A Knowledge-Based Model for Nitrogen Management in Rice and Wheat

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Abstract : Excessive nitrogen fertilization results in low nitrogen-use efficiency. To improve nitrogen management for high yield and high nitrogen efficiency in rice and wheat, we developed a knowledge-based nitrogen fertilization model by integrating the quantitative relationship between N fertilization and yield target with respect to N supply and demand balance. The total amount of nitrogen and ratio of basal to top dressing nitrogen could be determined by this nitrogen fertilization model, and the desirable nitrogen fertilizer strategies could be made under the conditions of different climates, soil types and managements. Furthermore, the function of dynamic regulation of pre-designed N dressing rate could be determined by using the nitrogen fertilization model on the basis of actual growth status under a specific production system. The nitrogen fertilization model is evaluated using the data from field experiments of rice and wheat at Nanjing, and the results on crop growth pattern and N use showed that the grain yield and N recovery were markedly improved by the N fertilization plan given by the model. The nitrogen fertilization model can be used as guidance for quantifying N fertilization strategy in cereal crop production.

Key words : Grain yield, Nitrogen fertilization model, Nitrogen strategy, Rice, Wheat.

Nitrogen (N) fertilizer has contributed much to grain yield and quality in cereal crops since 1960s (Hossain et al., 2005). N fertilizer input is expected to be useful to increase yields of rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) to cope with the growing population. Recently, yields of rice and wheat have leveled off or even declined even with high N fertilization rate in China (Ministry of Agriculture, PRC, 2005), due to low N recovery efficiency (Peng et al., 2002; Alam et al., 2005), which leads to the risk of environmental contamination (Beaudoin et al., 2005).

Quantification of N fertilizer demand of crop is essential to improve N management in crop production. Many methods have been used to estimate N fertilizer demand of crop, but most of these methods lack accuracy or are complicated such as empirical soil tests, except for the method that is based on soil N balance (Hou and Chen, 2004). The estimation of N fertilizer demand of crop on the basis of soil N balance is quite useful (Montaner et al., 1997; Dobermann and Cassman, 2002; Wijnhoud et al., 2003), but the method relies on accurate estimation of key parameters, such as indigenous soil N supply and N recovery efficiency (Brown, 1978; Zhu, 1991; Huang, 1993; Lu, 1998; Russell et al., 2006).

Generally, improving N fertilizer management is the process to adjust N supply to meet crop demands, which requires quantification of N situations in the soil and crop during the growing season. Many methods based on *in situ* and laboratory estimations including chemical extraction (Walsh and Beaton,

1982), chlorophyll meter (Fox et al., 1994; Peng et al., 1996; Scharf et al., 2006) and remote sensing (Yoder and Pettigrew-Crosby, 1995; Boegh et al., 2002) have been developed to improve the accuracy of nitrogen diagnosis in soil and crops. For example, Shukla et al. (2004) and Alam et al. (2006) used leaf color chart (LCC) to monitor N status of rice and wheat to improve N fertilizer management. Dobermann et al. (2002) suggested that SPAD (Soil Plant Analysis Development) and LCC were useful tools in associating N fertilizer management with a suitable amount of N fertilizer. These studies showed promising results in increasing yield combined with high N recovery efficiency. However in these studies, the parameters for diagnosis of N status in crops are deduced from limited number of genotypes, and the N fertilizer regimes are adapted for local soil conditions, which limit the obtained N strategies to specific genotypes and regions. In addition, these methods have a high labor requirement.

Here we developed a nitrogen fertilization model to improve N fertilizer management in rice and wheat. The algorithms and parameters in this model are formulated on the basis of soil supply capacity and plant N demand in relation to desired yield and quality. Next, nitrogen fertilization model was evaluated in the field experiments for designing basal N rate and dressing amount according to the actual field conditions and crop growth status. This work will help to facilitate N fertilizer management during crop production by overcoming the weakness of traditional
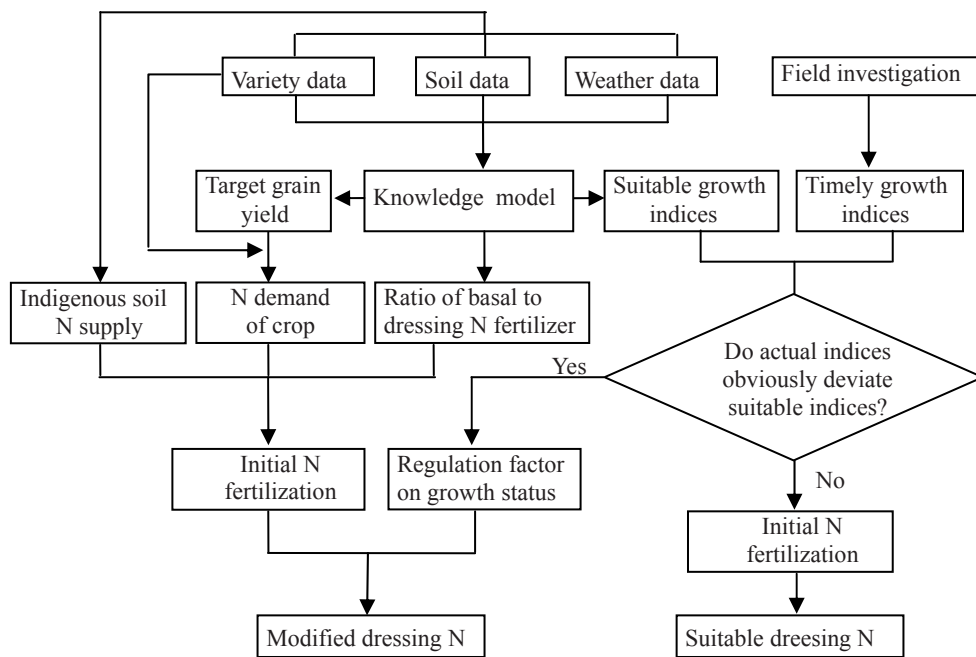
Fig. 1.   The structure of N fertilization model.

methods with poor quantification in production of rice and wheat.

Materials and Methods

1.   Data collection

Data used in the present study were collected from field experiments and literature (Wang et al., 2003; Ling et al., 2005; Ye et al., 2005; Zhu et al., 2005a; Li et al., 2006; Zhao and Yu, 2006). Data from literature were mainly used for model development, and a part of the data from literature and all data from field experiments were used for model evaluation.

Two field experiments (I and II) were carried out for model evaluation in this study.

Experiment I was conducted at Jiangning experiment station of Nanjing Agricultural University, China (118° 49´E, 32° 36´N) in 2006. Winter wheat Ningmai9 was grown at a density of 1.5×10^6 plants ha^{-1} on 8 November. The field was divided into two equal plots with 0.45 ha for each. One plot received the conventional N fertilizer strategy suggested by the expert as 270 kg N ha^{-1}, of which half was applied as basic fertilizer and the remaining as topdressing fertilizer at stem elongation. The other plot received the new N fertilizer strategy recommended by the model as 219.3 kg N ha^{-1}, of which 135 kg N ha^{-1} was applied as basic fertilizer and the remaining as topdressing fertilizer at stem elongation. In addition to N fertilization, 120 kg P$_2$O$_5$ ha^{-1} and 150 kg K$_2$O ha^{-1} were applied in both plots before sowing. The other managements followed local standard practice for high yield in wheat.

Experiment II was also conducted at Jiangning experiment station of Nanjing Agricultural University in 2006 and 2007. In the season of 2006, japonica rice cultivar 9915 was sown on 13 May, and transplanted on 18 June at a density of 2.67×10^5 plants ha^{-1}. The field was divided into two equal plots of 0.45 ha each. One plot received conventional N fertilizer rate of 300 kg N ha^{-1}, of which 40% before transplanting, 30% at stem elongation and 30% at booting. The other plot received the new N fertilizer strategy recommended by the model as 288.3 kg N ha^{-1}, of which 46% before transplanting, 33% at stem elongation and 21% at booting. In both plots, 135 kg P$_2$O$_5$ ha^{-1} and 203 kg K$_2$O ha^{-1} were applied before transplanting. The other managements followed local standard practices for high yield in rice. In the following season of 2007, the rice experiment was repeated, but with changed N fertilizer strategy recommended by the model as 277.5 kg N ha^{-1}, of which 45% before transplanting, 34% at stem elongation and 21% at booting.

In both experiments, plant growth data were collected at major growth stages. They were 2, 11, 20 and 29 April, 7 and 18 May, 1 June in 2007 in Experiment I; and in Experiment II they were 26 June, 8 and 18 July, 1, 13 and 23 August, 24 September, 13 October in 2006, and 25 June, 12, 16 and 24 July, 1, 12 and 23 August, 11 September, 9 October in 2007. Each time, tillers were counted in the field, and then 20 plants were randomly sampled from each treatment for determinations of leaf area and dry weight. Green leaf area was measured using the CI-203 Portable Laser Area Meter (CID Inc., Washington, USA) and leaf area index (LAI) was calculated. Dry weights of plant samples were determined after drying in oven

Table 1. The values of parameters used in the model.

Parameters	Values	
	Rice	Wheat
NDhym (kg)	2.2	3.2
α	0.4773	0.6841
β	0.50	0.32
GYmax (kg ha^{-1})	10500	9000
δ	–	0.7024
θ	–	0.1936
BNDhym (kg)	1.9	2.9
ϕ	0.37	0.52
γ	0.59	0.49

at 80°C for two days. Nitrogen contents of vegetative organs and grains were determined by the semi-micro Kjeldahl method.

2. Model description

Based on the framework of crop management knowledge model (Yan et al., 2006; Zhu et al., 2007), we developed a nitrogen fertilization model for N fertilizer management with the basic structure shown in Fig. 1.

(1) Crop management knowledge model

A basic crop management knowledge model was developed by integrating agricultural experts' knowledge and information from literature and historical experiment data collected by our group. The knowledge model quantifies the relationships of crop management plan and growth pattern to genotypes, ecological environments and production levels. The knowledge model of rice and wheat consisted of two major modules, driven by genotypic parameters, climatic factors, soil properties, and production levels. The cultural plan design module included target yield and quality calculation, variety selection, sowing date, plant density, fertilization and water management. The growth pattern design module included suitable growth indices at major stages, such as tiller number, leaf area index, and plant biomass. The crop management knowledge model provides basic output variables that are used in N fertilization model in this study, these variables are desirable yield target, total N rate, dynamics of tiller and leaf area index. A general description of the knowledge model can be seen in Zhu et al. (2007).

(2) N fertilization model

On the basis of N demand for yield target (ND, kg N ha^{-1}), indigenous soil N supply (ISN, kg N ha^{-1}) and N recovery efficiency (NRE, %), the total nitrogen application (TNA, kg N ha^{-1}) can be quantified by equation (1).

$$TNA = (ND-ISN)/NRE \tag{1}$$

where, the value of NRE is offered by users

according to local records and observations. In the present nitrogen fertilization model, NRE can be set as 40% in rice (Ling et al. 2005) and 50% in wheat for typical production systems in east China (Zhu et al., 2005b).

The ND is determined as:

$$ND = GYT \times NDh \tag{2}$$

where, GYT (kg ha^{-1}) is grain yield target provided by crop knowledge model, and NDh (kg) is N demand per 100 kg grain of crop. The NDh is calculated by the crop N demand per 100 kg grain under maximum grain yield (NDhym, kg) and the correction factors for grain yield (FY) and variety (FV) through Equation (3).

$$NDh = NDhym \times min(FY, 1)-FV \tag{3}$$

where, the value of NDhym is obtained from historical data under potential yield, and its values for rice and wheat are shown in Table 1. The min means that the minimum value between FY and 1 is adopted. FV is set as 0 and 0.2 for japonica and indica rice, respectively. In wheat, FY and FV are formulated following equations (4) and (5).

$$FY = \alpha \times \frac{GYT}{DYmax} + \beta \tag{4}$$

$$FV = \begin{cases} 0 & GPC \geq 14\% \\ \dfrac{1}{2} \times (\delta \times \dfrac{GYT}{DYmax} - \theta) & 11.5\% < GPC < 14\% \\ \delta \times \dfrac{GYT}{DYmax} - \theta & GPC \geq 11.5\% \end{cases} \tag{5}$$

In Eq. (4) and Eq. (5), GYmax (kg ha^{-1}) is the maximum grain yield and GPC (%) is grain protein content; and α, β, δ, θ are the model coefficients with values given in Table 1.

The ISN in Eq. (1) is determined by basic grain yield (BGY, kg ha^{-1}; as Eq. (7)) and crop N demand per 100 kg grain (BNDh, kg; as Eq. (8)) in the plot without external nitrogen fertilizer input:

$$ISN = BGY \times BNDh \tag{6}$$

$$BGY = BGYly \times SRFC \tag{7}$$

The grain yield in the plot without N fertilizer in previous year (BGYly, kg ha^{-1}) is modified by soil relative fertility coefficient (SRFC) through Eq. (7). The grain yields of rice and wheat crops are markedly related to soil organic matter, total N and alkali-hydrolyzable nitrogen (Gao et al., 2002; Duan et al., 2003; Gao et al., 2007), and these soil parameters determine SRFC.

$$BNDh = BNDhym \times min(FBY, 1) \tag{8}$$

$$FBY = \varphi \times \frac{BGY}{7500} + \gamma \tag{9}$$

where, BNDhm (kg) is crop N demand per 100 kg grain in the plot without N fertilizer under condition

of maximum grain yield (Table 1); the min means that the minimum value between FBY and 1 is used.; FBY is the factor of grain yield in the plot without N fertilizer; φ, γ are the coefficients in the model (Table 1).

According to the ratio of basic fertilizer to topdressing fertilizer obtained from crop knowledge model, averaging 1:1 as proposed by Zhu et al. (2007), the estimated total N fertilizer demand by crops is further distributed during the growing season to ensure the supply of N matching the demands of crops at the key growth stages.

Due to uncertain situations under a given season, such as weather and cultivation, crop growth performance may not be under a favorable status, as originally expected. Thus, it is necessary to adjust N fertilizer application on the basis of crop growth status, besides other possible regulation practices. A regulation factor (RF) is introduced for real-time N management and quantified with the following algorithm.

By comparing actual growth and nutrient indices (ADI) obtained from field investigation with suitable growth and nutrient indices (SDI) that are provided by the crop knowledge model, dynamic index difference ratio (DIDR) is calculated as:

$$DIDRi = (ADIi-SDIi)/SDIi$$
$$(i = STN, LAI, DMA, NC) \qquad (10)$$

where, STN (10000 ha^{-1}) is stem and tiller number; LAI is leaf area index; DMA (kg ha^{-1}) is dry matter accumulation; NC (%) is plant nitrogen content.

The maximal DIDR (DIDRmax) is identified among different DIDRs:

$$DIDRmax = max(|DIDRi|) \qquad (11)$$

In Eq. (11), when DIDRmax ≤ 10%, the N fertilizer is applied according to the initial plan, otherwise, the regulation of N fertilizer application happens.

The regulation factor of each index (RFi) changes with the crop growth progress. It is calculated by DIDRi and modified by phenological development regulation factor (PDRFi, as Eq. (13)~(14))

$$RFi = |DIDRi| \times PDRFi \qquad (i = STN, LAI, DMA, NC)$$
$$(12)$$
$$PDRFi = GDD/GDDh \qquad (i = STN) \qquad (13)$$
$$PDRFi = GDD/GDDm \qquad (i = LAI, DMA, NC) \qquad (14)$$

where, GDDh is the growing degree days till heading, GDDm is the growing degree days till maturity, GDD is the growing degree days till regulation, and these variables are estimated by crop knowledge model.

The regulation factor is obtained by:

$$RF = RFi/n \qquad (15)$$

where, n is the dynamic regulation index number, ranging from 1 to 4.

Based on the RF, total N rate (TNA) and ratio of basal to dressing fertilizer (BDR), the modified dressing N application (DNA) is formulated as:
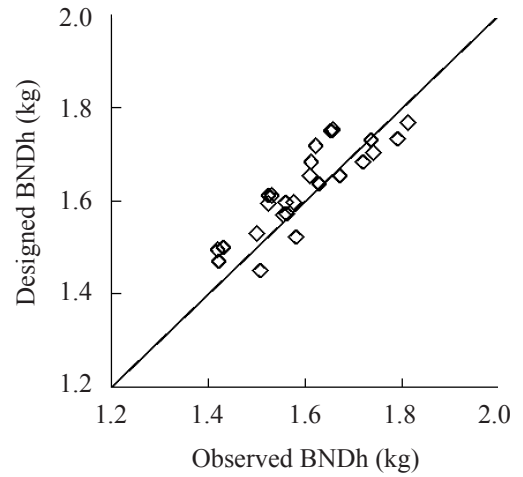

Fig. 2. Comparison between the designed and observed N demand per 100 kg grain in the plot without N fertilizer (BNDh) in rice.

$$DNA = \begin{cases} TNA \times BDR \times (1+RF) & DIDRi < -10\% \\ TNA \times BDR & -10\% \leq DIDRi \leq 10\% \\ TNA \times BDR \times (1-RF) & DiDRi > 10\% \end{cases}$$

$$(16)$$

3. Model evaluation

The values designed by the model were compared with the observed values to evaluate reliability and usefulness of the model under different cultural conditions. Normalized root mean square error (RMSE) was used to calculate the fitness between the designed and observed values (Rinaldi et al., 2003; Oyarzun et al., 2007; Soler et al., 2007):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(R_i - O_i)^2}{n}} \times \frac{100}{\overline{O}}$$

where, R_i and O_i are designed and observed values, respectively, and $\overline{O}$ is the mean of observed values. RMSE gives a measure (%) of relative difference between the designed versus observed data.

Results

Historical data from literature and our group were used to estimate N demand per 100 kg grain in the plot without N fertilizer (BNDh, kg) and N demand per 100 kg grain under different yield targets (NDh, kg) in this study. The observed BNDh values were plotted against the designed data for rice in Fig. 2. All the data points were close to the 1:1 line. The low RMSE of 3.70% indicates that the model gives good estimation of BNDh for rice. The observed values of NDh fit well with the designed NDh for rice under different levels of grain yield targets (Fig. 3) with the average RMSE of 2.46% for two rice cultivars. Similar
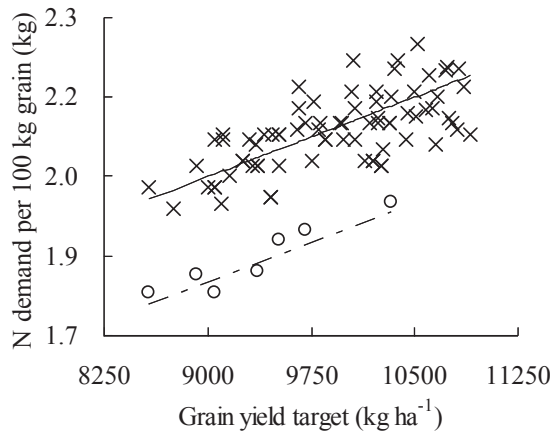
Fig. 3.   N demand per 100 kg grain versus grain yield target of observed and designed values in two types of rice. (×) Observed values and (—) designed values for japonica rice (○), Observed values and (—·—) designed values for indica rice.
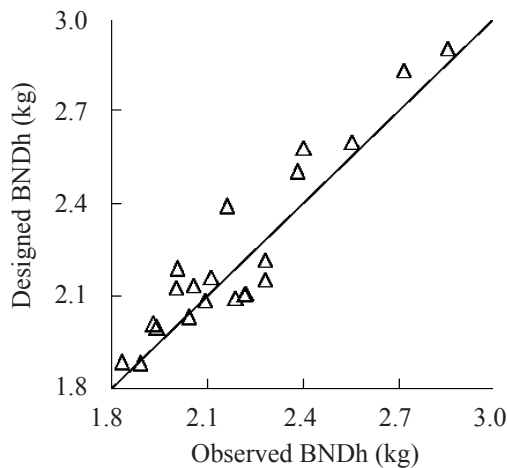

Fig. 4.   Comparison between the designed and observed N demand per 100 kg grain in the plot without N fertilizer (BNDh) in wheat.

to rice, the observed and designed BNDh for wheat are shown in Fig. 4 with low RMSE of 5.01%. Fig. 5 shows the observed and designed NDh for wheat under different levels of grain yield targets with the average RMSE of 5.95% for three wheat cultivars. The low RMSEs between the observed and designed values in different parameters of N demands suggest that the present model could give a satisfactory prediction of BNDh and NDh under different grain yields.

The nitrogen fertilization model was tested with the data from experiments I and II. The dynamics of tillers in rice under the N fertilizer treatment given by the model were compared with those by the expert in Fig. 6. With the nitrogen fertilization model, the tillers grew earlier after transplanting, tiller number was slightly lower before elongation but higher at booting,
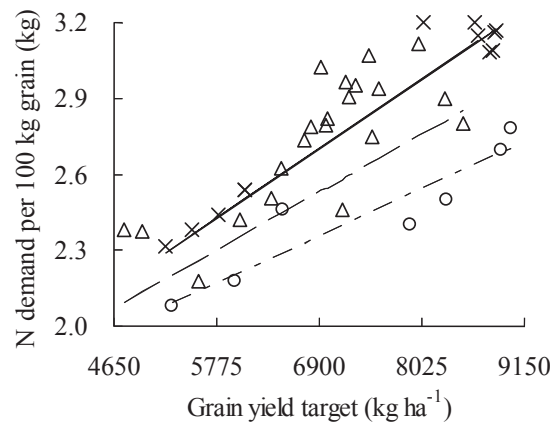

Fig. 5.   N demand per 100 kg grain versus grain yield target of observed and designed values in three types of wheat. (×) Observed values and (—) designed values of wheat with high gluten (protein) content, (△) observed values and (——) designed values in wheat with medium gluten (protein) content, (○) observed values and (—·—) designed values in wheat with low gluten (protein) content.
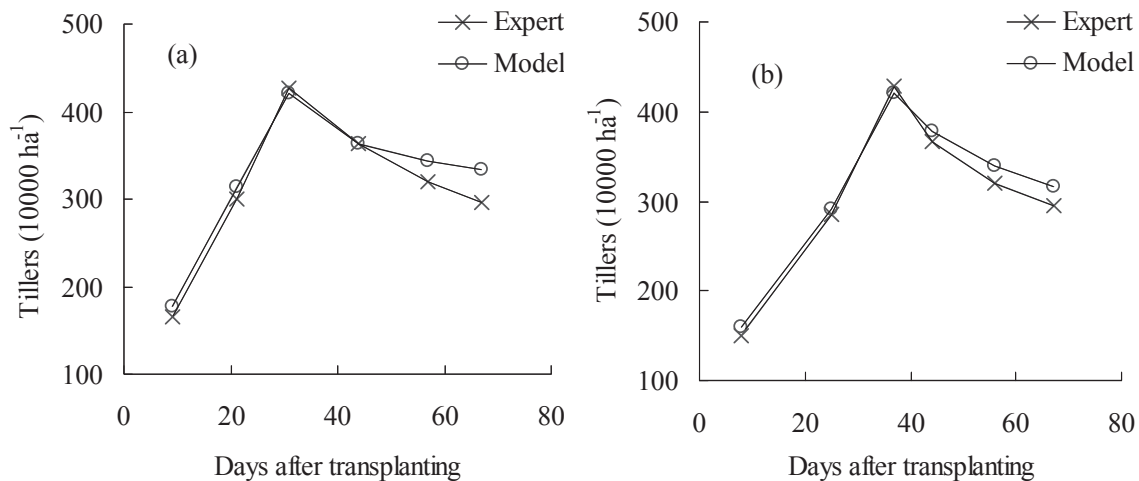

Fig. 6.   The dynamics of tiller numbers in rice under two N fertilization plans given by the model and expert at Nanjing in 2006 (a) and 2007 (b).
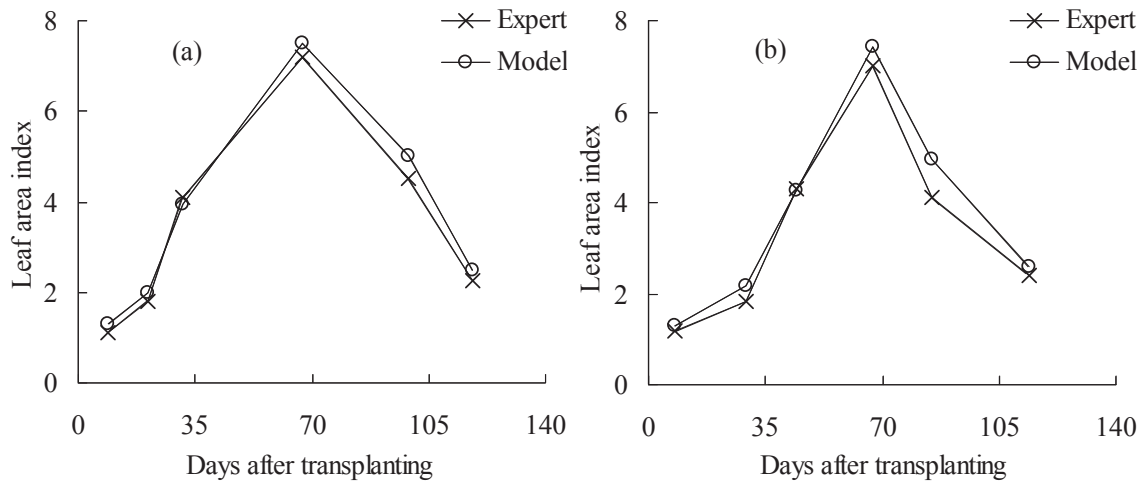
Fig. 7.   The dynamics of LAI in rice under two N fertilization plans given by the model and expert at Nanjing in 2006 (a) and 2007 (b).
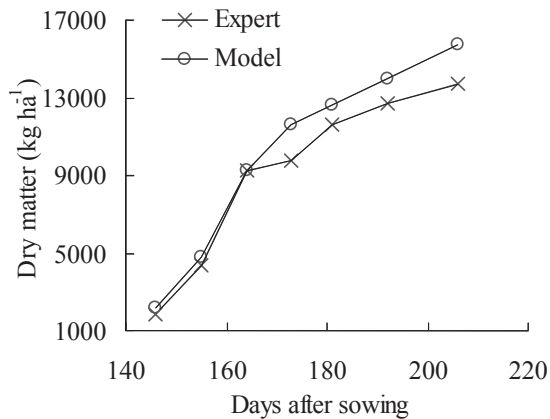

Fig. 8.   The dynamics of dry matter in wheat under two N fertilization plans given by the model and expert at Nanjing in 2006.
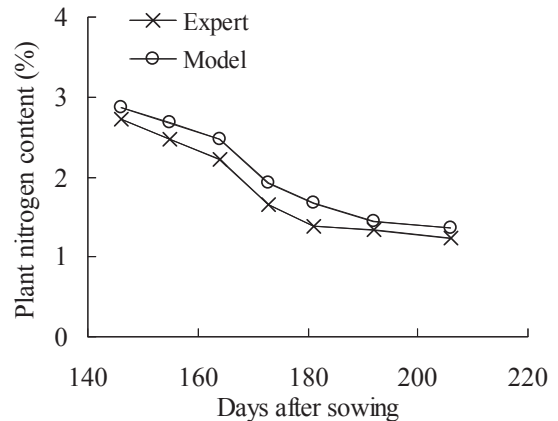

Fig. 9.   The dynamics of plant nitrogen content in wheat under two N fertilization plans given by the model and expert at Nanjing in 2006.

as compared to those with the expert. Generally, canopy LAI was greater under the model plan than under the expert plan (Fig. 7).

Fig. 8 shows the dynamics of dry matter accumulations for wheat under N fertilizer regimes given by the model and expert. The dry matter accumulation in the field under the model was higher than under the expert, averaging a 10.7% difference. In addition, the plant nitrogen concentration under N fertilizer regime designed by the model was 11.5% higher than those given by the expert (Fig. 9).

As shown in Table 2, the spike number, grain number per spike, 1000-grain weight and grain yield in rice under the model increased 4.14%, 0.72%, 0.78% and 5.72%, respectively, in 2006 and 4.87%, 0.83, 0.39 and 6.14% , respectively, in 2007. In wheat, the 1000-grain weight under the model decreased 3.74%, but the spike number and grain number per spike increased 3.16% and 7.29%, respectively, so the grain

yield also increased 6.68%.

The N recovery efficiencies (NRE, %) for rice and wheat under N fertilizer regimes given by both model and expert were listed in Table 2. The NRE was determined by the N application (kg N ha^{-1}), N uptake (kg N ha^{-1}) and indigenous soil N supply (ISN, kg N ha^{-1}). The indigenous soil N supply under two N fertilizer regimes was equivalent and the N uptake under the model was higher than that under the expert. Since the amount of N fertilizer applied under the model was less than that under the expert, the NRE in rice improved 19.31% in 2006 and 30.50% in 2007; in wheat NRE increased 51.24%.

Discussion and conclusions

Based on the framework of previous crop management knowledge models (Yan et al., 2006; Zhu et al., 2007), we developed a nitrogen fertilization model. The nitrogen fertilization model adopted soil

Table 2. Grain yields, yield components and N recovery efficiency of rice and wheat under two N fertilizer regimes given by the model and expert.

| | Rice | | | | Wheat | |
| | 2006 | | 2007 | | 2006 | |
	Expert	Model	Expert	Model	Expert	Model
Panicle (spike) number (10000 ha^{-1})	282.5	294.2	275.0	288.4	474.0	489.0
Grain number per panicle (spike)	125.8	126.7	132.0	133.1	42.5	45.6
1000-grain weight (g)	25.7	25.9	25.6	25.7	40.1	38.6
Grain yield (kg ha^{-1})	9133	9655	9293	9864	8085	8625
N application (kg N ha^{-1})	300.0	288.3	300.0	277.5	270.0	219.3
N uptake (kg N ha^{-1})	180.8	195.0	186.8	204.2	188.5	215.6
Indigenous soil N supply (kg N ha^{-1})	84.5	84.5	102.0	102.0	68.6	68.6
N recovery (%)	32.1	38.3	28.2	36.8	44.3	67.0

N balance and plant N uptake to determine the total N application rate and distribution ratio between basal and dressing fertilization. In the model components, rice and wheat varieties were classified according to yield and quality, which made the model parameters such as crop N demand per 100 kg grain (BNDh) easy to determine by the user. Yield target can be obtained from crop knowledge model or input by model users. The implemented nitrogen fertilization model can be used to design various nitrogen fertilizer strategies under different climates, soils types and production levels at different regions. In addition, the nitrogen fertilization model can be used to dynamically modify the amount of topdressing N fertilizer according to actual crop growth status, which improves the previous N fertilization methods (Ten Berge et al., 1997; Pathak et al., 2003; Schlegel et al., 2005).

The nitrogen fertilization model can give suitable diagnosis indices of crop growth by input of the local climatic factors, soil types and genotypic parameters, which made N fertilizer regulation generally applicable for different regions and genotypes, breaking through the previous methods' limitations on diagnosis indices and N recommendations for the specific region and variety (Rodrigues et al., 2005; Chen et al., 2006; Mengel et al., 2006). The actual growth and nutrient indices during crop growth can be obtained from destructive sampling, remote monitoring, and growth simulation. Thus, the nitrogen fertilization model can bridge the knowledge model and growth monitoring for realizing dynamic crop management, or link knowledge model to simulation model for developing digital and intelligent decision support system. The nitrogen fertilization model has also considered plant nitrogen content and grain quality index in wheat, which allows regulation of grain quality formation by proper dressing N fertilization.

The present nitrogen fertilization model was preliminarily evaluated using the field experiments conducted at Nanjing and it showed good applicability and guidance on production of rice and wheat. Overall, the nitrogen fertilization model avoids the deficiencies of regional limitation and empirical decision with traditional crop cultivation patterns and expert systems, and thus provides a promising quantitative tool for N fertilization management. Yet additional studies are needed to test the performance of the model under a wide range of production conditions, and improve the estimation of key parameters for model application.

Acknowledgements

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