorophyll meter (SPAD-502) to monitor leaf N status, and calculated N dressing rates according to the SPAD values at main crop growth stages. Compared to the general N management method, the SSNM method achieved a higher grain yield with a lower N dressing rate, thereby resulting in a higher economic benefit (Huang et al., 2008; Liu et al., 2009). However, since the chlorophyll meter records only the point data from a single leaf on a single plant many measurements would be needed to obtain the average N status of the whole canopy precisely.

In 2003, Wood et al. proposed a method for determining the N dressing rate based on leaf area index (LAI) in wheat, with which measurements could be made on a larger scale. The N dressing rate was determined by the difference between the measured LAI and target LAI, and also by the soil N supply and NUE of fertilizer. The LAI method is simple, but some parameters, such as NUE and soil N supply, are difficult to estimate at different eco-sites with a different soil type and fertility, climate and variety.

The N nutrition index (NNI) method was developed for the N dressing management (Farruggia et al., 2004; Lemaire et al., 2007, 2008; Xue and Yang, 2008). NNI was estimated directly from canopy chlorophyll concentration predicted by canopy reflectance. When NNI was less than one (NNI < 1), the N dressing rate should be increased, and when NNI was greater than one (NNI > 1), the N dressing rate should be decreased. These N dressing rates can be calculated from NNI based on the normal N dressing rate. However, since the soil N supply and NUE were not considered when calculating the N dressing rate the optimum N dressing rate could not be obtained precisely.

The central component underlying the N fertilization optimization algorithm (NFOA) (Lukina et al., 2001) was the ability to predict potential grain yield in the early-mid growth season. The N dressing rate was calculated based on the grain N content at maturity, the real time plant N content measured before N dressing and NUE from N dressing to maturity. The grain N content at maturity could be calculated from the grain yield and N demand for 100 kg grain yield, the plant N content could be estimated from the spectral index, and NUE could be estimated based on the previous experiments. NFOA has been suggested to be useful to obtain higher grain yields and higher NUE, with less N supply (Lukina et al., 2001; Jiang et al., 2007; Tubana et al., 2008), but it did not consider the soil N supply.

Flowers et al. (2004) used tiller density to determine the recommended N dressing for soft red winter wheat, and succeeded in reducing the total N input which contributed to optimizing the in-season N rate. Varvel et al. (2007) used the N sufficient index to assess optimum N dressing and obtained higher NUE in corn. Liu et al. (2009) reported a soil N$_{\text{min}}$ test (mainly used for NO$_3$-N) could be effective in optimizing the N dressing rate for precise N management.

It is important to determine the optimum N dressing rate to obtain a high yield, good quality, and high efficiency crop production (Peng et al., 1996; Liu et al., 2009). Although considerable progress has been made in N dressing management (Peng et al., 1996; Lukina et al., 2001; Wood et al., 2003), further optimization is needed (Jia et al., 2007; Samborski et al., 2008; Xue et al., 2008). We developed a new method, named canopy spectrum based nitrogen optimization algorithm (CSNOA), to obtain the optimum N dressing rate by comprehensively considering the target yield, soil N supply, NUE during the mid-late growing stage, plant N accumulation, and cultivar characters. We calibrated the parameters in four published N dressing methods (LAI, SSNM, NNI, NFOA) with experimental data in rice, and evaluated the performance of each method for optimizing the N dressing rate in the field experiments with rice.

**Material and Methods**

1. **Experimental design**

Five experiments were conducted from 2006 to 2009 at Nanjing Agricultural Bureau Experimental Station in Jiangning, Nanjing City, Jiangsu Province, China (118°59' E, 31°56' N). The region receives more than 2000 hours of sunshine and 1000 mm of rainfall annually, with an average temperature of 15.7°C. Rice-wheat rotation is the typical cropping system in this area. Basic soil information in the experimental area is shown in Table 1. All experiments were conducted in a randomized complete block design with three replicates for each N dressing method at a plant density of 5.33 × 10$^5$ plants ha$^{-1}$. Before transplanting, we applied to the soil a total of 135 kg ha$^{-1}$ P$_2$O$_5$ (as Ca(H$_2$PO$_4$)$_2$) in all experiments plus 190 kg ha$^{-1}$ K$_2$O (as KCl) in experiment 1 and 5 and 203 kg ha$^{-1}$ K$_2$O (as KCl) in experiment 2 – 4. The area of each plot was 31.5 m$^2$ (3.5 m × 9.0 m) in experiment 1, 27 m$^2$ (4.5 m × 6 m) in experiment 2, 4 and 5, and 29.25 m$^2$ (4.5 m × 6.5 m) in experiment 3.
Experiment 1: total N dressing at different rates in 2006
The japonica rice cultivar Wuxiangjing 14 (WXJ14) was planted on 18 May, and transplanted on 20 June. N (as urea) was applied at a rate of 0, 90, 270, and 405 kg ha\(^{-1}\), 40% at pre-planting, 10% at tillering, 25% at jointing, and 25% at booting stages.

Experiment 2: top-dressing of N at different rates with basal dressing of N at different rates using two cultivars in 2007
Two japonica rice cultivars, WXJ14 and 27123, were planted on 18 May, and transplanted on 20 June. Two N dressing methods were used: (1) Total N (as urea) at 0, 120, 240, and 360 kg ha\(^{-1}\) was applied split as in experiment 1. (2) Basal dressing and top dressing at the tillering stage (base-tiller N dressing), was applied at the rates of 60, 120 and 180 kg ha\(^{-1}\), with 80% applied as basal dressing and 20% applied at tillering on 10 July with both cultivars. Then 200 and 195 kg N ha\(^{-1}\) were applied according to the canopy spectrum-based N optimization algorithm method (CSNOA) split at jointing (3 August) and at booting (15 August).

Experiment 3: different top-N dressing rates under different basal N rates with two cultivars in 2008
The two cultivars were the same as those used in experiment 2. The plants were sown on 24 May, and transplanted on 25 June. Two N dressing methods were used: (1) Four total N (as urea) rates as 0, 130, 260, and 390 kg ha\(^{-1}\) were applied split as in experiment 1. (2) Two base-tiller N dressing rates as 65 and 95 kg ha\(^{-1}\) were applied, with N distributed as 80% before transplanting and 20% at tillering on 10 July with both cultivars. Then 200 and 195 kg N ha\(^{-1}\) were applied according to the CSNOA method for WXJ14 and 210 kg ha\(^{-1}\) and 210 kg ha\(^{-1}\) for 27123. The top-dressing of N split equally was applied at jointing (8 August) and booting (18 August) stages.

Experiment 4: different total N dressing rates using three cultivars in 2008
Two japonica rice cultivars (WXJ14 and Wuyujing 3

| Table 1. Soil parameters in different rice experiments. |
|--------------------------------------------------------|
| Experiment | Soil type           | SOC\(^{1}\), g kg\(^{-1}\) | TNC\(^{2}\), g kg\(^{-1}\) | Olsen P, mg kg\(^{-1}\) | Avail K, mg kg\(^{-1}\) |
| Exp. 1     | Yellow white soil   | 14.2                       | 1.1                        | 14.8                        | 80.5                        |
| Exp. 2     | Yellow white soil   | 16.1                       | 1.0                        | 10.4                        | 82.6                        |
| Exp. 3     | Yellow white soil   | 25.1                       | 1.4                        | 10.5                        | 80.6                        |
| Exp. 4     | Yellow white soil   | 18.1                       | 1.3                        | 11.3                        | 75.2                        |
| Exp. 5     | Yellow white soil   | 15.1                       | 1.4                        | 13.4                        | 85.6                        |

\(^{1}\)SOC, soil organic content. \(^{2}\)TNC, total nitrogen content.

| Table 2. Nitrogen fertilizer rates (kg ha\(^{-1}\)) of different N treatments in 2009 (Experiment 5). |
|---------------------------------------------------------------|
| Treatment\(^{a}\) | Basal | Tilling | Jointing | Booting | Whole period |
|-------------------|-------|---------|----------|---------|--------------|
| 0N                | 0     | 0       | 0        | 0       | 0            |
| CSNOA(L)          | 54    | 13.5    | 72.25    | 72.25   | 212          |
| LAI(L)            | 54    | 13.5    | 123.75   | 123.75  | 315          |
| SSNM(L)           | 54    | 13.5    | 100      | 100     | 267.5        |
| NNI(L)            | 54    | 13.5    | 146.25   | 146.25  | 360          |
| NFOA(L)           | 54    | 13.5    | 123.75   | 123.75  | 315          |
| CSNOA(G)          | 108   | 27      | 36       | 36      | 207          |
| LAI(G)            | 108   | 27      | 55       | 55      | 245          |
| SSNM(G)           | 108   | 27      | 40       | 70      | 245          |
| NNI(G)            | 108   | 27      | 51       | 51      | 237          |
| NFOA(G)           | 108   | 27      | 67.5     | 67.5    | 270          |
| SM                | 108   | 27      | 67.5     | 67.5    | 270          |

\(^{a}\)0N: zero N treatment. SM: standard method. CSNOA, LAI, SSNM, NNI and NFOA denote canopy spectrum based nitrogen optimization algorithm, leaf area index, site-specific N management, N nutrition index and N fertilizer optimization algorithm, respectively. (L), low basal N rate in which basal N rate was half of the SM. (G), general basal N rate in which basal N rate was same as the SM.
(WYJ3)) and one hybrid rice cultivar Liangyoupeijiu (LYP) were sown on 24 May, and transplanted on 25 June. Total N (as urea) was applied at 0, 130, 260, and 390 kg ha\(^{-1}\) split as in experiment 1.

(5) Experiment 5: top-dressing of N at different rates under basal dressing of N at two different rates in 2009

The rice variety, WXJ14 was sown on 18 May, and transplanted on 18 June. Twelve N dressing treatments were used to compare the performance of five N dressing methods (Table 2). The N dressing rate in the standard normal method (SM) was 270 kg ha\(^{-1}\), which was split: 108 kg ha\(^{-1}\) at pre-planting, 27 kg ha\(^{-1}\) at tilling, 67.5 kg ha\(^{-1}\) at jointing, and 67.5 kg ha\(^{-1}\) at booting, according to the local standard practices for high yield in rice. One treatment was carried out without N dressing but with a full rate of P and K (0N) to calculate NUE. The other ten dressing treatments were divided into two groups according to the basal N dressing rate: one received 50% of the basal N dressing in SM (low level dressing, L) and the other received the same basal N dressing as in SM (ground level dressing, G). After the basal dressing, top dressing was applied according to CSNOA, LAI, NNI, SSNM, and NFOA based on rice canopy reflectance or leaf color as shown in Table 2.

2. Measurement of canopy spectral reflectance

The spectral reflectance of the plant canopy was measured at 16 specific wavebands (approximate center wavelength = 460, 510, 560, 610, 660, 710, 760, 810, 870, 950, 1100, 1220, 1480, 1500, 1650 nm) using a portable ground MSRI6 radiometer (Cropscan, Rochester, MN). The bandwidth varied from 8.3 to 11.7 nm in the visible region, and from 9.9 to 16.3 nm in the near-infrared region. A data acquisition device (DLC Model 2000, Cropscan Inc.) having a sun angle cosine correction capacity was used to record reflectance data. Measurements were made with the radiometer at 1.5 m above the canopy, and the diameter of the field of view was one half the height of the radiometer over the crop canopy. Five measurements were obtained at each of three sites over each plot, with the average as an individual observation. All spectral measurements were made on cloudless or near cloudless days at 1100 – 1400. Radiometer calibration was conducted daily with an opal glass diffuser by the two-point (2-Pt. Up/Dn) method (Cropscan, 2000).

Before booting, spectral readings were obtained once in experiments 1 and 2, and twice in experiments 3 to 5. The spectral data from experiments 1 to 4 were used to calibrate five N dressing algorithms, and the data from experiment 5 at panicle initiation stage were used to calculate five N dressing rates based on five calibrated algorithms.

3. Plant sampling and analysis

After each measurement of canopy spectral reflectance, five plant samples from each plot were randomly taken for
measuring dry weight of plant organs (leaf, haulm, and grain) and leaf area index (LAI). From each plot, a sub-sample of 10 – 20 tillers and main stems was randomly selected for the measurement of green leaf area with a LAI 3000C meter (LI-COR Inc., USA). Different organs of each sub-sample were oven-deactivated at 105ºC for 0.5 hr, then oven-dried at 80ºC to a constant weight and finally weighed. LAI in each plot was calculated using specific leaf area (the ratio of green leaf area to dry weight). Total N concentration in tissues of each plot was determined by the micro-Keldjahl method (Siriwardene et al., 1966). The N accumulation of the above-ground plant was determined as the product of above-ground dry matter (kg ha⁻¹) and above-ground plant N concentration (g kg⁻¹). Grain yield was determined for each plot at maturity by harvesting 2 m² plants, with a moisture content of 13.5%.

4. Data analysis and parameter calculation

Data collected from experiments 1 to 4 were used to calibrate the parameters in the five N dressing methods. Data from experiment 5 were used to compare the performance of five different N dressing methods. Data collected before booting in experiments 1 to 4 were used to determine the threshold of LAI and SPAD at jointing and booting stages in the method of LAI (Wood et al., 2003) and SSNM (Peng et al., 1996). Data collected before booting in experiments 3 and 4 were used to construct the relationship between NNI and N dressing rate in NNI (Farruggia et al., 2004). Data in experiment 5 were used to calculate the dressing rate of fertilizer N in all five methods (Fig. 1).

Data-fitting was performed with Sigma Plot 12 (Systat Software Inc., California, USA) using different equations based on convergence. Linear, quadratic, logarithmic, exponential, and rational models were evaluated and the model with the highest coefficient of determination (R²) was used. Analysis of variance and multiple comparisons were carried out with SPSS.13 software package (SPSS Inc., Chicago, USA) to evaluate the effects of different N dressing rates on grain yield, plant N accumulation (PNA), NUE, and N harvest index (NHI).

Seven indices of NUE were calculated by equations (1) to (7) according to two different standards. (1) Agronomic efficiency of N (AE), partial factor productivity of applied N (PFP), and recovery efficiency of N (RE) were calculated based on the standard as yield per unit N application rate. (2) The other four indices including grain production efficiency of N (GPE), physiological efficiency of N (PE), N transportation efficiency (NTE) and NHI were calculated based on the standard as yield per unit plant nitrogen accumulation.

\[
AE = \frac{GY - GY_0}{NR_0} \quad (1)
\]
\[
PFP = \frac{GY}{NR_0} \quad (2)
\]
\[
RE = \frac{PTN - PTN_0}{NR_0} \quad (3)
\]
\[
GPE = \frac{GY}{PTN} \quad (4)
\]
\[
PE = \frac{GY - GY_0}{PTN - PTN_0} \quad (5)
\]
\[
NTE = \frac{HTNH - HTNM}{HTNH} \quad (6)
\]
\[
NHI = \frac{GTN}{PTN} \quad (7)
\]

where GY is the grain yield in the N applied plot, GY₀ is the grain yield with zero-N application, NR₀ is the total N application rate, PTN is the total N accumulation of plant at maturity, PTN₀ is the total N accumulation at maturity with zero-N application, HTNH is the total N accumulation of haulm at full heading in the N applied plot, HTNM is the total N accumulation of haulm at maturity in the N applied plot, GTN is the total N accumulation at maturity in the N applied plot.

Spectral vegetation index is a good indicator of plant N accumulation (Lukina et al., 2001; Xue and Yang, 2008). Three vegetation indexes calculated by equations (8) to (10) were selected:

\[
\text{Normalized differential vegetation index (NDVI)} = \frac{(R_{\lambda_1} - R_{\lambda_2})}{(R_{\lambda_1} + R_{\lambda_2})} \quad (8)
\]
\[
\text{Differential vegetation index (DVI)} = \frac{R_{\lambda_1} - R_{\lambda_2}}{R_{\lambda_1}} \quad (9)
\]
\[
\text{Ratio vegetation index (RVI)} = \frac{R_{\lambda_1}}{R_{\lambda_2}} \quad (10)
\]

Where, R and λ denote spectral reflectance and wave band, respectively.

Results

1. Development of canopy spectrum based nitrogen optimization algorithm (CSNOA) for recommending N dressing rate

The algorithm of CSNOA is based on the principle of nutrient balance, with the following equation:

\[
\text{DNF} = \frac{[\text{NRt} - \text{PNA}] - \text{NS}}{\text{NUE}} \quad (11)
\]

where DNF denotes dressing rate of fertilizer N, NRt denotes total N requirement calculated by Eq. (12), PNA is the real-time above-ground plant N accumulation calculated according to Eq. (15), NS denotes soil N supply after N dressing application calculated with Eq. (17), NUE means N-use efficiency after N dressing calculated by Eq. (20).

(1) Calculation of total N requirement (NRt)

\[
\text{NRt} = \frac{GY \times NR}{100} \quad (12)
\]

where GYT is grain yield target provided by the crop management knowledge model (Cao and Zhu, 2005), and NR is N requirement per 100 kg rice grain. NR (kg) is calculated from the crop N requirement per 100 kg grain under maximum grain yield (NRm, kg), and the correction factors for grain yield (FY) and variety (VY) by Eq. (13) (Cao et al., 2009).

\[
\text{NRh} = \text{NRm} \times \min (\text{FY}, 1) - \text{VY} \quad (13)
\]

where the value of NRm was set as 2.3, obtained from
historical data under the highest yield (Ling et al., 2005). The min \((F_Y, 1)\) is the minimum value between \(F_Y\) and 1. \(F_Y\) was set as 0 and 0.2 for japonica and indica rice, respectively. \(F_Y\) was formulated by following Eq. (14).

\[
F_Y = \frac{Q \times GYT}{GY_{\text{max}}} + \beta \tag{14}
\]

where \(GY_{\text{max}}\) (kg ha\(^{-1}\)) was the maximum grain yield, the average value of the highest yields in the past three years; and \(Q\) and \(\beta\) were the model coefficients with values of 0.4773 and 0.50, respectively (Cao et al., 2009).

(2) Calculation of plant N accumulation (PNA)

Plant N accumulation (PNA) was calculated from canopy spectral reflectance. The data collected before booting in experiments 1 to 4, showed a close relationship between PNA and DVI (760, 710) \((n = 114, R^2 = 0.94; \text{Fig. 2})\).

\[
PNA = 129.98 \times \text{DVI (760, 710)}^{1.5293} \tag{15}
\]

\[
\text{DVI (760,710)} = \frac{R_{760} - R_{710}}{R_{760}} \tag{16}
\]

where \(R_{760}\) and \(R_{710}\) are reflectance at 760 nm and 710 nm wave bands.

(3) Calculation of soil N supply after N dressing application

Soil N supply after N dressing (NS) could be calculated by Eq. (17).

\[
\text{NS} = \text{NS}_{\text{t}} \times K \tag{17}
\]

\[
\text{NS}_{\text{t}} = a \times \text{Yield}_{0} - b \tag{18}
\]

\[
K = c \times \text{Yield}_{0} - d \tag{19}
\]

where \(\text{NS}_{\text{t}}\) is the total soil N supply during the whole growth cycle, and could be calculated according to Eq. (18). \(K\) is the ratio of soil N supply before N dressing to \(\text{NS}_{\text{t}}\), \(\text{Yield}_{0}\) is the yield without N application, and \(a, b, c\) and \(d\) are the factors of soil type with values given in Table 3. Considering the reported data and the auxiliary field trials, the relationship between the \(\text{Yield}_{0}\) and \(K\) was determined (Eq. (19), Fig. 3) (Ling, 2000; Ling et al., 2005). In this study, the soil type was loam, then based on the values of \(a, b, c\) and \(d\) of loam soil in Table 3, and according to the Eq. (17) – (19), soil N supply after jointing was calculated as 66 kg ha\(^{-1}\).

(4) Calculation of NUE after N dressing

On the assumption that N dressing is appropriate, NUE after N dressing could be formulated with Eq. (20) – (23).

\[
\text{NUE} = \sum_{i=1}^{5} RW(i) \times F(i) \tag{20}
\]

\[
RW(i) = \frac{[1 - F(i)]^2}{\sum_{i=1}^{5} [1 - F(i)]} \tag{21}
\]

\[
\text{FAT} = \frac{0.5}{[0.5 + e^{(-x)}]} \tag{22}
\]

\[
\text{FBT} = \min(\frac{\text{FB}}{NRt}, 1) \tag{23}
\]

where \(RW(i)\) is the relative weight factor, described as Eq. (21). \(F(i)\) denotes N fertilizer type (FNT), N application mode (FAM), N application time (FAT), base-tiller N fertilizer rate (FBT), and rice type (FVT). FNT was set as 0.95, 0.9, 0.85, and 0.8 for controlled release fertilizer, ammonium sulfate, urea and ammonium bicarbonate, respectively (Fu, 2001; Zheng et al., 2001). FAM was set as 0.95, 0.9, and 0.85 for burying, sprinkling with water, and sprinkling without water, respectively. FAT could be formulated following Eq. (22), where \(x\) is the time of N dressing. FBT could be calculated according to Eq. (23),
where FB is the amount of base-tiller N dressing, FVT was set as 0.85, 0.90, 0.95 for conventional japonica, indica and hybrid rice, respectively (Zeng, 2006).

The model for calculating NUE during the mid to late growing stage was established using experimental data in 2007, 2008 and 2009. During the three years crops were dressed with N twice. For example, in 2008, FAT was 0.79, and FBT was 0.35 and 0.96 in two basal N treatments, respectively, urea was sprinkled over with water (FNT = 0.85, FAM = 0.9), the japonica rice was transplanted (FVT = 0.85), and RW was calculated according to Eq. (21), from which NUE from the mid to late growing stage was estimated as 0.45 and 0.74 after low and general base-tiller N dressing, respectively. In CSNOA, the predicted and measured values of NUE from the mid to late growing stage were similar at all base-tiller N dressing rates and there was no significant difference among rice cultivars (Table 4), indicating the good performance of the developed NUE model. However, in the methods of LAI and NFOA, the predicted NUE from the mid to late growing stage were higher than the measured values, because of higher N dressing rates. In the method of NFOA, the soil N supply was not considered, and as a result excess N dressing was used under both base-tiller N dressing levels, and the NUE was lower. Over all, the NUE model had a good performance when the N dressing rate was appropriate.

2. Calibration of parameters in different algorithms for recommending the N dressing rate

(1) Method based on leaf area index (LAI)

The LAI algorithm was modified for rice according to Chinese high-yield rice cultivation experience. In each N application method, LAI was estimated from the RVI (equation 10) based on the canopy reflectance spectra. If the LAI was above or below the optimum value, the N dressing rate was decreased or increased, and the increased rate was calculated as the product of LAI deficit factor and canopy N requirement (CNR) to produce each unit LAI. In this study, optimum LAI was set as that in SM, because the N dressing rate in SM had been proved to result in high yield in the last several years. CNR was determined from the relationship between N dressing rate and LAI. The whole procedure can be divided into several steps as follows.

i) Set target green leaf area index (GAIt). According to data from experiments 1 to 4, the GAIt at the booting stage for 9000 kg ha\(^{-1}\) grain yield target was set as 7.5.

ii) Estimate real-time GAIt(GAIt). According to data from experiments 1 to 4, the RVI (1100, 560) provided the best estimation of GAIt among several vegetation indices, and the relationship between GAIt and RVI \((n = 180, R^2 = 0.92; \text{Fig. 4})\) could be described by Eq. (24).
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\[ GAI_{rt} = 0.08 \times [RVI (1100, 560)]^2 - 0.07 \times RVI (1100, 560) + 0.48, \quad R^2 = 0.9215 \] (24)

iii) Set the canopy N requirement (CNR) for increasing one unit of GAI. According to data from experiment 1 to 4, the CNR for increasing unit GAI was 30 kg ha\(^{-1}\), which was consistent with previous studies with rice, wheat, and corn (Plénet and Lemaire, 1999; Lemaire et al., 2007; Xue and Yang, 2008).

iv) Determine the real-time N requirement (NR\(_{rt}\)) of the crop to reach the target GAI (GAI\(_{t}\)) from GAI\(_{rt}\) by Eq. (25).

\[ NR_{rt} = CNR \times (GAI_t - GAI_{rt}) \] (25)

v) Estimate the mineral N supply from soil after jointing (NS) by Eq. (17) to (19).

vi) Calculate the fertilizer N dressing rate of rice (DNF) by Eq. (26), in which NUE was set as 0.45 and 0.74 (Eq. (20) for the low and general base-tiller N dressinglevels, respectively.

\[ DNF = (NR_{rt} - NS) / NUE \] (26)

vii) The fertilizer N dressing was split into two equal parts, at the jointing and booting stages.

(2) Method of site-specific N management system (SSNM)

SSNM included two different approaches fixed-time adjustable-dose depending N management (FTNM) and real-time N management (RTNM). Peng et al. (1996) found that FTNM performed better than RTNM in China because the total N rate in FTNM was closer to the optimal level than RTNM. Thus, we chose FTNM for N application in this study. In this method, the timing and the number of N applications were fixed while the dose of each N application varied with the season and location based on the crop growth. According to the data from experiments 1 to 4, if SPAD\(_{rt}\) was greater than 45, between 43 and 45, and less than 43 both at the jointing and booting stages, the recommended N dressing rates were 40, 70 and 100 kg ha\(^{-1}\), respectively.

(3) Method based on nitrogen nutrition index (NNI)

In this method, the N dressing rate depended on NNI (Farruggia et al., 2004; Lemaire et al., 2007; Lemaire et al., 2008; Xue and Yang, 2008). If NNI < 1, the rate of N fertilizer dressing was increased, and if NNI > 1, the rate of N fertilizer dressing was reduced. According to the experimental data of 2008 (n = 12, \(R^2 = 0.91\), Fig. 5), the increased or reduced dressing rate of N fertilizer (\(\Delta\)DNF) was computed according to Eq. (27).

\[ \Delta DNF = 675.8 \times NNI - 699.3 \] (27)

The N fertilizer dressing rate (DNF) could be calculated with Eq. (28), in which DNF\(_{o}\) denotes the N fertilizer optimum N applied plot, and was set as 135 kg ha\(^{-1}\) according to the experiment data in 2008.

\[ DNF = DNF_{o} + \Delta DNF \] (28)

In this study, the NNI was determined by the ratio of DVI from the N applied plot (DVI\(_{fert}\)) and the optimum N applied plot (standard method, SM) (DVI\(_{ref}\)) (Eq. 29) (Farruggia et al., 2004; Lemaire et al., 2007), rather than from the chlorophyll meter reading.

\[ \text{NNI} = \frac{DVI_{fert}}{DVI_{ref}} \] (29)

(4) Nitrogen fertilization optimization algorithm (NFOA)

The NFOA method was modified for dressing fertilizer N requirement in rice with the following three steps:

i) Determine the N fertilizer dressing rate (DNF). DNF could be calculated by Eq. (30), where NUE could be calculated by Eq. (20), NR\(_{t}\) is total N demand calculated with Eq. (12), and PNA\(_{rt}\) is the real-time plant N accumulation calculated with Eq. (15).

\[ DNF = \frac{(NR_{t} - PNA_{rt})}{NUE} \] (30)

ii) Total N requirement (NR\(_{t}\)) is calculated by Eq. (12), where NR was set as 2.1, GYT is target grain yield which could be obtained at maturity.

iii) According to the data from experiments 1 to 4, GYT
is calculated by Eq. (31) (Fig. 6), where INSEY is the in-season estimated yield, which represents the plant N uptake per day (Lukina et al., 2001), and could be estimated according to Eq. (32), where DAT is the days from transplanting to PNA monitoring date.

\[
GYT (\text{kg ha}^{-1}) = 13456 \times \text{INSEY} + 3804.9 \quad (n = 120, R^2 = 0.71)
\]

\[
\text{INSEY} = \frac{\text{DVI (760, 710)}}{\text{DAT}} \quad (32)
\]

PNA could be calculated by Eq. (15).

3. Performance evaluation of five N dressing methods

Experiment 5 was carried out to evaluate the performance of five N dressing methods with different N dressing rates, in terms of the above-ground plant dry weight (PDW), PNA, grain yield, NUE, and economic benefit.

1) N dressing rates at jointing and booting stages in different dressing methods

In experiment 5, N dressing rates in different N dressing methods except SSNM, were calculated based on the canopy spectral reflectance measured at the panicle initiation stage (around 5 August), and N was equally applied at the jointing and booting stages (Table 2). The N dressing rates in the method of SSNM was calculated based on the SPAD measured at the panicle initiation stage (around 5 August) and booting (around 18 August), and N was applied at jointing and booting. At the jointing stage under the low base-tiller N dressing level (L), the N dressing rate was the lowest in CSNOA, and highest in NNI method, among the five N dressing methods and the order of N dressing rate was NNI > LAI = NFOA > SSNM > CSNOA > SM (Table 2). Under the general base-tiller N dressing level, the N dressing rate was the highest in NFOA, and the order of N dressing rate was NFOA = SM > LAI > NNI > SSNM > CSNOA. At booting under the low base-tiller N dressing level, the order of N dressing rate was the same as that at the jointing stage, while under the general base-tiller N dressing level, it was the highest in the SSNM algorithm, the order of N dressing rate was SSNM > NFOA = SM > LAI > NNI > SSNM > CSNOA. In addition, as Table 2 shows, under the low base-tiller N dressing level, the total N dressing rate was lower in CSNOA and SSNM than in

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Table 5. Plant dry weight (PDW), plant N accumulation (PNA), and N transportation efficiency (NTE) of different treatments at heading and maturity stages in 2009.

| Treatment* | PDW (t ha\(^{-1}\)) | PNA (kg ha\(^{-1}\)) | NTE (kg kg\(^{-1}\)) |
|------------|----------------------|----------------------|----------------------|
|            | Heading to maturity | Heading to maturity | Heading to maturity |
| 0N         | 8.6 d                | 12.5 d               | 3.6 d               |
| CSNOA(L)   | 12.3 c               | 18.6 bc              | 6.3 a               |
| LAI(L)     | 12.7 bc              | 18.9 b               | 6.3 a               |
| SSNM(L)    | 12.4 c               | 18.6 bc              | 6.2 a               |
| NNI(L)     | 13.2 b               | 19.1 ab              | 6.0 ab              |
| NFOA(L)    | 12.7 bc              | 19.0 b               | 6.3 a               |
| CSNOA(G)   | 12.5 c               | 18.4 c               | 6.0 ab              |
| LAI(G)     | 13.1 b               | 18.7 b               | 5.7 b               |
| SSNM(G)    | 13.0 b               | 18.7 b               | 5.7 b               |
| NNI(G)     | 12.8 bc              | 18.6 bc              | 5.8 b               |
| NFOA(G)    | 13.6 a               | 19.0 b               | 5.4 c               |
| SM         | 13.6 a               | 19.5 a               | 6.0 ab              |
| CV         | 10.46%               | 10.11%               | 12.83%              |

*0N: zero N treatment. SM: standard method. CSNOA, LAI, SSNM, NNI and NFOA denoted canopy spectrum based nitrogen optimization algorithm, leaf area index, site-specific N management, N nutrition index and N fertilizer optimization algorithm, respectively. (L): low basal N rate in which basal N rate was half of the SM. (G): general basal N rate in which basal N rate was same as the SM. CV: coefficient of variation. 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.
SM, and the total N dressing rate in the other methods were higher than in SM; under the general base-tiller N dressing level, the total N dressing rate in all N dressing methods was lower than in SM except in NFOA which was equal to that in SM.

(2)  Plant dry weight, plant N accumulation and N transportation efficiency at heading and maturity under different N dressing methods

At heading, under the low base-tiller N dressing level, the lowest and highest above-ground plant dry weight (PDW) were observed on the methods of CSNOA and NNI, respectively, and the nearly equal results were observed with the methods of LAI and NFOA. The PDW was SM > NNI > LAI = NFOA > SSNM > CSNOA. Under the general base-tiller N dressing level, PDW was heaviest in NFOA and lightest in CSNOA (Table 5). Among five N dressing methods and SM, the order of PDW was NFOA = SM > LAI > SSNM > NNI > CSNOA. At maturity there was a significant difference in PDW among the five N methods under both base-tiller N dressing levels (p < 0.05). Under the low base-tiller N dressing level, the order of PDW was SM > NNI > LAI > NFOA > SSNM = CSNOA, while under the general base-tiller N dressing level, the order of PDW was SM > NFOA > LAI > SSNM > NNI > CSNOA. PDW gain from heading to maturity was in the order of CSNOA = SSNM > SM > NNI = LAI > NFOA. In addition the PDW gain from heading to maturity was greater under the low base-tiller dressing level than under the general base-tiller N dressing level (Table 5).

The above-ground plant N accumulation (PNA) showed the same tendency as that of PDW at heading and maturity (Table 5). At heading, under the low base-tiller N dressing level, the order of PNA was SM > NNI > NFOA > LAI > SSNM > CSNOA, and under the general base-tiller N dressing level, it was NFOA = SM > LAI > SSNM > NNI > CSNOA. Under the low base-tiller N dressing level, the order of PNA was SM > NFOA > NNI > LAI > SSNM > CSNOA, and under the general base-tiller N dressing level, it was SM > NFOA > NNI = SSNM > LAI > CSNOA. Under the low base-tiller N dressing level, the order of PNA gain from heading to maturity was CSNOA > SSNM > SM > NFOA > LAI > NNI, and under the general base-tiller N dressing level, it was CSNOA > NNI > SM > SSNM > LAI > NFOA.

N transportation efficiency (NTE) (equation 6) showed significant differences with different N dressing methods. Under the low base-tiller N dressing level, the highest NTE were observed in NNI and lowest in CSNOA. The order of NTE was NNI > LAI > NFOA = SSNM > SM, under the general base-tiller N dressing level, NTE was highest in NFOA, and lowest in CSNOA and NNI (Table 5). The order of NTE was NFOA > LAI > SSNM > SM > NNI = CSNOA.

(3)  Grain yield under different N dressing methods

There were significant differences among five N dressing methods in panicle number, spikelet number, and the total N dressing rate in the other methods were higher than in SM; under the general base-tiller N dressing level, the total N dressing rate in all N dressing methods was lower than in SM except in NFOA which was equal to that in SM.
filled grain rate and 1000-grain weight, but not in grain yield (Table 6) under each base-tiller N dressing level. With increasing N dressing rate, the filled grain rate and 1000-grain weight declined and the panicle number increased, while the spikelet number showed no marked change.

Under the low base-tiller N dressing level, the order of panicle number was NNI > SM > LAI > NFOA > SSNM > CSNOA, while that of the filled grain rate was opposite. In the method of NNI, the filled grain rate was lower and 1000-grain weight lighter, though the panicle number increased, because of excessive N input during the late stage. Under the general base-tiller N dressing level, in CSNOA, the panicle number was smallest, the filled grain rate was highest and 1000-grain weight was the heaviest. In the methods of LAI and NFOA, the filled grain rate was low and 1000-grain weight was lighter. The order of panicle number was NFOA = SM > LAI > SSNM > NNI > CSNOA, and that of the filled grain rate was CSNOA > SSNM = NNI = LAI > NFOA > SM.

(4) Benefit analysis of different N dressing methods

AE, PFP, and RE all decreased with increasing N rates (Table 7) as reported in rice (Peng et al., 1996; Cui et al., 2000; Huang et al., 2007), which indicates that the rice plants were unable to absorb excess N at higher fertilizer N dressing rates, thus resulting in the N loss. AE indicates the capacity of increased yield per unit N rate, and varied between 11.7 kg kg⁻¹ and 20.1 kg kg⁻¹ depending on the N dressing method (Table 7). Under the low base-tiller N dressing level, the order of AE was CSNOA > SSNM > SM > LAI = NFOA > NNI. PFP, is the grain yield per unit applied N, and RE indicates the capacity of increased PNA per unit N dressing rate. These two indices were in the same order of CSNOA > SSNM > SM > NFOA > LAI > NNI. Under the general base-tiller N dressing level, the order of AE was CSNOA > NNI > LAI = SSNM > SM > NFOA, that of PFP was CSNOA > NNI > SSNM = LAI > SM > NFOA, and that of RE was CSNOA > NNI > SM > SSNM > LAI > NFOA, respectively. These results showed that AE, PFP, and RE showed a similar dependency to N dressing method under each base-tiller N dressing level, probably because they were homologous and directly related to N input.

PE was considered as the efficiency with which the plant used acquired N to produce grain or total plant dry matter. In general, PE was negatively associated with N dressing rate, GPE was similar to PE. Meanwhile, GPE and PE under the low base-tiller N dressing level were higher than those under the general base-tiller N dressing level. Furthermore, they were quite stable at a certain N dressing rate, while PE and GPE declined when superfluous N was applied, and postponed N application could improve PE and GPE.

The nitrogen harvest index (NHI) shows how efficiently the plant utilized acquired N for grain production, and it was significantly influenced by N dressing methods.

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**Table 7.** Agronomic efficiency (AE), partial factor productivity (PFP), recovery efficiency (RE), grain production efficiency (GPE), physiological efficiency (PE) and N harvest index (NHI) of different treatments in 2009.

| Treatment* | AE, kg kg⁻¹ | PFP, kg kg⁻¹ | RE, % | GPE, kg kg⁻¹ | PE, kg kg⁻¹ | NHI |
|------------|-------------|--------------|-------|--------------|-------------|-----|
| 0N         |             |              |       |              |             | 0.57c |
| CSNOA(L)   | 19.7 b      | 50.1 b       | 59.0 b| 48.0 a       | 33.4 a      | 0.67 a |
| LAI(L)     | 13.4 e      | 33.8 f       | 41.0 g| 47.3 a       | 32.7 b      | 0.66 a |
| SSNM(L)    | 15.7 d      | 39.8 e       | 48.0 f| 47.5 ab      | 33.0 ab     | 0.66 a |
| NNI(L)     | 11.7 f      | 29.6 g       | 36.7 h| 46.6 a       | 31.8 c      | 0.66 a |
| NFOA(L)    | 13.4 e      | 33.9 f       | 42.7 g| 46.2 bc      | 31.4 cd     | 0.64 ab|
| CSNOA(G)   | 20.1 a      | 51.2 a       | 63.9 a| 46.5 bc      | 31.6 c      | 0.65 a |
| LAI(G)     | 17.0 c      | 43.3 d       | 54.5 d| 46.3 bc      | 31.4 cd     | 0.65 a |
| SSNM(G)    | 17.0 c      | 43.3 d       | 55.2 cd| 45.9 bc      | 30.9 d      | 0.64 ab|
| NNI(G)     | 17.5 c      | 44.7 c       | 56.9 bc| 45.9 c      | 31.0 d      | 0.64 ab|
| NFOA(G)    | 15.4 d      | 39.3 e       | 51.3 e| 45.3 c      | 30.2 d      | 0.63 b |
| SM         | 15.5 d      | 39.4 e       | 56.6 cd| 42.7 d      | 27.5 e      | 0.60 bc|
| CV         | 16.19%      | 16.45%       | 16.35%| 3.03%       | 5.09%       | 4.45% |

*0N: zero N treatment. SM: standard method. CSNOA, LAI, SSNM, NNI and NFOA denoted canopy spectrum based nitrogen optimization algorithm, leaf area index, site-specific N management, N nutrition index and N fertilizer optimization algorithm, respectively. L: low basal N rate in which basal N rate was half of the SM. G: general basal N rate in which basal N rate was same as the SM. CV: coefficient of variation.

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.
Among five N dressing methods, NHI ranged from 63 to 67%, showing that about two-thirds of N stored in the plant was incorporated into grain. Increasing N dressing rate could increase plant N accumulation, while most of the increase in N was used to increase plant biomass and contributed little to N supply to the grain. Thus, NHI decreased with increasing N dressing rate.

The economic benefit of N fertilizer for the farmers depends on the AE and the quantity of N applied. The gross profit due to N fertilizer was calculated by the following equation:

\[
\text{Gross profit} = \text{Yield} \times \text{grain price} - \text{N Fertilizer price} \times \text{N dressing rate}
\] (33)

Average prices at the local market of rice grain, urea, KCl and monocalcium phosphate were 0.26, 0.26, 0.63 and 0.06 $ kg\textsuperscript{-1}, respectively. The water, electricity, and pesticide costs were not considered because the cost was the same for all treatments. Furthermore, net profit values did not include the costs for soil sampling and sample analysis. The net benefit ranged from 1412 to 2573 $ ha\textsuperscript{-1} (Table 8). Under the low base-tiller N dressing level, the order of net benefit was CSNOA > SSNM > SM > LAI > NFOA > NNI, while under the general base-tiller N dressing level, the order was CSNOA > NNI > LAI > SSNM > SM > NFOA. Under the low base-tiller N dressing level, the order of yield cost ratio was CSNOA > SSNM > SM > LAI = NFOA > NNI, and under the general base-tiller N dressing level, it was CSNOA > NNI > LAI > SSNM > SM > NFOA. The highest yield cost ratio was 7.19 in CSNOA under the general base-tiller N dressing level, and the lowest was 5.84 for NNI under the low base-tiller N dressing level.

**Table 8. Economic benefits of different N treatments in 2009.**

| Treatment* | Cost of fertilizer, $ ha\textsuperscript{-1} | Return from grain, $ ha\textsuperscript{-1} | Net profit, $ ha\textsuperscript{-1} | Yield-cost ratio |
|------------|------------------------------------------|------------------------------------------|------------------------------------------|-----------------|
| 0N         | 265                                      | 1677                                     | 1412                                     | 6.33            |
| CSNOA(L)   | 386                                      | 2759                                     | 2373                                     | 7.15            |
| LAI(L)     | 445                                      | 2777                                     | 2332                                     | 6.24            |
| SSNM(L)    | 419                                      | 2782                                     | 2363                                     | 6.64            |
| NNI(L)     | 471                                      | 2751                                     | 2280                                     | 5.84            |
| NFOA(L)    | 445                                      | 2775                                     | 2330                                     | 6.24            |
| CSNOA(G)   | 383                                      | 2753                                     | 2370                                     | 7.19            |
| LAI(G)     | 405                                      | 2761                                     | 2356                                     | 6.82            |
| SSNM(G)    | 405                                      | 2753                                     | 2348                                     | 6.80            |
| NNI(G)     | 400                                      | 2766                                     | 2366                                     | 6.92            |
| NFOA(G)    | 419                                      | 2748                                     | 2329                                     | 6.56            |
| SM         | 419                                      | 2753                                     | 2334                                     | 6.57            |

*0N: zero N treatment. SM: standard method. CSNOA, LAI, SSNM, NNI and NFOA denoted canopy spectrum based nitrogen optimization algorithm, leaf area index, site-specific N management, N nutrition index and N fertilizer optimization algorithm, respectively. (L): low basal N rate in which basal N rate was half of the SM. (G): general basal N rate in which basal N rate was same as the SM.

**Discussion**

The optimum total N dressing rate for rice in the Tai’hu Lake region of China has been estimated at 225 – 270 kg ha\textsuperscript{-1} (Cui et al., 2000; Yan et al., 2005; Huang et al., 2007). However, in this study, the significant difference in rice grain yield was not observed under 8 – 23% reduction in total N dressing rate. Field experiments conducted in major rice-growing provinces in China also showed that similar or higher yields can be produced using N dressing rates below normal farmer-based levels (Peng et al., 2006). Grain yield and NUE were associated with total N dressing rate and the N application time. Ding et al. (2004) showed that 30 kg ha\textsuperscript{-1} could be reduced from the present base-tiller N dressing rate to 100 kg ha\textsuperscript{-1} in japonica and to 85 kg ha\textsuperscript{-1} in indica, maintaining normal grain yield. N dressing management for high yielding has been proved to be scientific and feasible (Liu et al., 2003; Wood et al., 2003; Peng et al., 2007; Tubana et al., 2008). In rice cultivation practice, there are large differences in the base-tiller N dressing rate with the farmer and with the region, so effective and precise N dressing during the mid-late stages under the different base-tiller N dressing levels is of great significance (Yan et al., 2005; Wu et al., 2007).

In this study, five top-N dressing methods were adopted under two different base-tiller N dressing levels to evaluate the performances of these methods. No significant difference was observed in grain yield and NHI with the N dressing method, while there were significant differences in yield components. Under the low base-tiller N dressing level, LAI, NNI, and NFOA methods prolonged the growth period, lowered the filled grain rate and reduced the
1000-grain weight compared with the other methods. In contrast, CSNOA reduced N loss, and panicle number, but significantly increased the filled grain rate and 1000-grain weight. In addition, under the general base-tiller N dressing level, there was no significant difference in the spike number among LAI, SSNM, and NNI methods, although CSNOA reduced the panicle number and spikelet number, and increased the filled grain rate and 1000-grain weight compared with the other methods. Thus the method of CSNOA still achieved high grain yield. Meanwhile, there were significant differences in AE, PFP, RE, GPE and PE. Under the low base-tiller N dressing level, AE, PFP, RE, GPE and PE were lowest in the LAI method (Table 7), and under the general base-tiller N dressing level, these efficiencies were lowest in NFOA. Compared with the SM, under both base-tiller N dressing levels, method of CSNOA and SSNM had higher AE, PFP, GPE and PE. In addition, with lower N input, under both base-tiller N dressing levels, method of CSNOA and SSNM generated higher net profit and yield-cost ratio with lower N input than the other methods. Under the general base-tiller N dressing level, the N dressing rate after panicle initiation was lower, and total N dressing rate was also lower than under the low base-tiller N dressing level, but the grain yield was similar, resulting in higher AE, PFP and RE, and lower GPE and PE. This may be because the plants under the low base-tiller N dressing level had lower biomass at the early stage, and in order to produce a similar yield, they required much more N dressing.

In the methods of LAI and NNI, the effects of base-tiller N dressing levels on target LAI, DVI and grain yield were not considered (Wood et al., 2003; Farruggia et al., 2004; Lemaire et al., 2007), so different performances were observed under different base-tiller N dressing levels. In the method of NFOA, N supply from soil after N dressing was not considered (Lukina et al., 2001; Tubana et al., 2008), and the relationship between actual grain yield and INSEY was not very good, thus poor performances were observed under both base-tiller N dressing levels. In the method of SSNM, all the SPAD values were measured, and different N dressing rates were set based on different SPAD values (Peng et al., 1996; Varvel et al., 2007), thus it performed well under both base-tiller N dressing levels. In addition, in this study, the recommended N dressing rates of 40, 70, and 100 kg ha\(^{-1}\) were based on the local standard method, and did not strictly comply with the entire process of SSNM, so the total N dressing rate was slightly higher than that in normally used SSNM method. Otherwise, the performance of SSNM could be better. Overall, the present method of CSNOA showed good performance with new algorithms of N supply from soil (NS) and NUE during mid-late stage, and using DVI to monitor PNA. Compared with the methods of LAI, SSNM, NNI, and NFOA, the CSNOA strengthened several aspects of the N dressing technology, such as calculating the N dressing rate by comprehensively considering the effects of target grain yield, soil fertility and crop N status, construction of the model for monitoring real-time PNA, development of algorithms for soil N supply and NUE at the mid-late growing stage in rice. However, due to the limited data, the models for calculating the NS and NUE were still needed to be improved. In addition, the experimental data used to evaluate the five N dressing methods were only from one year at one location with two base-tiller N dressing levels. These methods should be tested at different eco-sites and with more rice cultivars and base-tiller N dressing levels.

**Conclusions**

Based on the comprehensive consideration of target yield, the N supply from soil and NUE during the mid-late growing stage, and plant N accumulation, the CSNOA method for recommending the N dressing rate was developed. Further, using the data from different experiments under various N dressing rates with different cultivars, the parameters in five N dressing methods were calibrated. Comparisons of five N dressing methods with traditional N management approaches showed that LAI, NNI, and NFOA methods produced excessive N dressing rates, and declined NUE and economic benefit under the low base-tiller N dressing level. Under the general base-tiller N dressing level, all N dressing methods, except for NFOA, reduced N input and increased the economic benefit. Among the five N dressing methods, CSNOA and SSNM were two good techniques for N dressing in rice.

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