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Calculation of theoretical nitrogen rate for simple nitrogen recommendations in intensive cropping systems: A case study on the North China Plain

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ABSTRACT

Nitrogen (N) is a crucial nutrient that requires careful management in intensive cropping systems because of its diverse beneficial and detrimental effects. Here we propose the concept of theoretical N rate (TNR) to answer the important question of how much fertilizer N should be applied to intensive systems based on the N fluxes due to transformation processes in the soil–crop–environment continuum. We define TNR as the theoretically calculated fertilizer N rate with the quantitative relationships of the core N fluxes among fertilizer N, soil N and crop uptake N in the crop root zone to obtain high target yield, maintain soil N balance and minimize environmental risk. We deduced one basic mathematical expression \( N_{\text{fert}} = N_{\text{uptake}} - N_{\text{straw}} + N_{\text{loss}} \) and two simplified expressions \( N_{\text{fert}} = (N_{\text{uptake}} - N_{\text{straw}})/(1 - \text{Coeff}); N_{\text{fert}} = N_{\text{uptake}} \) for calculating the TNR. These expressions do not need much field experimentation or elaborate soil and plant testing to obtain information on crop N demand and soil N supply, and are simple to implement in farming practice to provide a very cost-effective approach. We consider this scheme to be a useful contribution to rational fertilizer practice, especially in developing countries where other N recommendation systems are usually not available and agricultural extension services are poorly developed or absent.

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1. Introduction

Agricultural intensification plays an important role in producing enough food for an increasing world population and also in mitigating greenhouse gas emissions (Bumey et al., 2010). However, current intensive cropping systems with high-yielding plant varieties, excessive use of fertilizers and pesticides, and increased use of irrigation and mechanization are unsustainable in the long term (Matson et al., 1997; Tilman et al., 2002). Nitrogen especially needs to be managed with great care because of the detrimental effects of elevated fluxes of reactive nitrogen on ecosystems and environments (Matson et al., 1998; Galloway et al., 2008; Townsend and Howarth, 2010).

Despite many years of research effort there is still no accurate method available for determining how much fertilizer N can be applied to intensively managed cereal crops to obtain high target yields, maintain adequate soil fertility and minimize environmental risk (Zhu, 2006; Robertson and Vitousek, 2009). Generally, two categories of fertilizer N recommendation method are used worldwide (Defra, 2010). One is based on statistical calculations using yield response curves under different fertilizer N application rates with field experiments, and another is based on techniques using soil and plant analysis. In principle, these methods calculate an N application rate according to input–output relationships, with the soil–crop system regarded to some extent as a “black box”, resulting from our poor understanding of the complex N cycling processes occurring in soils. Methods based on yield response curves cannot explain the spatial and temporal variation found in practice (i.e. curves often obtained from former field trials and other sites) (Williams et al., 2007). Methods based on soil testing involve the problem of searching for a reliable testing index. So far no good practical index has been found to reflect the soil N supply in waterlogged rice fields (Zhu and Chen, 2002). Although the storage of nitrate in the soil profile of the crop root zone can be used as an index in upland cropping systems (Chen et al., 2006; Mengel et al., 2006; Cui et al., 2008a,b, 2010a,b), this also presents problems such as large spatial and temporal variation in soil nitrate and strong movement and large errors during sampling and measurement of soil nitrate. There is also the problem of converting the soil test data into a fertilizer N application rate. In this process a series of parameters need to be introduced and the uncertainty in selecting parameters often leads to an unrealistic calculated rate (Defra, 2010). All these problems restrict the practical application of these methods and lead either to substantial environmental pollution due to overuse of fertilizer N (Zhu et al., 2006) or to failure to reach the target yield due to inadequate N rate.
Another important issue is the financial cost of implementing these approaches in agricultural practice (Lobell, 2007) and they need considerable resources in the form of extensive field experiments over many years to obtain reliable information on the N requirements of crops and the N supply from the soil (Chen et al., 2006). These operations are too complex and expensive to apply in intensively managed cropping systems over the long term.

Here we propose for the first time a novel concept, the theoretical N rate (TNR), and derive its mathematical expressions to address this problem.

### 2. TNR and its mathematical expressions

We define TNR as the calculated theoretical fertilizer N rate based on the quantitative relationships among the N fluxes of N (Fig. 1), namely fertilizer N, soil N and crop N uptake. In fact, the N fluxes and losses in these three pools are the essential data required to determine the N application rate, crop yield and the environmental effects. Here we propose for the first time a novel concept, the theoretical N rate (TNR), and derive its mathematical expressions to address this problem.

By combining the above two expressions with expression (1), we can derive the basic mathematical expression of the TNR as follows:

\[ N_{\text{fert}} = N_{\text{uptake}} - N_{\text{soil}} - N_{\text{straw}} + N_{\text{fert3}} \]

(4)

As stated above, \( N_{\text{uptake}} \) and \( N_{\text{straw}} \) are easily obtained and their ranges of variation are relatively narrow for a specific crop at a specific site. Overall results of field experiments worldwide show that fertilizer N losses (\( N_{\text{fert3}} \)) can be reduced to relatively low values if the fertilizer N application rate is not extremely high and applications are made carefully together with other good crop management practices. In most cases, the inevitable N loss in wheat or maize can be controlled within the range 20–35% of fertilizer rate (Coefıcient of the loss rate) or even lower (Liu et al., 2003; Ladha et al., 2005; Zhao et al., 2006; Ju et al., 2007; Lobell, 2007; Ju et al., 2009; Cui et al., 2010a,b). Expression (4) can therefore be further simplified as follows:

\[ N_{\text{fert}} = \frac{N_{\text{uptake}} - N_{\text{straw}}}{1 - \text{Coef}} = \frac{N_{\text{uptake}} - N_{\text{straw}}}{0.65-0.80} \]

(5)

Expression (5) can be considered as a simple expression of the TNR. Certainly, the coefficient of the loss rate in expression (5) can be adjusted according to the local soil, climate, fertilizer application techniques and other management practices. But overall results of field experiments on the North China Plain showed that fertilizer N losses (\( N_{\text{fert3}} \)) were the narrow range if the fertilizer N application rate is rational, and the application techniques are not much changed.

According to the results of numerous field experiments using wheat and maize (Zhu et al., 2006, 2009; Cui et al., 2008a,b,c,d,e; Liu et al., 2010; Chen et al., 2010; Ju et al., 2010), the N uptake of wheat was around 45 kg N ha\(^{-1}\) at 6500 kg ha\(^{-1}\) of conventional yield level, and the N uptake of maize was around 75 kg N ha\(^{-1}\) at 8500 kg ha\(^{-1}\) of conventional yield level. If we use the regional mean optimal N (RMON) application rate of 150–180 kg N ha\(^{-1}\) for wheat and 170–190 kg N ha\(^{-1}\) for maize (Zhu et al., 2010), the inevitable loss rate of fertilizer N is 25% during the wheat growing season and 35% in the maize growing season (Liu et al., 2003; Zhao et al., 2006; Ju et al., 2009; Liu et al., 2010), the fertilizer N loss is 38–45 kg N ha\(^{-1}\) in wheat and 60–77 kg N ha\(^{-1}\) in maize. On the North China Plain maize usually has higher loss rate of N fertilizer than wheat because two surface top-dressings of urea are combined with irrigation or rainfall or shallow incorporation of urea at third leaf stage and tenth leaf stage altogether lead to high ammonia volatilization and nitrate leaching in the hot and wet summer maize season. In contrast, in the winter wheat season the basal N fertilizer before sowing is incorporated deep in the soil combined with ploughing and top-dressing combined with 40–60 mm irrigation at planting stage lead to low ammonia volatilization and nitrate leaching in the cold and dry winter wheat season (Ju et al., 2009).

Thus, we can conclude that \( n_{\text{fert3}} \equiv n_{\text{straw}} \) at moderate N application rate and fertilizer application techniques together with good
crop management. When introducing the above expression to expression (4), we can further simplify expression (4) as follows:

\[ N_{\text{fert}} \approx N_{\text{uptake}} \]  

This indicates that the TNR is approximately equal to the total aboveground N uptake. Expression (6) can be considered as another simple expression of the TNR. In practice, we can easily estimate the N fertilizer rate through \( N_{\text{uptake}} \) according to the target yield.

Expressions (4)–(6) above are progressively simpler and the associated parameters are smaller, with a corresponding slight decrease in accuracy. Users can select the most appropriate expression according to the parameters available and level of accuracy required. TNR does not require much soil or plant testing but can be calculated as accurately as local information will allow.

3. Examples of applying TNR

Maize grown on the North China Plain can be taken as an example to demonstrate how to use expressions (4)–(6) to calculate the TNR and how much discrepancy there is among them. If the target yield is set at a level of about 8500 kg ha\(^{-1}\) according to the local production conditions and the conversion coefficient is 2.23 kg of total aboveground N uptake per one hundred kilograms of grain yield based on numerous field experiments (Cui et al., 2008e; Liu et al., 2010; Chen et al., 2010), \( N_{\text{uptake}} \) is about 190 kg N ha\(^{-1}\). At this yield level the N content of the grain is around 1.35% (Cui et al., 2008e; Liu et al., 2010; Chen et al., 2010), thus \( N_{\text{grain}} \) will be about 115 kg N ha\(^{-1}\) and \( N_{\text{straw}} = N_{\text{grain}} - N_{\text{uptake}} = 75 \text{ kg N ha}^{-1} \).

As mentioned above, if the N fertilizer rate is not extreme and application is made carefully together with good crop management, N fertilizer loss rate (\( N_{\text{fert3}} \)) can be reduced to a relative low level. The N fertilizer loss rate is about 35% and \( N_{\text{fert3}} \) is about 67 kg N ha\(^{-1}\) in the maize season (Liu et al., 2003; Zhao et al., 2006, 2009; Ju et al., 2007, 2009; Liu et al., 2010,) on the North China Plain. In practice, the TNR can be calculated by the basic mathematical expression (4):

\[ N_{\text{fert}} = N_{\text{uptake}} - N_{\text{straw}} + N_{\text{fert3}} = 190 - 75 + 67 = 182 \text{ kg N ha}^{-1} \]

We can also calculate the TNR from the simple expression (5):

\[ N_{\text{fert}} = \frac{N_{\text{uptake}} - N_{\text{straw}}}{0.65} = \frac{190 - 75}{0.65} = 177 \text{ kg N ha}^{-1} \]

The TNR can also be estimated by the simple expression (6):

\[ N_{\text{fert}} \approx N_{\text{uptake}} \approx 190 \text{ kg N ha}^{-1} \]

The results show that the maximum discrepancy is within 13 kg N ha\(^{-1}\) among above three expressions. This uncertainty is quite acceptable in agricultural practice but may be more problematic from an environmental perspective.

The quantitative relationships among fertilizer N, soil N, crop N uptake, inevitable fertilizer N losses, and the N deposition back to the soil can be further illustrated using the N flux diagram (Fig. S1) for a 6500 kg ha\(^{-1}\) target yield of wheat according to our \( ^{15} \text{N} \) field experiment (Liu et al., 2003; Ladha et al., 2005; Ju et al., 2009). As Fig. S1 shows, \( N_{\text{uptake}} \) is 180 kg N ha\(^{-1}\) in order to reach the target yield. When the TNR is also 180 kg N ha\(^{-1}\), the N recovery rate and residual rate are 45% and 35%, respectively, and the N loss rate can be lowered to 20%. The losses include nearly 10% as ammonia volatilization, 10% as nitrate leaching, and a small amount as denitrification (Ju et al., 2009). In the total aboveground N uptake, 45% of \( N_{\text{uptake}} \) is derived from N fertilizer (81 kg N ha\(^{-1}\)) and 55% from the soil (99 kg N ha\(^{-1}\)). The soil N consumption can be replenished by the residual fertilizer N, the N in straw return and the deposition of N to maintain soil N balance. This shows that the simple TNR (\( N_{\text{fert}} \approx N_{\text{uptake}} \)) can reach the target yield, soil N balance, and controlled environmental risk simultaneously.

4. Validation of TNR using \( ^{15} \text{N} \) field experiment data

Published data from \( ^{15} \text{N} \) field experiments in wheat and maize conducted on the North China Plain since 2000 have been used to validate the calculation of TNR (Tables S1 and S2). We have analyzed the relationships under three scenarios: low, high and moderate levels of the N application rate. In general, the results have vindicated the rationale of expressions (1)–(6) when the N fertilizer rate was in the range of the RMON (Ju et al., 2009; Zhu et al., 2010).
Fig. 2. Relationships between fertilizer N uptake by crop (Nfert1), fertilizer N residual in the soil (Nfert2), fertilizer N losses (Nfert3) and N loss rate (percentage of Nfert3 divided by corresponding fertilizer N rate) with the fertilizer N rate in wheat (ABCD) and maize (EFGH) in 15N field experiments.

4.1. Relationships between Nfert1, Nfert2, and Nfert3 and fertilizer N rate

As the N fertilizer rate increases, the fertilizer N uptake (Nfert1) by wheat increases as a unitary quadratic equation ($R^2 = 0.7326$, $P<0.01$). Then $N_{fert1}$ reaches its maximum value when the N fertilizer rate is 340 kg N ha$^{-1}$ (Fig. 2A). Meanwhile, residual fertilizer N in the soil ($N_{fert2}$, Fig. 2B) and fertilizer N losses ($N_{fert3}$, Fig. 2C) increase linearly as the fertilizer N rate increases ($R^2 = 0.6570$, $P<0.01$; $R^2 = 0.7097$, $P<0.01$, respectively). According to the regression equations in Fig. 2A–C, $N_{fert1}$, $N_{fert2}$, and $N_{fert3}$ are 62–72, 47–57, and 46–59 kg N ha$^{-1}$, respectively, when the N fertilizer rate is in the range (150–180 kg N ha$^{-1}$) of the RMON (Ju et al., 2009). This quantitative relationship is illustrated in expression (1).

The loss rate of the fertilizer N generally increases linearly as the fertilizer N rate increases (Fig. 2D). Although this relationship is weak and $P>0.05$ ($R^2$) with the data collected from all field experiments in different sites, this relationship could exist in each experiment in the fixed site (Ju et al., 2007, 2009). The low N fertilizer rate stimulates crop uptake of soil N, and the high N fertilizer rate reduces crop uptake of soil N and substitutes with more N from applied fertilizer (Ju et al., 2007). The N uptake from the soil almost reaches the maximum value (around 175 kg N ha$^{-1}$) in wheat when the N fertilizer rate is in the range (150–180 kg N ha$^{-1}$) of the RMON, and the corresponding data are around 144 kg N ha$^{-1}$ in maize within the range of RMON (170–190 kg N ha$^{-1}$). Because the total aboveground N uptake ($N_{uptake}$) is generally higher in 15N field experiments (Tables S1 and S2) than that in field plot experiments, these $N_{soil}$ results are usually higher than those in practical field experiments.

4.2. Relationship between $N_{soil}$ and fertilizer N rate

As fertilizer N rate increases, N uptake from the soil ($N_{soil}$) increases initially and then decreases, following a unitary quadratic equation ($R^2$ values $P<0.05$ in wheat and $P>0.05$ in maize, Fig. 3A and B). Although this relationship is weak with the data collected from all field experiments in different sites, the relationship exists in each experiment in the fixed site (Ju et al., 2009). The low N fertilizer rate stimulates crop uptake of soil N, and the high N fertilizer rate reduces crop uptake of soil N and substitutes with more N from applied fertilizer (Ju et al., 2007). The N uptake from the soil almost reaches the maximum value (around 175 kg N ha$^{-1}$) in wheat when the N fertilizer rate is in the range (150–180 kg N ha$^{-1}$) of the RMON, and the corresponding data are around 144 kg N ha$^{-1}$ in maize within the range of RMON (170–190 kg N ha$^{-1}$). Because the total aboveground N uptake ($N_{uptake}$) is generally higher in 15N field experiments (Tables S1 and S2) than that in field plot experiments, these $N_{soil}$ results are usually higher than those in practical field experiments.

4.3. Replenishment of soil N consumption by $N_{fert2}$ and $N_{straw}$

From the 15N field experiment data on wheat (Fig. 4A), it can be seen that most of the data are in the range $N_{soil} < N_{fert2} + N_{straw}$ under the range of low fertilizer N rate (0–150 kg N ha$^{-1}$), indicating that soil N consumption cannot be replenished. However, under the range of high fertilizer N rates (>180 kg N ha$^{-1}$) the data are in the range $N_{soil} < N_{fert2} + N_{straw}$, indicating that soil N accumulates. $N_{soil}$ should be equal to the sum of $N_{fert2}$ and $N_{straw}$ when the N fertilizer rate is within the range (150–180 kg N ha$^{-1}$) of the RMON. However, there is a paucity of experimental data and more 15N field studies are required. Nevertheless, it can still be seen that most data are distributed uniformly on both sides of the 1:1 line from Fig. 4A when the fertilizer N rate is below 180 kg N ha$^{-1}$.

From the 15N field experiment data on maize (Fig. 4B), $N_{soil}$ and the sum of $N_{fert2}$ and $N_{straw}$ are distributed uniformly on both sides of the 1:1 line under the range of low fertilizer N rates (0–170 kg N ha$^{-1}$) or RMON (170–190 kg N ha$^{-1}$), indicating that soil N consumption can be replenished. This is because of the high N content in maize straw (Cui et al., 2008e; Chen et al., 2010). Under the range of high fertilizer N rates (>190 kg N ha$^{-1}$), the data
are in the range $N_{\text{soil}} < N_{\text{fert2}} + N_{\text{straw}}$, which indicates that soil N accumulates and increases the environmental risk.

In summary, crop N uptake from the soil can be replenished by residual fertilizer N and N from straw return under a moderate range of fertilizer N rates, which is an ideal situation and demonstrates the rationale of expression (3).

4.4. Relationship between $N_{\text{fert3}}$ and $N_{\text{straw}}$

From the $^{15}$N field experiments on wheat, it can be seen that most data of $N_{\text{fert3}}$ with $N_{\text{straw}}$ are distributed uniformly on both sides of the 1:1 line under the range of 95% confidence (Fig. 5A), which indicates that N from straw return is approximately equal to the fertilizer losses. Therefore, it is reasonable to estimate the TNR in wheat by using the simplified expression (6). From the $^{15}$N field experiments on maize (Fig. 5B), most data of $N_{\text{fert3}}$ with $N_{\text{straw}}$ are seldom distributed on both sides of the 1:1 line under the range of 95% confidence, due to the high N content in maize straw and more N returned in straw (Cui et al., 2008e; Chen et al., 2010). Therefore, the fertilizer N rate could reduced by 10–30 kg N ha$^{-1}$ when using expression (6) to estimate the fertilizer N rate under straw return to the maize field.

5. Comparing four approaches for determining fertilizer N rate

A three-year field experiment was conducted in Huantai county, Shandong province on the North China Plain to compare the fertilizer N rate, crop yield, nitrate accumulation and leaching among four approaches for determining the fertilizer N rate, i.e. the TNR using expression (6) with other three methods commonly used worldwide, namely soil nitrate testing (NIT) (Chen et al., 2006; Cui et al., 2008a,b, 2010b), balance calculation (BAL) and conventional rate used locally. Five treatments were devised and the methods for calculating fertilizer N rate shown in Table 1.

The soil NO$_3^-$-N testing method is based on synchronization of crop N demand and soil NO$_3^-$-N supply, and is considered to be a soil N supply index because of the large amounts of NO$_3^-$-N frequently found in the root zone in farmers’ N management prac-
Fig. 5. Relationship between fertilizer N losses ($N_{\text{fert3}}$) and N in straw return ($N_{\text{straw}}$) in wheat (A) and maize (B) in $^{15}$N field experiments.

Table 1
Treatments and methods for calculating fertilizer N rate. CK, control; TNR, theoretical N rate; BAL, balance calculation; NIT, soil nitrate testing; CON, conventional farming rate.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Methods for calculating fertilizer N rate</th>
<th>B:T</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK</td>
<td>No N application</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TNR</td>
<td>N uptake (160–180 kg N ha$^{-1}$) = N rate</td>
<td>1:1</td>
<td>Using expression (6) in this study</td>
</tr>
<tr>
<td>BAL&lt;sup&gt;a&lt;/sup&gt;</td>
<td>[Total aboveground N uptake (160–180 kg N ha$^{-1}$) + NO$_3$–N after harvest (80 kg N ha$^{-1}$) – NO$_3$–N before sowing] /0.7</td>
<td>1:1</td>
<td>Cui et al. (2008e); Meisinger (2008); Defra (2010)</td>
</tr>
<tr>
<td>NIT&lt;sup&gt;b&lt;/sup&gt;</td>
<td>B: 100 kg N ha$^{-1}$ – NO$_3$–N in 0–60 cm soil</td>
<td></td>
<td>Chen et al. (2006); Cui et al. (2008a,b); Cui et al. (2010b)</td>
</tr>
<tr>
<td>CON</td>
<td>T: 200/180 kg N ha$^{-1}$ – NO$_3$–N in 0–100 cm soil</td>
<td>260 kg N ha$^{-1}$</td>
<td>1:1</td>
</tr>
</tbody>
</table>

Note: B, basal fertilizer; T: topdressing fertilizer.
<sup>a</sup> In BAL method, NO$_3$–N is in the 0–100 cm soil depth, 0.7 is the fertilizer recovery rate.
<sup>b</sup> In NIT method, basal fertilizer is from sowing to shooting stage; topdressing fertilizer is from shooting to maturity stage; 200/180 is 200 kg N ha$^{-1}$ for wheat and 180 kg N ha$^{-1}$ for maize.

Table 2
Yield (kg ha$^{-1}$) and nitrate accumulation (kg N ha$^{-1}$) in the top 2 m of the soil profile with four approaches for determining fertilizer N rate in wheat. CK, control; TNR, theoretical N rate; BAL, balance calculation; NIT, soil nitrate testing; CON, conventional farming rate.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fertilizer N rate</th>
<th>Grain yield</th>
<th>Total aboveground N uptake</th>
<th>Nitrate in 0–100 cm soil</th>
<th>Nitrate in 100–200 cm soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>07/08 08/09 09/10</td>
<td>07/08 08/09 09/10</td>
<td>07/08 08/09 09/10</td>
<td>07/08 08/09 09/10</td>
<td>07/08 08/09 09/10</td>
</tr>
<tr>
<td>CK</td>
<td>0 0 0</td>
<td>5101.4b&lt;sup&gt;*&lt;/sup&gt; 4882.6c</td>
<td>2039.9a</td>
<td>96.3b 96.9c 54.4b</td>
<td>46.5c 18.0b 42.9c</td>
</tr>
<tr>
<td>TNR</td>
<td>160.0 180.0 160.0</td>
<td>6196.7a 6285.6b</td>
<td>5319.3b</td>
<td>143.9a 169.7b 157.9a</td>
<td>63.8bc 80.2ab 99.6b</td>
</tr>
<tr>
<td>BAL</td>
<td>255.4 131.1 190.4</td>
<td>6597.8a 6995.5ab</td>
<td>5293.2b</td>
<td>156.5a 192.9a 168.5a</td>
<td>150.0ab 72.7ab 100.4b</td>
</tr>
<tr>
<td>NIT</td>
<td>183.3 182.0 102.5</td>
<td>6559.6a 6877.3ab</td>
<td>5090.3b</td>
<td>161.9a 194.7a 146.2a</td>
<td>140.8ab 95.2ab 57.4bc</td>
</tr>
<tr>
<td>CON</td>
<td>260.0 260.0 260.0</td>
<td>6436.2a 7261.9a</td>
<td>5346.0b</td>
<td>151.9a 199.2a 159.6a</td>
<td>133.5a 107.4a 152.5a</td>
</tr>
</tbody>
</table>

<sup>*</sup> Different letters denote significant differences among treatments using least significant difference at the 5% level.
Table 3
Yield (kg ha⁻¹) and nitrate accumulation (kg N ha⁻¹) in the top 2 m of the soil profile with four approaches for determining fertilizer N rate in maize. CK, control; TNR, theoretical N rate; BAL, balance calculation; NIT, soil nitrate testing; CON, conventional farming rate.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fertilizer N rate</th>
<th>Grain yield</th>
<th>Total aboveground N uptake</th>
<th>Nitrate in 0–100 cm soil</th>
<th>Nitrate in 100–200 cm soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7012.7b</td>
<td>3863.0b</td>
</tr>
<tr>
<td>TNR</td>
<td>180.0</td>
<td>160.0</td>
<td>160.0</td>
<td>8557.2a</td>
<td>5972.0a</td>
</tr>
<tr>
<td>BAL</td>
<td>117.2</td>
<td>207.6</td>
<td>164.2</td>
<td>8483.1a</td>
<td>6049.2a</td>
</tr>
<tr>
<td>NIT</td>
<td>123.3</td>
<td>142.3</td>
<td>216.3</td>
<td>8806.1a</td>
<td>5836.1a</td>
</tr>
<tr>
<td>CON</td>
<td>260.0</td>
<td>260.0</td>
<td>260.0</td>
<td>9212.0a</td>
<td>5811.3a</td>
</tr>
</tbody>
</table>

*Different letters denote significant differences among treatments using least significant difference at the 5% level.

6. Relationship between EONR or MYNR and the corresponding N uptake

The rationale of the TNR using expression (6) was further tested by examining the published literature on wheat and maize field experiments since 2000 (Tables S3 and S4), and analyzing the relationship between the economic optimum N rate (EONR) or maximum yield N rate (MYNR) and the corresponding N uptake (Fig. 6). The results showed most EONR or MYNR data with their corresponding N uptake distributed on both sides of the 1:1 line within the 95% confidence limits. There is much variation in economic optimal N rate (EONR) or maximum yield N rate (MYNR) among different field experiments (Tables S3 and table** S4), which might be result from historic variation in N fertilizer rate in the individual fields. In the future, if the N application rate is moderate at all the sites, the variation will be lower and should be in a narrow range with the same crop in specific site.

7. Discussion

Information on soil N supply (available N or indigenous N) is not shown in expressions (4)–(6) because of the idea of maintaining soil N balance without depletion of indigenous N. Maintenance of soil N balance is very important in intensively managed systems for continued attainment of high target yields. If the soil N pools are greatly depleted in one season it is very difficult to achieve high target yields the following season (Cui et al., 2008a,f) and large amounts of fertilizer N may be required to compensate for such depletion (Zhao et al., 2006). Interaction between the soil N pool and applied fertilizer N is crucial to crop N supply because crops always take up soil N during growth. Soil N pools are a very important buffer to maintain sustainable N supply to crops because fertilizer N can only be applied at key crop growth stages. In addition, as Lobell (2007) said: “The lack of a consistent relationship between total soil N and available N and large temporal variations in available N, make it unclear whether utilization of indigenous N does in fact have an effect on future available N”. Indeed, efforts to estimate soil indigenous N have not been very helpful for accurate calculation of the fertilizer N rate in historic carefully managed fields in the long term. Success in estimating soil indigenous N for calculating fertilizer N rate has been only temporary and has been observed to be helpful only as a result of very high or very low fertilizer N supply for preceding crops (Zhao et al., 2006; Lobell, 2007).

Traditional methods of soil testing or determination of N balance have been based on calculation of fertilizer N rate by crop N demand minus soil indigenous N. None of these methods has addressed the question of how depleted soil N is replenished; in fact, it is replenished by residual fertilizer N and N retained in straw. When fertilizer N recovery rate was calculated, only the part removed by the crop was taken into account (Ladha et al., 2005), with no consideration of residual N in the soil. Residual fertilizer N is inevitable and also necessary, and is an efficient source of replenishment of soil N consumption but is subject to N transformation processes. In the current paper we explicitly propose the important view that residual fertilizer N should be regarded as replenishing soil N consumption, and the most important improvement in N management depends on how to minimize actual losses through fertilizer appli-
culation of fertilizer N rate depends largely on estimating the
ensure adequate yield.
ment practices as in many parts of Africa (Sanchez, 2002; Vitousek
might build up briefly and thereby increasing the fertilizer N rate
calculated by TNR to some extent to minimize environmental risk.
If the soil N fertility is poor and greatly depleted by historic manage-
might be transiently depleted, thus reducing the fertilizer N rate
deficient by historic manage-
ated by historic manage-
might be transiently depleted, thus reducing the fertilizer N rate
calculated by TNR to some extent to minimize environmental risk.
If the soil N fertility is poor and greatly depleted by historic manage-
care highly and there is much residual nitrate in the root
zation of target yield based on a crop model driven by observed meteor-
ology and using the typical relationship between grain yield and
N uptake to estimate the N uptake (Dobermann and Cassman, 2002;
Lobell et al., 2004; Lobell, 2007). Generally, the total aboveground
N uptake per one hundred kilograms grain yield will decrease with
increasing target yield. If we can establish the relationship between
the total aboveground N uptake per one hundred kilograms grain
yield and the target yield by collecting the field data in a specific region,
we can estimate this parameter more accurately. However, without
large changes in other production conditions (such as plant variety,
irrigation, management techniques etc.), in a specific region,
the target yield should not change markedly, and this parameter
will remain relatively stable. If the required resources are avail-
able, the above approaches will help greatly in the estimation of
the two most important parameters (the target yield and N uptake)
of the TNR.

Because crop growth is influenced by many factors such as cli-
imate, soil and management practices across locations and cropping
systems, it is not always possible to determine a very accurate
fertilizer N rate and some uncertainty must be accepted when
determining the fertilizer N rate. It may be regarded as acceptable
when the uncertainty range is within 15 kg N ha⁻¹ in intensively
managed systems. The actual fertilizer N rate should be within a
narrow range to avoid influencing the target yield while minimizing
the environmental risk. In fact, the aim of most N recommendation
systems developed worldwide is to control the recommendation rate
within this narrow range (Ladha et al., 2005; Lobell, 2007; Peng et al.,
2010). If the total amount of applied fertilizer N has been set
and the timing and technique of application are followed properly,
most of the practical problems for farmers’ fertilization will have
been solved. Proper timing and application techniques of fertilizer
N are important factors for efficient use of fertilizer N (Ladha et al.,
2005; Robertson and Vitousek, 2009; Defra, 2010; Peng et al., 2010).
Proper timing and method of application need to be followed after
calculation of the fertilizer N rate according to TNR.

Other N inputs such as manures or biological N fixation have
not been considered here. These N inputs should be deducted from
the N application rate of the chemical fertilizer. It is well known
that estimation of the N supply from manures or biological N fixa-
tion can also be complicated (Robertson and Vitousek, 2009; Zhao
et al., 2009; Defra, 2010). In most soil–crop systems there are addi-
tional N inputs such as air deposition, irrigation water, seed and
non-biological N fixation, but these are usually not important in
intensively managed systems (Ju et al., 2009).

The cropping system discussed is typical extensive irrigated
wheat or maize without other major sources of yield limitation
such as water supply. Although irrigated rice has not been included,
the results of numerous published studies would indicate that the
TNR approach would most likely be appropriate for this cropping
system also (Ladha et al., 2005; Lobell, 2007; Peng et al., 2010).

Regarding the important issue of costs, as Lobell (2007)
commented, “widespread adoption of technologies that reduce
uncertainty for N management will occur only if the reduction in
costs with lower N rates exceeds the cost of the technology itself”,
and costs of currently employed methods appear too high
for widespread adoption (Mengel et al., 2006). In this context,
we believe that the concept of the TNR and its mathematical
expressions can be a very cost-effective option and will be a very
useful driver of optimum N fertilizer application rates, especially in
developing countries where other N recommendation systems are
usually not available and agricultural extension services are poorly
developed or absent (Zhu and Chen, 2002; Vitousek et al., 2009; Ju
et al., 2009).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found,

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