Behavior of Nitrogen in Paddy Soils

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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 N_2, while ammonium volatilization increases in quantity in alkari soils. The behavior of ammonium nitrogen which is applied to soils can be made clear by the use of fertilizer NH_4-^{15}N. The behaviors are shown in Table 1.[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 M_{jn_j} during a period T_j (composed of successive times t_{j0}, t_{ji},....., t_{jn_j}) can be obtained theoretically by using the ^{15}N tracer method. The method is as follows[2]: The whole amount of NH_4-N at the time t_{ji} is expressed as N_{ji}; the amount of NH_4-^{14}N (including natural ^{15}N) at the time t_{ji} as $^{14}N_{j0i}$, which was $^{14}N_{j00}$ at the time t_{j0}, the tracer NH_4-^{15}N at the time t_{ji} as $^{15}N_{ji}$, which was $^{15}N_{j0}$ at the time t_{j0}; the amount of NH_4-N existing at the time t_{ji}, which was continuously released from soil organic nitrogen in a period from t_{j0} to t_{ji} as N_{sji}; NH_4-N, newly released in a period from t_{ji-1} to t_{ji} as a_{ji}; and the rate of decrease of each NH_4-N from the time t_{ji-1} to the time t_{ji} as α_{ji}. Then, a_{ji} becomes $a_{ji}(1-\alpha_{ji+1})(1-\alpha_{ji+2})\,.....\,(1-\alpha_{jn_j})$ at the time t_{jn_j}. Then we can write

$$N_{sji} = a_{ji} + a_{ji-1}(1-\alpha_{ji}) + a_{ji-2}(1-\alpha_{ji-1})(1-\alpha_{ji}) + \dots + a_{ji}(1-\alpha_{j2})(1-\alpha_{j3})\dots(1-\alpha_{ji+2}).....$$

$$j = 1, 2,....., n\ ;\ i = 0, 1, 2,....., n_j.$$

These relations are shown in Table 2. Quantities of $^{15}N_{ji}$ are related each other as follows:

$$^{15}N_{jn_j} = {}^{15}N_{jn_j-1}(1-\alpha_{jn_j}) = {}^{15}N_{ji}(1-\alpha_{ji+1})(1-\alpha_{ji+2}).....(1-\alpha_{jn_j})$$

so that $\alpha_{ji} = 1 - (^{15}N_{ji}/^{15}N_{ji-1})$, and

$$N_{ji} = {}^{14}N_{j0i} + {}^{15}N_{ji} + N_{sji}$$

So we can write $N_{sji} = N_{ji} - (^{15}N_{ji}/^{15}N_{j0})N_{j0}$. Therefore, the algebraic form of the normal equations for the case of n_j independent variables can be written:

$$a_{jn_j} + a_{jn_j-1}(1-\alpha_{jn_j}) + \dots + a_{ji}(1-\alpha_{ji+1})(1-\alpha_{ji+2})\dots(1-\alpha_{jn_j}) + \dots + a_{j1}(1-\alpha_{j2})(1-\alpha_{j3})\dots(1-\alpha_{jn_j}) = N_{jn_j} - (^{15}N_{jn}/^{15}N_{j0})\,N_{j0}$$

$$a_{jn_j-1} + \dots\dots\dots + a_{ji}(1-\alpha_{ji+1})(1-\alpha_{ji+2})\dots(1-\alpha_{jn_j-1}) + \dots + a_{j1}(1-\alpha_{j2})(1-\alpha_{j3})\dots(1-\alpha_{jn_j-1}) = N_{jn_j-1} - (^{15}N_{jn_j-1}/^{15}N_{j0})\,N_{j0}$$

$$\dots\dots\dots\dots \quad (1)$$

$$a_{ji} + a_{ji-1}(1-\alpha_{ji}) + \dots\dots\dots + a_{j1}(1-\alpha_{j2})(1-\alpha_{j3})\dots(1-\alpha_{ji}) = N_{ji} - (^{15}N_{ji}/^{15}N_{j0})\,N_{j0}$$

$$\dots\dots\dots\dots$$

$$a_{j1} = N_{j1} - (^{15}N_{j1}/^{15}N_{j0})\,N_{j0}$$

From the equation (1), the amount of nitrogen mineralization (M_{jn_j}) from soil organic nitrogen to

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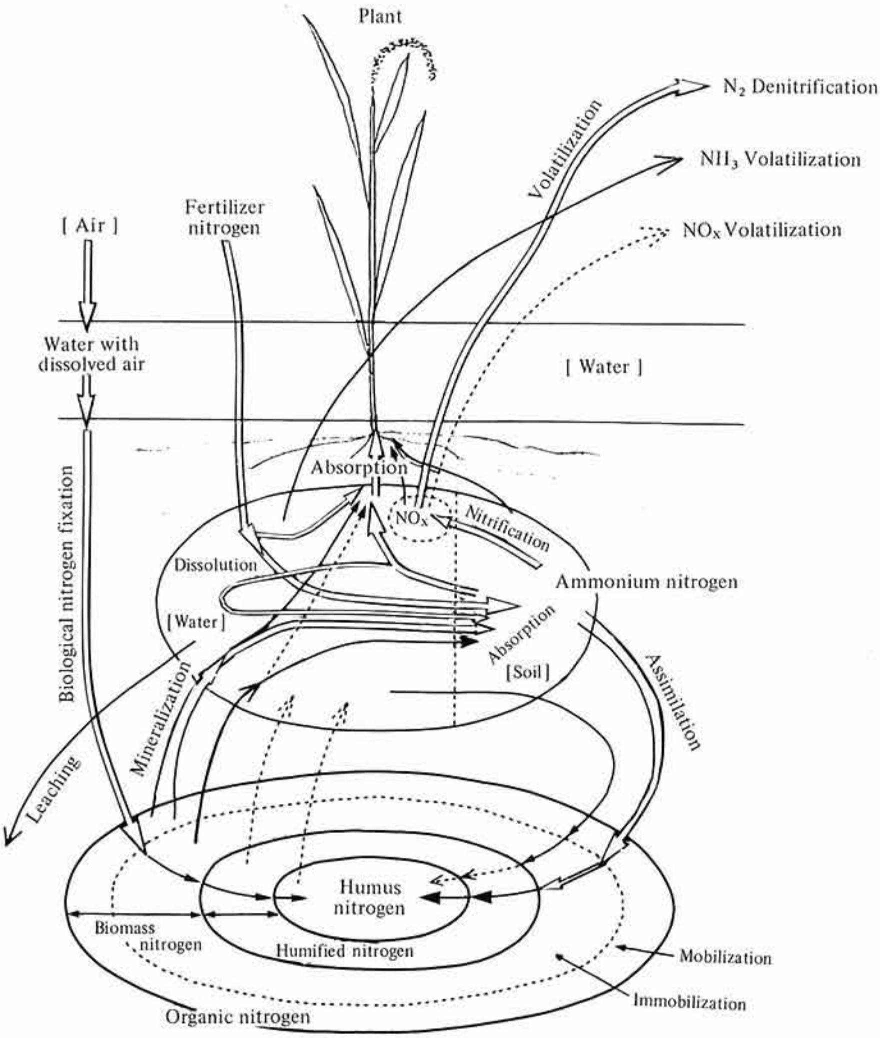

Fig. 1. Nitrogen cycle in paddy field

ammonia pool in the period of T_j, can be obtained by

$$M_{jn_j} = \sum_{i=1}^{n_j} a_{ji} = \sum_{i=1}^{n_j} (N_{ji} \cdot {}^{15}N_{ji-1} - N_{ji-1} \cdot {}^{15}N_{ji}) / {}^{15}N_{ji-1} \quad \cdots\cdots\cdots\cdots \quad (2)$$

If n_j is large, re-minelalized nitrogen which passed through the process of assimilation and remineralization comes to be included in M_{jn_j}, so that the value of ${}^{15}N_{ji}$ 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_{ji}. In the equation (2), if $a_{ji} = a$ (constant), and $\alpha_{ji} = \alpha$ (constant), an approximate value (m_{jn_j}) for M_{jn_j} will be obtained from the following equation:

$$m_{jn_j} = n_j\, a = n_j \{N_{jn_j} - ({}^{15}N_{jn}/{}^{15}N_{j0})\, N_{j0}\} / \sum_{i=1}^{n_j} \left(\sqrt[n_j-1]{{}^{15}N_{jn}/{}^{15}N_{j0}}\right)^{i-1} \quad \cdots\cdots\cdots\cdots \quad (3)$$

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.[2] 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[7] to paddy soils,[8] as revealed by the ^{15}N tracer experiment

Compost (t/10 a)	I_{jn_jF} (g/m^2)[1]			D_{jn_jF} (g/m^2)[2]			P_{jn_jF} (g/m^2)[3]		
	I[4]	II[5]	III[6]	I[4]	II[5]	III[6]	I[4]	II[5]	III[6]
Compost 0	1.16	0.82	0.86	1.83	1.81	0.56	1.01	1.37	2.58
Compost 1	1.46	0.67	0.78	1.71	1.69	0.58	0.84	1.64	2.64
Compost 2	1.45	0.73	0.80	1.84	1.56	0.51	0.71	1.72	2.70
Compost 3	1.22	0.96	0.67	2.15	1.80	0.72	0.63	1.24	2.61
Rice straw 0.6	2.33	1.42	0.97	1.34	1.67	0.89	0.32	0.90	2.14
Rice straw 1.2	2.89	1.49	1.08	1.11	2.09	1.16	0.05	0.42	1.76
Rice straw 1.8	3.14	1.72	1.21	0.83	2.05	2.47	0.04	0.24	0.32

(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_{ji} and its changes

t_{j0},	t_{j1},	...................,	t_{ji}, ...,	t_{jn_j}	Time (i = 0, 1, ..., n_j)
N_{j0},	N_{j1},	...................,	N_{ji}, ...,	N_{jn_j}	Total amount of NH_4-^{14}N + NH_4-^{15}N at t_{ji}
$^{14}N_{j00}$,	$^{14}N_{j01}$,	...................,	$^{14}N_{j0i}$, ...,	$^{14}N_{j0n_j}$	Amount of NH_4-^{14}N started from $^{14}N_{j00}$ at t_{j0}
$^{15}N_{j0}$,	$^{15}N_{j1}$,	...................,	$^{15}N_{ji}$, ...,	$^{15}N_{jn_j}$	Tracer NH_4-^{15}N applied at t_{j0}
	a_{j1},	.........., $a_{j1}(1-\alpha_{j2})(1-\alpha_{j3})$ ..... $(1-\alpha_{ji})$, ..., $a_{j1}(1-\alpha_{j2})(1-\alpha_{j3})$ ..... $(1-\alpha_{jn_j})$			
		a_{ji}, ..., $a_{ji}(1-\alpha_{ji+1})(1-\alpha_{ji+2})$ ..... $(1-\alpha_{jn_j})$			Amount of soil nitrogen mineralized in a period from the time t_{ji-1} to the time t_{ji}, and its change after t_{ji}.
				a_{jn_j}	
N_{sj0},	N_{sj1},	...............,	N_{sji}, ...,	N_{sjn_j}	Total amount of mineralized soil nitrogen at t_{ji}.
$=0$	$=a_{j1}$		$= a_{ji} + a_{ji-1}(1-\alpha_{ji}) +$ ..... $+ a_{j1}(1-\alpha_{j2})(1-\alpha_{j3})$ ..... $(1-\alpha_{ji})$	$= a_{jn_j} + a_{jn_j-1}(1-\alpha_{jn_j}) +$ ..... $+ a_{j1}(1-\alpha_{j2})(1-\alpha_{j3})$ ..... $(1-\alpha_{jn_j})$	

Table 3. The amount of NH_4-N existed in soil and mineralized soil nitrogen

Stage T_j $t_{j0} \sim t_{jn_j}$	Semi-ill-drained				Converted well-drained			
	NH_4-N(1) (g/m²)	$^{15}N_{jn_j}/^{15}N_{j0}$	m_{jn_j} (g/m²)	$\Delta m_{jn_j}/\Delta t$(2)	NH_4-N(1) (g/m²)	$^{15}N_{jn_j}/^{15}N_{j0}$	m_{jn_j} (g/m²)	$\Delta m_{jn_j}/\Delta t$(2)
May 18 ~ May 30	2.24	0.743	0.88	0.074	2.16	0.684	1.00	0.083
May 30 ~ June 8	2.57	0.670	0.74	0.083	2.44	0.656	1.52	0.168
June 8 ~ June 16	2.37	0.429	1.50	0.188	2.88	0.387	1.33	0.166
June 16 ~ June 22	2.07	0.408	2.06	0.344	2.01	0.346	2.04	0.341
June 22 ~ June 29	2.27	0.399	2.19	0.313	2.02	0.211	2.76	0.394
June 29 ~ July 6	2.40	0.342	2.37	0.339	1.90	0.227	3.03	0.433
July 6 ~ July 13	2.34	0.221	1.93	0.276	2.09	0.114	2.88	0.411
July 13 ~ July 20	1.57	0.105	2.57	0.368	1.50	0.096	2.86	0.409
July 20 ~ July 27	1.27	0.161	2.44	0.349	1.34	0.274	1.95	0.279
July 27 ~ Aug. 2	1.40	0.311	2.01	0.335	1.53	0.357	1.85	0.308
Aug. 2 ~ Aug. 9	1.70	0.325	1.55	0.221	1.96	0.429	1.42	0.203
Aug. 9 ~ Aug. 19	1.54	0.371	1.22(3)	0.122	1.83	0.289	1.58	0.158

(1) At the time t_{j0}, 1.40 in semi-ill-drained and 1.48 in converted well-drained field on Aug. 19. (2) N(g/m²)/day. (3) This is calculated as follows: $10 \times 0.1043\,(1.40 - 0.371 \times 1.66)/0.6677$; $0.1043 = 1 - \sqrt[9]{0.371}$, $1.66 = (1.54 + 0.185) - 0.325 \times 0.185$, 0.185 is the amount of tracer ^{15}N applied. $0.6677 = 1 - (\sqrt[9]{0.371})^{10}$ as the equation (3) is changed $n_j\,(1 - \sqrt[n_j-1]{^{15}N_{jn_j}/^{15}N_{j0}})\,\{N_{jn_j} - (^{15}N_{jn_j}/^{15}N_{j0})N_{j0}\}/\{(1 - (\sqrt[n_j-1]{^{15}N_{jn_j}/^{15}N_{j0}})^{n_j}\}$

more NH_4-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/m² in the semi-ill-drained field, and 24.2 g/m² 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_{jn_js}, which consists of assimilation, denitrification and absorption by rice plants can be obtained as the amount of mineralized soil nitrogen M_{jn_j} minus the amount of transition of NH_4-N from mineralized soil nitrogen in a T_j time interval as shown obviously in Fig. 1. That is,

$$G_{jn_js} = M_{jn_j} - (NH_4\text{-}N_{jn_js} - NH_4\text{-}N_{j0s})$$

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

$$g_{jn_js} = m_{jn_j} - (NH_4\text{-}N_{jn_js} - NH_4\text{-}N_{j0s}) \quad \ldots\ldots (4)$$

The amount of assimilation A_{jn_js}, denitrification D_{jn_js}, and absorption by rice plants P_{jn_js}can be shown by $G_{jn_js} \times B_j$, where B_j is a mean of ratios of

Table 4. Transfer from miniralized soil nitrogen to assimilation, denitrification and absorption by rice plants

Stage T_j $t_{j0} \sim t_{jn_j}$	Semi-ill-drained				Converted well-drained			
	A_{jn_js} (1)	D_{jn_js} (2)	P_{jn_js} (3)	G_{jn_js} (4)	A_{jn_js} (1)	D_{jn_js} (2)	P_{jn_js} (3)	G_{jn_js} (4)
May 18 ~ May 30	0.47	0.07	0.15	0.69	0.69	0.08	0.07	0.85
May 30 ~ June 8	0.39	0.14	0.40	0.94	0.53	0.10	0.44	1.07
June 8 ~ June 16	0.64	0.48	0.63	1.75	1.17	0.38	0.60	2.15
June 16 ~ June 22	0.71	0.72	0.42	1.86	1.07	0.53	0.42	2.02
June 22 ~ June 29	0.83(4)	0.61(5)	0.61(5)	2.05(5)	1.38	0.82	0.66	2.86
June 29 ~ July 6	1.06	0.68	0.68	2.42	1.15	0.98	0.71	2.85
July 6 ~ July 13	1.13	0.96	0.59	2.68	1.41	1.34	0.69	3.44
July 13 ~ July 20	1.67	0.68	0.50	2.85	1.27	1.11	0.64	3.02
July 20 ~ July 27	1.46	0.45	0.41	2.32	0.81	0.41	0.57	1.79
July 27 ~ Aug. 2	1.36	0.17	0.21	1.74	0.79	0.33	0.32	1.44
Aug. 2 ~ Aug. 9	1.00	0.31	0.40	1.71	0.55	0.42	0.59	1.56
Aug. 9 ~ Aug. 19	0.53	0.32	0.52	1.37	0.47	0.46	0.71	1.64
May 18 ~ Aug. 19	11.25	5.59	5.52	22.38(6)	11.29	6.95	6.42	24.69(6)

(1) Assimilation. (2) Denitrification. (3) Absorption by rice plants. (4) Transferred nitrogen from mineralized soil nitrogen. (5) From Table 3 and equation (4), $2.19 - \{(2.40 - 0.185 \times 0.408) - (2.27 - 0.185 \times 0.399)\} = 2.05$, $B_j = (0.405, 0.298, 0.298)$, 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_s in equation (7).

distribution of the tracer NH_4-^{15}N, applied uniformly into soil, to each of assimilation, denitrification and absorption by rice plants, i.e., $B_j = (B_{jA}, B_{jD}, B_{jP})$.

The amount of transfer from mineralized soil nitrogen is shown in Table 4.[1] 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. 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_{jn_j} 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.[3] 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 ($t_{11}, t_{12}, \ldots\ldots, t_{1i_1}, \ldots\ldots, t_{1n_1}$), T_2 ($t_{21}, t_{22}, \ldots\ldots, t_{2i_2}, \ldots\ldots, t_{2n_2}$), ..., T_j ($t_{j1}, t_{j2}, \ldots\ldots, t_{ji_j}, \ldots\ldots, t_{jn_j}$), ..., T_n ($t_{n1}, t_{n2}, \ldots\ldots, t_{ni_n}, \ldots\ldots, t_{nn_n}$), where $j = 1, 2, \ldots\ldots, n$: $i = 1, 2, \ldots\ldots, n_j$. When the mineralized soil nitrogen NH_4-N existed at the time of t_{ji_j} is expressed by NH_4-N_{ji_j}, and when a tracer NH_4-$^{15}N_{ji_j}$ is quite uniformly mixed with NH_4-N_{ji_j} and absorbed on the soil particles, both NH_4-N_{ji_j} and NH_4-$^{15}N_{ji_j}$ 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_{ji_jA} (a rate of assimilation at t_{ji_j}), b_{ji_jD} (a rate of denitrification at t_{ji_j}) and b_{ji_jP} (a rate of absorption by plant at t_{ji_j}) 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_{j1} (b_{j1A}, b_{j1D}, $b_{j1P}, \ldots$), ..., b_{ji_j}(b_{ji_jA}, b_{ji_jD}, $b_{ji_jP}, \ldots$), ..., b_{jn_j}(b_{jn_jA}, b_{jn_jD}, $b_{jn_jP}, \ldots$). Here, we can write the mean of each behavior as B_j (B_{jA}, B_{jD}, $B_{jP}, \ldots$). Then, we define **B** as the matrix of behaviors, and $\mathbf{B}_A$, $\mathbf{B}_D$, $\mathbf{B}_P$,... as the vectors of the component of behaviors in the stage of $T_1, T_2, \ldots, T_j, \ldots, T_n$. We can write them as follows:

$$\mathbf{B}=\begin{bmatrix} B_{1A} & B_{1D} & B_{1P} \\ B_{2A} & B_{2D} & B_{2P} \\ \vdots & \vdots & \vdots \\ B_{jA} & B_{jD} & B_{jP} \\ \vdots & \vdots & \vdots \\ B_{nA} & B_{nD} & B_{nP} \end{bmatrix} \quad \mathbf{B}_A=\begin{bmatrix} B_{1A} \\ B_{2A} \\ \vdots \\ B_{jA} \\ \vdots \\ B_{nA} \end{bmatrix}, \mathbf{B}_D=\begin{bmatrix} B_{1D} \\ B_{2D} \\ \vdots \\ B_{jD} \\ \vdots \\ B_{nD} \end{bmatrix}, \mathbf{B}_P=\begin{bmatrix} B_{1P} \\ B_{2P} \\ \vdots \\ B_{jP} \\ \vdots \\ B_{nP} \end{bmatrix}$$

When the amount of assimilation, denitrification and absorption by rice plants originated from soil NH_4-N in the period of T_j is expressed as A_{jn_js}, D_{jn_js} and P_{jn_js}, respectively, they are given as follows:

$$A_{jn_js} = B_{jA} \cdot G_{jn_js},\ D_{jn_js} = B_{jD} \cdot G_{jn_js},$$
$$P_{jn_js} = B_{jP} \cdot G_{jn_js} \ \ldots\ldots\ldots\ldots\ldots\ldots \ (5)$$

When $1/B_{jP}$, B_{jA}/B_{jP} and B_{jD}/B_{jP} are replaced by E_{jP}, E_{jA} and E_{jD}, the equation (5) can be written as follows:

$$G_{jn_js} = E_{jP} \cdot P_{jn_js},\ A_{jn_js} = E_{jA} \cdot P_{jn_js},$$
$$D_{jn_js} = E_{jD} \cdot P_{jn_js} \ \ldots\ldots\ldots\ldots\ldots\ldots \ (6)$$

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:

$$G_S = \mathbf{E}'_P \cdot \mathbf{P}_S \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (7)$$
$$A_S = \mathbf{E}'_A \cdot \mathbf{P}_S,\ D_S = \mathbf{E}'_D \cdot \mathbf{P}_S \ \ldots\ldots\ldots \ (8)$$

where $\mathbf{E}'_P = (E_{1P}, E_{2P}, \ldots, E_{jP}, \ldots, E_{nP})$, $\mathbf{E}'_A = (E_{1A}, E_{2A}, \ldots, E_{jA}, \ldots, E_{nA})$, $\mathbf{E}'_D = (E_{1D}, E_{2D}, \ldots, E_{jD}, \ldots, E_{nD})$, $\mathbf{P}_s = (P_{1n_1s}, P_{2n_2s}, \ldots, P_{jn_js}, \ldots, P_{nn_ns})'$

By replacing $B_1, B_2, \ldots, B_n$, by b_{lr}, b_{mu}, b_{nv}, b_{qw}.... at the adequate time t_{lr}, t_{mu}, t_{nv}, t_{qw},...., respectively, an approximate total amount of transferred soil nitrogen g_s, can be obtained as follows:

$$g_S = \left(\frac{e_{lrp} + e_{mup}}{2}\right) \times P_{lrmus} + \left(\frac{e_{mup} + e_{nvp}}{2}\right)$$
$$\times P_{munvs} + \left(\frac{e_{mvp} + e_{qwp}}{2}\right) \times P_{nvqws} + \ \ldots \ (9)$$

where P_{lrmus} is the amount of absorption by rice plants from soil nitrogen mineralized from the t_{lr} time to the t_{mu} time, and $e_{lrp} = 1/b_{lrP}$.

If $E_{1P} = E_{2P} = \ldots = E_{nP} = E_P$ (constant) in the equation (7), it becomes $G_S = E_P \sum_{j=n}^{n} P_{jn_js} = P_S/B_P$. This equation is just the same as the equation of Hunter et al.[4] 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-^{15}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:[5] 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 t_0, t_1,...., t_i,...., 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+1} and $\triangle A_{i+1}$, respectively, the total amount of immobilization I_i at the time t_i can be written as

$$I_i = K_1 H_1 \cdot \triangle A_1 + K_2 H_2 \cdot \triangle A_2 + \ldots +$$
$$K_i H_i \cdot \triangle A_i \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (10)$$

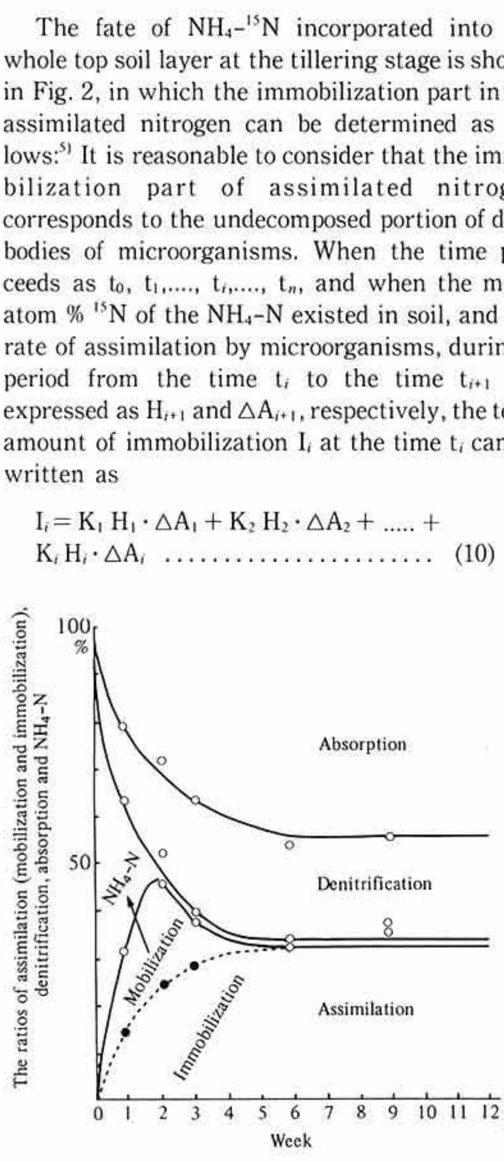

Fig. 2. The fate of NH_4-^{15}N incorporated into the soil at the tillering stage

Table 5. Transfer of mineralized soil nitrogen to assimilation (including mobilization and immobilization part of assimilated nitrogen), denitrification, and absorption by rice plant

T_j $t_{j0} \sim t_{jn_j}$	E_{jPI} (1)	MO_{jn_js} (2)	I_{jn_js} (3)	A_{jn_js} (4)	D_{jn_js} (5)	P_{jn_js}	G_{jn_jsc} (6)
May 20 ~ June 5	13.1	0.61	0.73	1.34	0.36	0.09	1.18
June 5 ~ June 18	3.8	0.56	0.97	1.53	0.65	0.55	2.07
June 18 ~ July 3	1.9	1.61	1.68	3.29	1.32	3.29	6.25
July 3 ~ July 16	1.5	0.74	0.59	1.33	0.60	2.41	3.62
July 16 ~ Aug. 6	1.5	0.06	0.06	0.12	0.06	0.22	0.33
May 20 ~ Aug. 6	2.1	3.58	4.03	7.61	2.93	6.56	13.5 (7)

(1) $E_{jPI} = 1/B_{jPI}$, B_{jPI} is the ratio of absorption by rice plant P_{jn_js} to the sum of I_{jn_js}, D_{jn_js} and P_{jn_js}. (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_{sc} in equation (12).

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

$$I_i = K(H_1 \cdot \Delta A_1 + H_2 \cdot \Delta A_2 + \ldots + H_i \cdot \Delta A_i) \quad \ldots\ldots\ldots\ldots (11)$$

From the equation (6), the rate of transfer $\Delta G_{jn_js}/\Delta t$ from mineralized soil nitrogen is changed to $E_{jP} \cdot \Delta P_{jn_jP}/\Delta t$. 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_{jPI} in place of E_{jP} can remove the overlapping. Where, $E_{jPI} = 1/B_{jPI}$, and B_{jPI} is the ratio of absorption by rice plants to the sum of immobilization, denitrification and absorption except NH_4-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:

$$G_{SC} = \mathbf{E'}_{PI} \cdot \mathbf{P}_S \quad \ldots\ldots\ldots\ldots\ldots (12)$$

where $\mathbf{E'}_{PI} = (E_{1PI}, E_{2PI}, \ldots, E_{jPI}, \ldots, E_{nPI})$.

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:[6,7]

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

Duration of the ^{15}N-water application	Soil depth (cm)	Semi-ill-drained			Converted well-drained		
		^{15}N atom % of the soil nitrogen	Mean atom % ^{15}N in the water(1)	The amount of fixed nitrogen ($N \cdot mg/m^2$)	^{15}N atom % of the soil nitrogen	Mean atom % ^{15}N in the water(1)	The amount of fixed nitrogen ($N \cdot mg/m^2$)
June 10 ~ 13	0 ~ 1	0.382	9.17	38	0.381	8.51	34
	1 ~ 2	0.371		12	0.371		12
	2 ~ 4	0.366		0	0.370		21
	4 ~ 6	0.366		0	0.367		5
June 23 ~ 27	0 ~ 1	0.379	10.7	27	0.381	10.4	28
	1 ~ 2	0.371		10	0.368		4
	2 ~ 4	0.366		0	0.366		0
	4 ~ 6	0.366		0	0.366		0
July 11 ~ 14	0 ~ 1	0.383	9.51	39	0.373	8.21	17
	1 ~ 2	0.377		25	0.366		0
	2 ~ 4	0.373		35	0.366		0
	4 ~ 6	0.367		5	0.366		0
Aug. 9 ~ 13	0 ~ 1	0.386	13.1	34	0.372	12.7	9
	1 ~ 2	0.378		20	0.371		8
	2 ~ 4	0.370		14	0.366		0
	4 ~ 6	0.366		0	0.366		0

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

duce electric discharge tubes to be used for measuring ^{15}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}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/m^2 in the semi-ill-drained field, and 1.2 g/m^2 in the converted well drained field.

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