Behavior of Nitrogen in Paddy Soils

By SigeKazu YAMAMURO*

Environment Division, Hokuriku National Agricultural Experiment Station
(Inada, Joetsu, Niigata, 943-01 Japan)

Research on the nitrogen cycle in paddy soils, which is composed of mineralization, assimilation, immobilization, volatilization, leaching, and absorption by rice plants of nitrogen applied and of soil nitrogen, as well as biological nitrogen fixation, is regarded to be important for the field management to maintain a long-term and stable productivity. The whole aspect of the nitrogen cycle in paddy soils is shown in Fig. 1. In the great majority of paddy soils, more than 99% of volatilization is caused by denitrification of N₂, while ammonium volatilization increases in quantity in alkali soils. The behavior of ammonium nitrogen which is applied to soils can be made clear by the use of fertilizer NH₄-¹⁵N. The behaviors are shown in Table 1. However, it is very difficult for soil scientists to determine quantitatively the amount of mineralization of organic soil-nitrogen and the transfer of the mineralized nitrogen to assimilation, immobilization, volatilization, leaching, and absorption by rice plants. Theoretical approach to this problem was attempted by the author. The results obtained are presented in this paper.

Mineralization from organic soil-nitrogen

The amount of mineralized soil nitrogen M₁ₙj during a period Tj (composed of successive times t₀, t₁, ..., tₙ) can be obtained theoretically by using the ¹⁵N tracer method. The method is as follows⁵: The whole amount of NH₄-N at the time tₙ is expressed as Nₙ; the amount of NH₄-¹⁴N (including natural ¹⁵N) at the time tₙ as ¹⁴N₀; which was ¹⁴N₀ at the time t₀, the tracer NH₄-¹⁵N at the time tᵢ as ¹⁵Nᵢ; which was ¹⁴N₀ at the time t₀; the amount of NH₄-N existing at the time tᵢ, which was continuously released from soil organic nitrogen in a period from t₀ to tᵢ as Nᵢ; NH₄-N, newly released in a period from tᵢ₋₁ to tᵢ as aᵢ; and the rate of decrease of each NH₄-N from the time tᵢ₋₁ to the time tᵢ as aᵢ. Then, aᵢ becomes aᵢ(1 - αᵢ₋₁) (1 - αᵢ₋₂) ... (1 - αᵢ₋ₙ), then we can write:

\[ Nᵢ = aᵢ + aᵢ₋₁(1 - αᵢ₋₁) + aᵢ₋₂(1 - αᵢ₋₂) + ... + aᵢ₋ₙ(1 - αᵢ₋ₙ) \]

where \( aᵢ \) is the rate at which NH₄-N is released from soil organic nitrogen at the time tᵢ, \( αᵢ \) is the rate at which NH₄-N is assimilated by rice plants at the time tᵢ, and \( αᵢ₋₁, αᵢ₋₂, ..., αᵢ₋ₙ \) are the rates at which NH₄-N is assimilated by rice plants at the times tᵢ₋₁, tᵢ₋₂, ..., tᵢ₋ₙ, respectively. The relations are shown in Table 2. Quantities of ¹⁵Nᵢ are related each other as follows:

\[ ¹⁵Nᵢ = ¹⁵Nᵢ₋₁(1 - αᵢ₋₁) + ¹⁵N₀(1 - αᵢ₋₁) \]

where \( ¹⁵N₀ \) is the amount of ¹⁵N existing at the time t₀, \( ¹⁵Nᵢ₋₁ \) is the amount of ¹⁵N at the time tᵢ₋₁. Therefore, the algebraic form of the normal equations for the case of n₁ independent variables can be written:

\[ aᵢ + aᵢ₋₁(1 - αᵢ₋₁) + ... + aᵢ₋ₙ(1 - αᵢ₋ₙ) = Nᵢ₋₁ - ¹⁴Nᵢ₋₁/¹⁴N₀ \]

\[ aᵢ + aᵢ₋₁(1 - αᵢ₋₁) + ... + aᵢ₋ₙ(1 - αᵢ₋ₙ) = Nᵢ₋₁ - ¹⁴Nᵢ₋₁/¹⁴N₀ \]

From the equation (1), the amount of nitrogen mineralization (Mᵢ) from soil organic nitrogen to

---

Present address:
*Soils and Crop Nutrition Division, Kyushu National Agricultural Experiment Station (Chikugo, Fukuoka, 833 Japan).
ammonia pool in the period of $T_j$, can be obtained by

$$M_{nj} = \sum_{i=1}^{n_j} a_{ji} = \sum_{i=1}^{n_j} (N_{ji} - \frac{^{15}N_{ji}}{^{15}N_{j0}}) / (\frac{^{15}N_{j0}}{^{15}N_{j0}} - 1)$$

If $n_j$ is large, re-mineralized nitrogen which passed through the process of assimilation and remineralization comes to be included in $M_{nj}$, so that the value of $^{15}N_j$ becomes larger than the expected one not including re-mineralization. The corrections for that can be done easily by using the $^{15}N$ tracers at each time of $T_j$. In the equation (2), if $a_{ji} = a$ (constant), and $a_{ji} = a$ (constant), an approximate value ($m_{nj}$) for $M_{nj}$, will be obtained from the following equation:

$$m_{nj} = n_j a = n_j \left( N_{j0} - \frac{(^{15}N_{j0})}{^{15}N_{j0}} \right)$$

The amounts of NH$_4$-N existed in soil and that of mineralized soil nitrogen observed in 2 types of paddy field are shown in Table 3. The semi-ill-drained field showed a greater amount of NH$_4$-N than the converted well drained field* in the vegetative period. But the latter showed a little

* Well-drained field converted from the semi-ill-drained field.
Table 1. Immobilization, denitrification, and absorption by rice plants of nitrogen applied\(^{(1)}\) to paddy soils,\(^{(2)}\) as revealed by the \(^{15}\)N tracer experiment

<table>
<thead>
<tr>
<th>Compost (t/10 a)</th>
<th>(I_{N_{j},F} (g/m^2)^{(1)})</th>
<th>(D_{N_{j},F} (g/m^2)^{(2)})</th>
<th>(P_{N_{j},F} (g/m^2)^{(3)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compost 0</td>
<td>1.16</td>
<td>1.81</td>
<td>1.01</td>
</tr>
<tr>
<td>Compost 1</td>
<td>1.46</td>
<td>1.69</td>
<td>0.84</td>
</tr>
<tr>
<td>Compost 2</td>
<td>1.45</td>
<td>1.56</td>
<td>0.71</td>
</tr>
<tr>
<td>Compost 3</td>
<td>1.22</td>
<td>2.15</td>
<td>0.63</td>
</tr>
<tr>
<td>Rice straw 0.6</td>
<td>2.33</td>
<td>1.34</td>
<td>0.32</td>
</tr>
<tr>
<td>Rice straw 1.2</td>
<td>2.89</td>
<td>1.11</td>
<td>0.05</td>
</tr>
<tr>
<td>Rice straw 1.8</td>
<td>3.14</td>
<td>0.83</td>
<td>0.04</td>
</tr>
</tbody>
</table>

(1) The amount of immobilization of applied fertilizer nitrogen. (2) The amount of denitrification of applied fertilizer nitrogen. (3) The amount of absorption by rice plant of applied fertilizer nitrogen. (4) Nitrogen applied at planting stage. (5) Tillering stage. (6) Panicle initiation stage. (7) 4 g N/m\(^2\) at each stage. (8) Well-drained.

Table 2. The amount of ammonium nitrogen existing at the time \(t_{j}\) and its changes

\[
\begin{align*}
&\text{Time (i = 0, 1, \ldots, n)} \\
&\text{Total amount of NH}_4\text{-}\text{N + NH}_3\text{-}\text{N at } t_{j} \\
&\text{Amount of NH}_4\text{-}\text{N started from } \text{N}_{j,00} \text{ at } t_{j,0} \\
&\text{Tracer NH}_3\text{-}\text{N applied at } t_{j,0} \\
&a_{j,1} (1-a_{j,1})(1-a_{j,2}) \ldots (1-a_{j,n}) \\
&a_{j,2} (1-a_{j,2})(1-a_{j,3}) \ldots (1-a_{j,n}) \\
&\ldots \\
&a_{j,n} (1-a_{j,n})(1-a_{j,1}) \ldots (1-a_{j,n-1}) \\
&\text{Amount of soil nitrogen mineralized in a period from the time } t_{j-1} \text{ to the time } t_{j}, \\
&\text{and its change after } t_{j}. \\
&\text{Total amount of mineralized soil nitrogen at } t_{j}. \\
&\text{Total amount of mineralized soil nitrogen at } t_{j}. \\
\end{align*}
\]
Table 3. The amount of NH$_3$-N existed in soil and mineralized soil nitrogen

<table>
<thead>
<tr>
<th>Stage $T_i$</th>
<th>Semi-ill-drained</th>
<th>Converted well-drained</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_m$</td>
<td>NH$_3$-N$^{(1)}$ (g/m$^2$)</td>
<td>$^{15}$N$_m$/$^{15}$N$_i$</td>
</tr>
<tr>
<td>May 18 – May 30</td>
<td>2.24</td>
<td>0.743</td>
</tr>
<tr>
<td>May 30 – June 8</td>
<td>2.57</td>
<td>0.670</td>
</tr>
<tr>
<td>June 8 – June 16</td>
<td>2.37</td>
<td>0.429</td>
</tr>
<tr>
<td>June 16 – June 22</td>
<td>2.07</td>
<td>0.408</td>
</tr>
<tr>
<td>June 22 – June 29</td>
<td>2.27</td>
<td>0.399</td>
</tr>
<tr>
<td>June 29 – July 6</td>
<td>2.40</td>
<td>0.342</td>
</tr>
<tr>
<td>July 6 – July 13</td>
<td>2.34</td>
<td>0.221</td>
</tr>
<tr>
<td>July 13 – July 20</td>
<td>1.57</td>
<td>0.105</td>
</tr>
<tr>
<td>July 20 – July 27</td>
<td>1.27</td>
<td>0.161</td>
</tr>
<tr>
<td>July 27 – Aug. 2</td>
<td>1.40</td>
<td>0.311</td>
</tr>
<tr>
<td>Aug. 2 – Aug. 9</td>
<td>1.70</td>
<td>0.325</td>
</tr>
<tr>
<td>Aug. 9 – Aug. 19</td>
<td>1.54</td>
<td>0.371</td>
</tr>
</tbody>
</table>

(1) At the time $t_m$, 1.40 in semi-ill-drained and 1.48 in converted well-drained field on Aug. 19.
(2) N(g/m$^2$)/day. (3) This is calculated as follows: $10 \times 0.1043 (1.40 - 0.371 \times 1.66)/0.6677; 0.1043 = 1 - \sqrt{0.371}; 1.66 = (1.54 + 0.185) - 0.325 \times 0.185, 0.185$ is the amount of tracer $\text{N}_i$ applied. $0.6677 = 1 - (\sqrt{0.371})^{(1)}$ as the equation (3) is changed $n_i (1 - n_i \sqrt{15N_i'/15N_i}) (15N_i - (15N_i'/15N_i')N_{np} / (1 - (n_i \sqrt{15N_i'/15N_i})))$.

more NH$_3$-N in the ripening period. The rate of mineralization from organic soil nitrogen increased with the advance of plant growth from the planting stage to the active tillering stage. The increased rate was kept nearly constant, though some fluctuations occurred, from the active tillering stage to the heading stage. Then it lowered rapidly. The total amount of nitrogen mineralized from organic soil nitrogen during the period from May 18 to August 19 was 21.5 g/m$^2$ in the semi-ill-drained field, and 24.2 g/m$^2$ in the converted well-drained field.

Transfer of mineralized soil nitrogen to assimilation, denitrification and absorption by rice plants

Denitrification of mineralized soil nitrogen was estimated by subtracting the amount of assimilated nitrogen and absorbed nitrogen by rice plants from the total amount of transferred nitrogen of soil, because losses of nitrogen caused by leaching to subsoil and volatilization in the form of NH$_3$ and NO$_2$ were negligible in the great majority of paddy fields. The amount of transferred mineral nitrogen, $G_{mnp}$, which consists of assimilation, denitrification and absorption by rice plants can be obtained as the amount of mineralized soil nitrogen $M_{mnp}$ minus the amount of transition of NH$_3$-N from mineralized soil nitrogen in a $T_i$ time interval as shown obviously in Fig. 1. That is,

$$G_{mnp} = M_{mnp} - (\text{NH}_3-N_{mnp} - \text{NH}_3-N_{np})$$

When the amount of mineralized soil nitrogen $M_{mnp}$ is known, $G_{mnp}$ is calculated from the above mentioned formula, so that, an approximate value ($g_{mnp}$) of $G_{mnp}$ will be written as

$$g_{mnp} = m_{np} - (\text{NH}_3-N_{mnp} - \text{NH}_3-N_{np})$$

The amount of assimilation $A_{np}$, denitrification $D_{np}$, and absorption by rice plants $P_{np}$ can be shown by $G_{mnp} \times B_i$, where $B_i$ is a mean of ratios of
distribution of the tracer NH$_4$$^{+}$-$^{15}$N, applied uniformly into soil, to each of assimilation, denitrification and absorption by rice plants, i.e., $B_i = (B_{iA}, B_{iD}, B_{iP})$.

The amount of transfer from mineralized soil nitrogen is shown in Table 4. The total amount of nitrogen transferred from mineralized soil nitrogen was 22.4 g/m$^2$ in the semi-ill-drained field, and 24.7 g/m$^2$ in the converted well-drained field. The total amount of nitrogen assimilated in soil was 11.2 g/m$^2$ in the semi-ill-drained field and 11.3 g/m$^2$ in the converted well-drained field. The total amount of nitrogen denitrified was 5.59 g/m$^2$ in the semi-ill-drained field and 6.95 g/m$^2$ in the converted well-drained field. The total amount of nitrogen absorbed by rice plants was 5.52 g/m$^2$ in the semi-ill-drained field and 6.42 g/m$^2$ in the converted well-drained field.

When the value of $M_{nj}$ is unknown, the amount of transfer from mineralized soil nitrogen in the $T_j$ period can be obtained theoretically by using the $^{15}$N tracer method. The theory of this method is as follows: The whole growth stage of rice plants is divided into several short periods, and the time which constitutes each period, as follows: $T_1 (t_{11}, t_{12}, \ldots, t_{1n})$, $T_2 (t_{21}, t_{22}, \ldots, t_{2n})$, $T_j (t_{j1}, t_{j2}, \ldots, t_{jn})$, $T_n (t_{n1}, t_{n2}, \ldots, t_{nn})$, where $j = 1, 2, \ldots, n$; $i = 1, 2, \ldots, n_j$. When the mineralized soil nitrogen NH$_4$-$N$ existed at the time of $t_{ij}$ is expressed by NH$_4$-$N_{ij}$, and when a tracer NH$_4$$^{+}$-$^{15}$N$_{ij}$ is quite uniformly mixed with NH$_4$-$N_{ij}$ and absorbed on the soil particles, both NH$_4$-$N_{ij}$ and NH$_4$$^{+}$-$^{15}$N$_{ij}$ show the same movement except isotope effect. Therefore, when the ratios of assimilation, denitrification and absorption by rice plants to the transferred amount of a tracer NH$_4$$^{+}$-$^{15}$N are indicated by $b_{ijA}$ (a rate of assimilation at $t_{ij}$), $b_{ijD}$ (a rate of denitrification at $t_{ij}$) and $b_{ijP}$ (a rate of absorption by plant at $t_{ij}$) etc., and if the period $T_j$ is short enough, a nearly linear relationship may be established among each component of behavior of transferred nitrogen, i.e., $b_{1j} (b_{1jA}, b_{1jD}, b_{1jP}, \ldots), b_{2j}(b_{2jA}, b_{2jD}, b_{2jP}, \ldots), b_{nj}(b_{njA}, b_{njD}, b_{njP}, \ldots)$. Here, we can write the mean of each behavior as $B_j (B_{jA}, B_{jD}, B_{jP}, \ldots)$. Then, we define $B$

<table>
<thead>
<tr>
<th>Stage $T_j$, $t_{nj} - t_{nj}$</th>
<th>Semi-ill-drained</th>
<th>Converted well-drained</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_{nj}$ ($^{(1)}$)</td>
<td>$D_{nj}$ ($^{(2)}$)</td>
</tr>
<tr>
<td>May 18 – May 30</td>
<td>0.47</td>
<td>0.07</td>
</tr>
<tr>
<td>May 30 – June 8</td>
<td>0.39</td>
<td>0.14</td>
</tr>
<tr>
<td>June 8 – June 16</td>
<td>0.64</td>
<td>0.48</td>
</tr>
<tr>
<td>June 16 – June 22</td>
<td>0.71</td>
<td>0.72</td>
</tr>
<tr>
<td>June 22 – June 29</td>
<td>0.83$^{(4)}$</td>
<td>0.61$^{(4)}$</td>
</tr>
<tr>
<td>June 29 – July 6</td>
<td>1.06</td>
<td>0.68</td>
</tr>
<tr>
<td>July 6 – July 13</td>
<td>1.13</td>
<td>0.96</td>
</tr>
<tr>
<td>July 13 – July 20</td>
<td>1.67</td>
<td>0.68</td>
</tr>
<tr>
<td>July 20 – July 27</td>
<td>1.46</td>
<td>0.45</td>
</tr>
<tr>
<td>July 27 – Aug. 2</td>
<td>1.36</td>
<td>0.17</td>
</tr>
<tr>
<td>Aug. 2 – Aug. 9</td>
<td>1.00</td>
<td>0.31</td>
</tr>
<tr>
<td>Aug. 9 – Aug. 19</td>
<td>0.53</td>
<td>0.32</td>
</tr>
<tr>
<td>May 18 – Aug. 19</td>
<td>11.25</td>
<td>5.59</td>
</tr>
</tbody>
</table>

(1) Assimilation. (2) Denitrification. (3) Absorption by rice plants. (4) Transferred nitrogen from mineralized soil nitrogen. (5) From Table 3 and equation (4), $2.19 - (2.40 - 0.185 \times 0.408) - (2.27 - 0.185 \times 0.399) - 2.05$, $B_i = (0.405, 0.298, 0.298)$, so, $2.05 \times 0.405 - 0.83, 2.05 \times 0.298 - 0.61, 2.05 \times 0.298 - 0.61$ (6) Total amount of transferred nitrogen $G$, in equation (7).
as the matrix of behaviors, and $B_i, B_j, B_k, \ldots$ as the vectors of the component of behaviors in the stage of $T_1, T_2, \ldots, T_n$. We can write them as follows:

$$B_i = \begin{bmatrix} B_{1i} & B_{2i} & B_{3i} & \cdots & B_{ni} \end{bmatrix}, \quad B_j = \begin{bmatrix} B_{1j} & B_{2j} & B_{3j} & \cdots & B_{nj} \end{bmatrix}, \quad B_k = \begin{bmatrix} B_{1k} & B_{2k} & B_{3k} & \cdots & B_{nk} \end{bmatrix}, \quad \cdots$$

When the amount of assimilation, denitrification and absorption by rice plants originated from soil $EN_A$ in the period of $T_1$ is expressed as $A_{1,n}$, $D_{1,n}$ and $P_{1,n}$, respectively, they are given as follows:

$$A_{1,n} = B_{1i} \cdot D_{1,n} = B_{1D} \cdot G_{1,n},$$
$$P_{1,n} = B_{1P} \cdot G_{1,n} \quad \cdots \cdots \cdots \cdots (5)$$

When $1/B_{1R}$, $B_{1i}/B_{iR}$ and $B_{1D}/B_{DR}$ are replaced by $E_{1R}$, $E_{1i}$ and $E_{1D}$, the equation (5) can be written as follows:

$$G_{1,n} = E_{1P} \cdot P_{1,n}, \quad A_{1,n} = E_{1A} \cdot P_{1,n},$$
$$D_{1,n} = E_{1D} \cdot P_{1,n} \quad \cdots \cdots \cdots \cdots (6)$$

Therefore, by taking the total amount of transferred nitrogen, that of assimilated nitrogen, and that of denitrified nitrogen, during the entire growth period of rice plants as $G_S, A_S$, and $D_S$, respectively, the following equations are obtained:

$$G_S = E'_{1R} \cdot P_S \quad \cdots \cdots \cdots \cdots (7)$$
$$A_S = E'_{1A} \cdot P_S, \quad D_S = E'_{1D} \cdot P_S \quad \cdots \cdots \cdots \cdots (8)$$

where $E'_{1R} = (E_{1R}, E_{2R}, \ldots, E_{nR})$, $E'_{1A} = (E_{1A}, E_{2A}, \ldots, E_{nA})$, $E'_{1D} = (E_{1D}, E_{2D}, \ldots, E_{nD})$, $P_S = (P_{t_1, t_2, \ldots, t_n}, P_{t_1, t_2, \ldots, t_n})$

By replacing $B_i, B_j, B_k, \ldots$ by $b_{iR}, b_{iA}, b_{iD}, b_{iS}, \ldots$ at the adequate time $t_{iR}, t_{iA}, t_{iD}, t_{iS}, \ldots$, respectively, an approximate total amount of transferred soil nitrogen $G_S$ can be obtained as follows:

$$G_S = \left(\frac{e_{nR} + e_{nA}}{2}\right) \times P_{\text{trans}}, \quad \left(\frac{e_{nA} + e_{nP}}{2}\right) \times P_{\text{trans}} + \cdots (9)$$

where $P_{\text{trans}}$ is the amount of absorption by rice plants from soil nitrogen mineralized from the $t_{iR}$ time to the $t_{iA}$ time, and $e_{np} = 1/b_{nP}$.

If $E'_{1R} = E'_{2R} = \ldots = E'_{nR} = E_{1R}$ (constant) in the equation (7), it becomes $G_S = E_{1R} \sum_{i=1}^{n} P_{i,n} = P_S/B_{1P}$. This equation is just the same as the equation of Hunter et al.\(^2\) That is, the equation (7) is an expanded type of the equation introduced by Hunter.

### Mobilization and immobilization of assimilated soil nitrogen

The fate of NH$_4$-N incorporated into the whole top soil layer at the tillering stage is shown in Fig. 2, in which the immobilization part in the assimilated nitrogen can be determined as follows:\(^3\) It is reasonable to consider that the immobilization part of assimilated nitrogen corresponds to the undecomposed portion of dead bodies of microorganisms. When the time proceeds as $l_0, t_1, \ldots, l_n, t_n$, and when the mean atom % $^{15}$N of the NH$_4$-N existed in soil, and the rate of assimilation by microorganisms, during a period from the time $t_i$ to the time $t_{i+1}$ are expressed as $H_i$, and $\Delta A_i, \ldots$, respectively, the total amount of immobilization $I_i$ at the time $t_i$ can be written as

$$I_i = K_1 H_i \cdot \Delta A_1 + K_2 H_2 \cdot \Delta A_2 + \ldots + K_n H_n \cdot \Delta A_n \quad \cdots \cdots \cdots \cdots (10)$$

![Fig. 2. The fate of NH$_4$-N incorporated into the soil at the tillering stage](image-url)
Table 5. Transfer of mineralized soil nitrogen to assimilation (including mobilization and immobilization part of assimilated nitrogen), denitrification, and absorption by rice plant

<table>
<thead>
<tr>
<th>T</th>
<th>E_{r1}^{(1)}</th>
<th>M_{m1}^{(2)}</th>
<th>I_{m1}^{(3)}</th>
<th>A_{m1}^{(4)}</th>
<th>D_{m1}^{(5)}</th>
<th>P_{m1}</th>
<th>G_{m1}^{(6)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 20 ~ June 5</td>
<td>13.1</td>
<td>0.61</td>
<td>0.73</td>
<td>1.34</td>
<td>0.36</td>
<td>0.09</td>
<td>1.18</td>
</tr>
<tr>
<td>June 5 ~ June 18</td>
<td>3.8</td>
<td>0.56</td>
<td>0.97</td>
<td>1.53</td>
<td>0.65</td>
<td>0.55</td>
<td>2.07</td>
</tr>
<tr>
<td>June 18 ~ July 3</td>
<td>1.9</td>
<td>1.61</td>
<td>1.68</td>
<td>3.29</td>
<td>1.32</td>
<td>3.29</td>
<td>6.25</td>
</tr>
<tr>
<td>July 3 ~ July 16</td>
<td>1.5</td>
<td>0.74</td>
<td>0.59</td>
<td>1.33</td>
<td>0.60</td>
<td>2.41</td>
<td>3.62</td>
</tr>
<tr>
<td>July 16 ~ Aug. 6</td>
<td>1.5</td>
<td>0.06</td>
<td>0.06</td>
<td>0.12</td>
<td>0.06</td>
<td>0.22</td>
<td>0.33</td>
</tr>
<tr>
<td>May 20 ~ Aug. 6</td>
<td>2.1</td>
<td>3.58</td>
<td>4.03</td>
<td>7.61</td>
<td>2.93</td>
<td>6.56</td>
<td>13.5^{(7)}</td>
</tr>
</tbody>
</table>

(1) \( E_{r1} = 1/B_{r1} \), \( B_{r1} \) is the ratio of absorption by rice plant to the sum of \( I_{m1}, D_{m1}, \) and \( P_{m1} \). (2) The amount of mobilization part of assimilated N derived from mineralized soil nitrogen. (3) The amount of immobilization part. (4) Assimilation. (5) Denitrification. (6) The amount of transfer. (7) Total amount of transferred nitrogen after the overlapping in estimation was corrected by using \( G_{m1} \), in equation (12).

where \( K_1 \) is the constant value related with the ratio of the rate of immobilization to that of assimilation at the time \( t \). We can make an approximation with a following equation if the flora of microorganisms does not change within the short time.

\[
I_t = K_1 (H_1 \cdot \Delta A_1 + H_2 \cdot \Delta A_2 + \ldots + H_n \cdot \Delta A_n)
\]

(11)

From the equation (6), the rate of transfer \( \Delta G_{m1}/\Delta t \) from mineralized soil nitrogen is changed to \( E_{r1} \Delta P_{m1} / \Delta t \). However, since the overlapping of the amount of the mineralized nitrogen caused by recycling of the same nitrogen, such as remineralization or repeated remineralization is not taken into account in the equation (7), the use of \( E_{r1} \) in place of \( E_{r1} \) can remove the overlapping. Where, \( E_{r1} = 1/B_{r1} \), and \( B_{r1} \) is the ratio of absorption by rice plants to the sum of immobilization, denitrification and absorption except \( NH_3-N \) existed and mobilization part of assimilation. When the total amount of nitrogen actually transferred from mineralized soil nitrogen without the overlapping, during the whole growth stage of rice plants is taken as \( G_{sc} \), it can be shown as follows:

\[
G_{sc} = E'_{r1} \cdot P_s ......... (12)
\]

where \( E'_{r1} = (E_{r1}, E_{r2}, \ldots, E_{rn}) \).

The amount of transfer from mineralized soil nitrogen to mobilization, immobilization, denitrification and absorption by rice plants is shown in Table 5.

#### Biological nitrogen fixation in paddy soils

The method of measuring biological nitrogen fixation by the use of \( ^{15}N \) tracer is as follows:

Water, in which air containing \( ^{15}N_2 \) is dissolved, was applied, and its atom % was successively measured at a given time interval. The same procedure was repeated by renewing the water containing \( ^{15}N_2 \). Finally, the amount of nitrogen fixed and assimilated was calculated from the mean value of atom % of \( ^{15}N \) in water and atom % of soil nitrogen. After about a month, atom % of soil nitrogen is measured and the amount of nitrogen fixed and immobilized was calculated. To carry out this tracer method, it is necessary to master the techniques to prepare the water in which air containing \( ^{15}N_2 \) is dissolved and to pro-
Table 6. The amount of biological nitrogen fixation in paddy soils

<table>
<thead>
<tr>
<th>Duration of the $^{15}\text{N}$-water application</th>
<th>Soil depth (cm)</th>
<th>Semi-ill-drained</th>
<th>Converted well-drained</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$^{15}\text{N}$ atom% of the soil nitrogen</td>
<td>Mean atom% of $^{15}\text{N}$ in the water</td>
</tr>
<tr>
<td>June 10 ~ 13</td>
<td>0 ~ 1</td>
<td>0.382</td>
<td>9.17</td>
</tr>
<tr>
<td></td>
<td>1 ~ 2</td>
<td>0.371</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2 ~ 4</td>
<td>0.366</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4 ~ 6</td>
<td>0.366</td>
<td>0</td>
</tr>
<tr>
<td>June 23 ~ 27</td>
<td>0 ~ 1</td>
<td>0.379</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>1 ~ 2</td>
<td>0.371</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2 ~ 4</td>
<td>0.366</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4 ~ 6</td>
<td>0.366</td>
<td>0</td>
</tr>
<tr>
<td>July 11 ~ 14</td>
<td>0 ~ 1</td>
<td>0.383</td>
<td>9.51</td>
</tr>
<tr>
<td></td>
<td>1 ~ 2</td>
<td>0.377</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2 ~ 4</td>
<td>0.373</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4 ~ 6</td>
<td>0.367</td>
<td>0</td>
</tr>
<tr>
<td>Aug. 9 ~ 13</td>
<td>0 ~ 1</td>
<td>0.386</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>1 ~ 2</td>
<td>0.378</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2 ~ 4</td>
<td>0.370</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4 ~ 6</td>
<td>0.366</td>
<td>0</td>
</tr>
</tbody>
</table>

(1) $^{15}\text{N}$ atom% in the water at the time of application was 22.6. The water was applied every 12 hr.

produce electric discharge tubes to be used for measuring $^{15}\text{N}$ concentration of the air dissolved in water.

The amount of biologically fixed nitrogen in paddy soils at each growth stage of rice plants is shown in Table 6. $^{15}\text{N}$ atom% of the water used was 22.6 immediately before the application. The water was applied every 12 hr. Mean atom% of the water used was 8.51 - 13.1 during the whole application period. On the other hand atom% of the soil nitrogen after a month from the application was also measured. The total amount of nitrogen fixed during the whole growing period was estimated at 2.1 g/m² in the semi-ill-drained field, and 1.2 g/m² in the converted well-drained field.

References


(Received for publication, September 20, 1985)