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Characteristics of Nitrogen Discharge from a Barley Field and Estimation Model

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Abstract

Nutrient discharge from a paddy field cultivated with barley was investigated. It was shown that 1) T-N concentration gradually rose to the maximum value (approximately 40 mg/l concentration) about 60-70 days after the fertilization and fell rapidly to a low level (1-3 mg/l), 2) 99-100% of T-N in drainage water was in the NOx-N form and 3) 96-100% of the N was discharged through the underdrain. Based on these data, a mathematical model to estimate the N discharge from the field was developed. The unique features of this model are as follows: 1) nitrogen in a field occurs in 6 forms; stable organic N, unstable organic N, exchangeable ammonium N, soluble ammonium N, nitrate/nitrite N and urea N, 2) various transformation processes; nitrification, denitrification, mineralization, demineralization, urea hydrolysis and ion exchange were assumed to follow a first-order kinetics, 3) Arrhenius law was applied to the temperature dependence of transformation rates, and 4) N concentration of the field drainage is assumed to be directly proportional to the nitrate/nitrite nitrogen content in the field. It is possible to trace the observed data of N discharge from the underdrain during 2 periods of barley cultivation in the paddy field. This model can contribute to the prediction of N discharge from a field in conjunction with a field drainage model.

Discipline: Agricultural environment
Additional key words: underdrain, genetic algorithm, mathematical model

Introduction

Presently the water environment is undergoing a process of degradation along with eutrophication or nitrogen accumulation in rural and agricultural areas, mainly due to farmland drainage. The water quality is often characterized by a high N concentration while the farmland is cultivated under oxidative conditions. Accordingly, it is important to reduce the N load from farmland to preserve the water environment in rural and agricultural areas.

The objective of the current study is to investigate the N discharge from a paddy field cultivated with barley and to develop a simulation model to estimate the N load.

Materials and methods

1) Test field

The test field shown in Fig. 1 is located on a lowland with alluvial soil on the shore of Ariake Bay. Major clay mineral is montmorillonite and soil texture of the field is LiC in the top 20 cm layers and HC in deeper layers. Specific gravity of the soil particles is 2.56 in the top layers, 2.63 in the plowsole and 2.62 in the subsoil, respectively. Annaka and Shiratani[1] suggested that cracks grew in the subsoil due to drying and contraction of the soil through the conversion of paddy fields to upland fields.

In the field shown in Fig. 2, the farmland consolidation project was implemented in 1970 and the main underdrain system was constructed at the depth of 0.5–0.7 m. Supplementary drains were burrowed at right angles to the main underdrain before cultivation at about 0.3 m depth. Field drainage reaches the creek from the outlet of the under-drainage and surface drainage.

Formerly, rice had been cultivated in summer and barley in winter, but after 1982, the rice summer crop was replaced by soybean.

We investigated the water quality and quantity of the test field drainage for 2 periods of barley cultivation, December 1983–June 1984 (referred to as 1984 barley) and December 1984–June 1985 (referred to as 1985 barley).

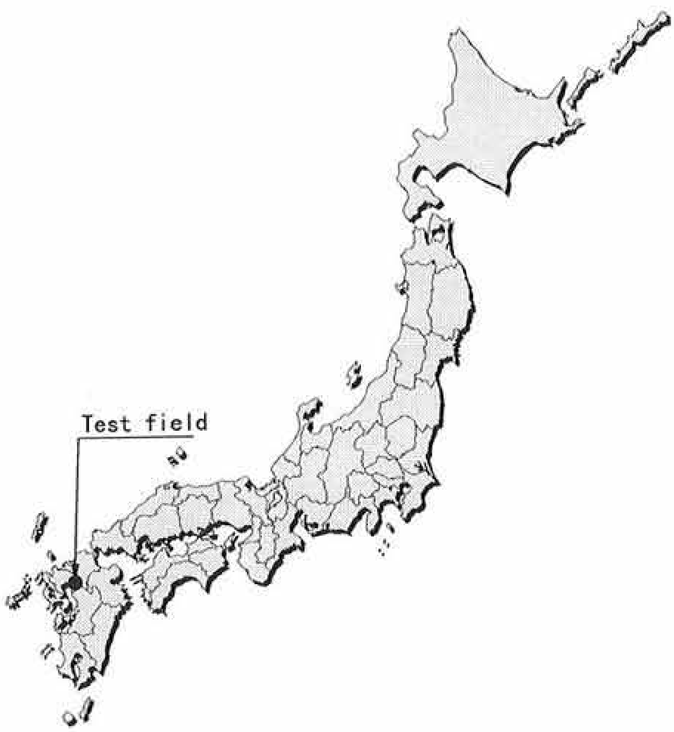

Fig. 1. Location of the test field

2) Measurement

As shown in Fig. 2, surface drainage discharge was automatically measured using a 3 inch Parshall measuring flume connected to the outlet of the surface drain, while the under-drainage discharge was measured with a flow meter (40 mm in diameter) connected to the outlet of the pipe drain. Here, it is assumed that percolation through the levee is negligible and that the outlet of the underdrain operates within the center lines between the pipe drain and neighbor drain with a width of 13.75 m and length of 113.0 m. Rainfall was observed in the neighboring farmer's house.

The field drainage water was sampled at 4.5-h intervals using an auto-sampling system developed for this investigation, and in the laboratory, total N (T-N) concentration, nitrate/nitrite N (NO_X-N) concentration, total P (T-P) concentration and phosphate P (PO_4-P) concentration of the samples were analyzed.

Characteristics of nitrogen discharge

1) Input and output of N

(1) Precipitation and field drainage

Table 1 shows the precipitation, field drainage discharge and the field drainage ratio (in parentheses) for 1984 barley and 1985 barley. Precipitation in

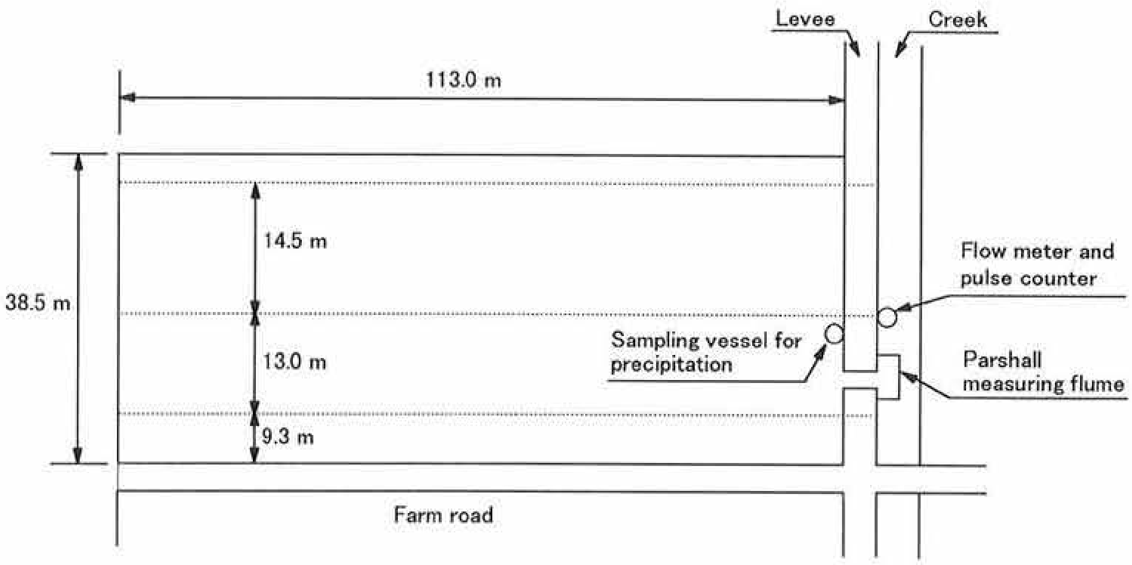

Fig. 2. Outline of the test field and measuring stations

the 1984 barley cultivation period was lower than that in 1985 barley, especially in December–March (approximately one half), and the frequency of precipitation was low in 1984 barley. As a result, the field drainage ratio in 1984 barley was lower than that in 1985 barley.

(2) Input and output of N

Major input of N to the test field was associated with fertilization and precipitation. Just before the field was sown with barley, at the end of November, 400 kg/ha of chemical fertilizer was applied as basal dressing and thereafter, no fertilizer was applied. The fertilizer was mainly composed of N, P and K, in the form of urea, ammonium phosphate sulfate and potassium chloride. T-N concentration of precipitation in 1984 barley was 0.88 mg/l, and 0.63 mg/l in 1985 barley (weighted mean). T-N concentration multiplied by the precipitation flux corresponded to an input N load of 5.28 kg/ha in 1984 barley and 5.61 kg/ha in 1985 barley.

On the other hand, outputs were composed of surface discharge, under discharge and barley uptake. We observed the surface drainage 4 times and 7 times in 1984 and 1985 barley, respectively. T-N concentration of the surface drainage was almost as high as that of the under-drainage at the same time.

Table 2 summarizes inputs and outputs of N in the test field. Here, inputs consisted of precipitation and fertilization (basal dressing) and outputs of surface discharge, underdrain discharge and barley uptake, though inputs and outputs included other components, for example, dry fallout as an input, denitrification as an output, etc.

Since the sum of outputs exceeded that of inputs, the deficiency was compensated by the N stock in the soil. Discharged N from the field amounted to 34.2% of fertilized N in 1984 barley and 60.8% in 1985 barley. And, 99.5% of the amount of N was discharged through the underdrain in 1984 barley, and 96.4% in 1985 barley.

2) Characteristics of N discharge

Table 2 indicates that it is more efficient to reduce the N discharge through under-drainage for water quality conservation or fertilizer saving. Therefore, the characteristics of N discharge through the underdrain should be more carefully analyzed.

Fig. 3 shows the changes of T-N concentrations of under-drainage with time in several barley cropping periods. The variations of the T-N concentration in 1984 barley and 1985 barley were similar, with a clear peak at a critical time. After fertilization, the concentration reached a peak with time and after the critical time (mid-March in 1984 barley

Table 1. Rainfall, field drainage discharge and field drainage ratio

(Unit: mm)

	1984 Barley			1985 Barley		
	Rainfall	Under-drainage	Surface drainage	Rainfall	Under-drainage	Surface drainage
Dec. – Mar.	190.0	37.0	0.1	357.5	149.4	4.3
	(100)	(19.5)	(0.1)	(100)	(41.8)	(1.2)
Apr. – Jun.	330.0	74.2	0.5	414.5	185.0	5.1
	(100)	(22.6)	(0.2)	(100)	(44.6)	(1.2)
Dec. – Jun.	520.0	111.7	0.6	772.0	334.4	9.4
	(100)	(21.5)	(0.1)	(100)	(43.3)	(1.2)

( ): Percentage.

Table 2. Inputs and outputs of nitrogen in the test field

	Inputs (kg/ha)		Outputs (kg/ha)		
	Fertilization (Basal dressing)	Precipitation	Uptake by barley	Under-drainage	Surface drainage
1984	64.0	5.3	69.8	21.8	0.1
Sum	69.3			91.7	
1985	64.0	5.6	66.0	37.5	1.4
Sum	69.6			104.9	

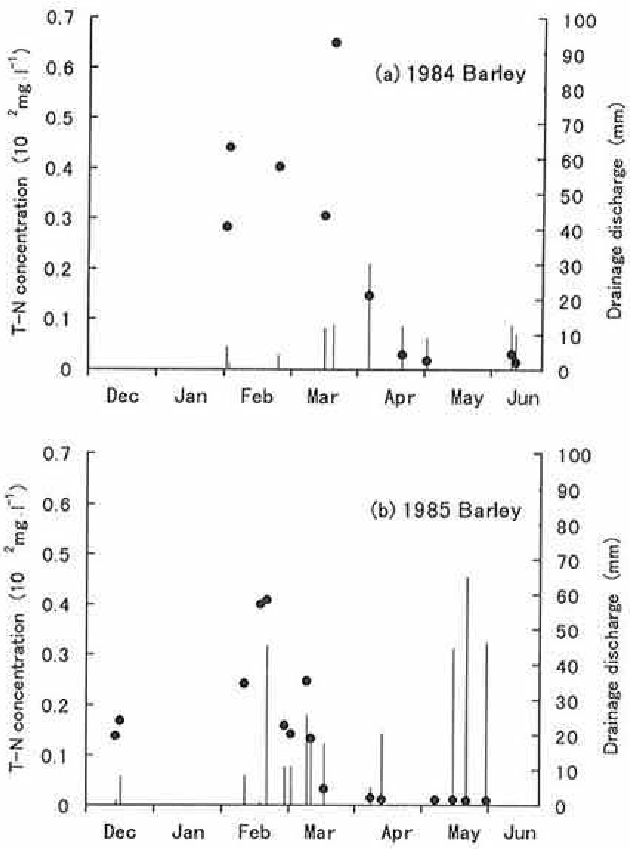

Fig. 3. Under-drainage discharge and T-N concentration during the barley cultivation period

and mid-February in 1985 barley), it decreased rapidly to a low level, ranging from 1 to 3 mg/l. As most of the T-N drained through the underdrain at the rate of 99–100%, was in the form of NO_X-N, it appears that the change of T-N concentration corresponded to that of NO_X-N in the field due to the multiple transformations of N.

We can easily estimate that the N discharge is high when a large amount of under-drainage falls on the field with a high NO_X-N content.

The N behavior in the field is assumed to be as follows. N discharged with field drainage is in the form of NO_X-N produced from organic matter derived from the previous planting and fertilization by basal dressing. Nitrification is accelerated by initial fertilization, and since the amount of nitrate/nitrite N in the field gradually increases, the T-N concentration of field drainage becomes high. It is suggested that, during this period, the nitrification rate exceeds the overall loss rate of NO_X-N due to barley uptake, bacterial uptake and denitrification, while the opposite occurs during the period when the T-N concentration decreases.

Model of nitrogen discharge through underdrain[11]

1) Basic concept

Although N leaching from soils has been exten-

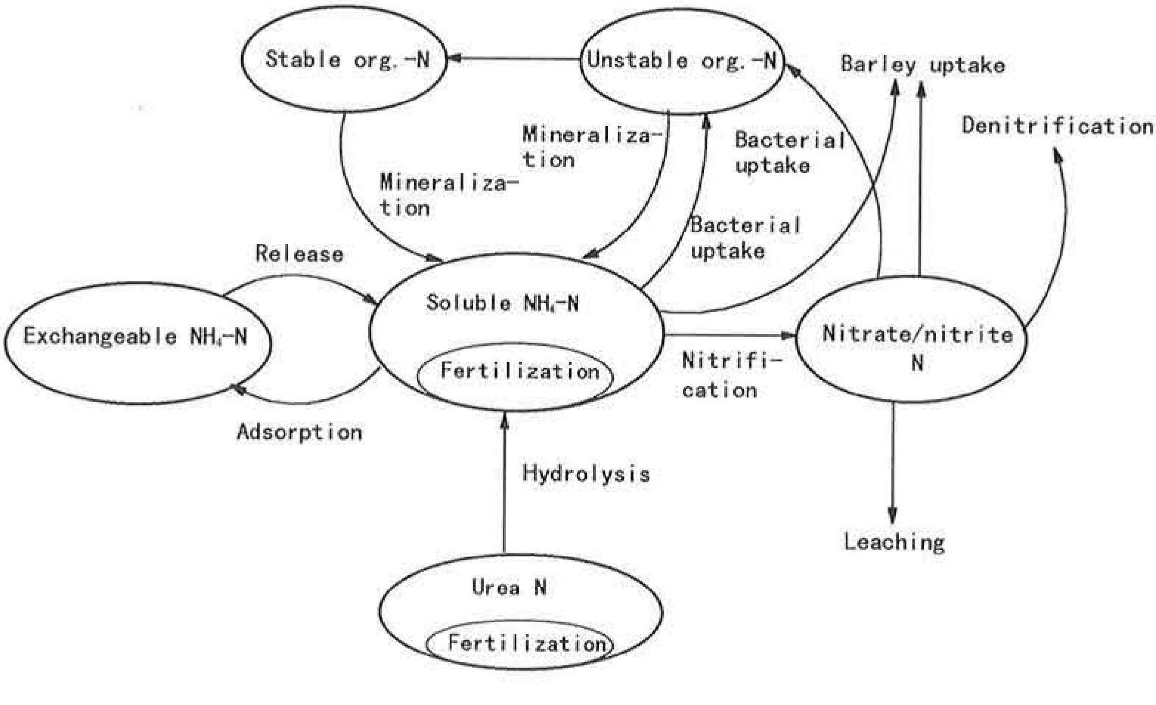

Fig. 4. Nitrogen cycle in a barley field

sively investigated and modeled by many researchers, in few studies only the nitrogen cycle was considered on a field scale, mainly due to various factors affecting the N cycle, complex N behavior in non-uniform field soils and also due to the difficulty in the measurement of the phenomena *in situ*.

For the model, main processes in the N cycle which were reported in the literature, such as nitrification, denitrification, mineralization, bacterial uptake, etc., were combined into a single system by relating them to each other. Parameters in the equations describing the processes were determined in reference to experimental results reported in the literature, or by estimation from the measured data[10].

For the model, we treated the field soil from the surface to the depth of the drain pipes as a single component of the N cycle (one box model), and state variables in the model expressed the values representing the whole field soil (113 × 13.75 m and 0.6 m in depth).

2) Nitrogen cycle in soil

In soil, nitrogen is known to occur in the form of organic N (org.-N), ammonium N (NH_4-N) and nitrate/nitrite N (NO_X-N) based on the reactions in the N cycle such as nitrification, denitrification, mineralization, bacterial uptake, etc.

In this paper, since we dealt with the N cycle during a single cultivation period of barley, the cycle in the short term is shown schematically in Fig. 4 and by equations describing the reactions in the cycle (Eq. (1))*.

$$\frac{dN_{mO}}{dt} = U_{mH} + U_N - M_{mO} - S,$$

$$\frac{dN_{iO}}{dt} = S - M_{iO},$$

$$\frac{dN_{mH}}{dt} = M_{mO} + M_{iO} + E_{iH} + H - U_{mH} - E_{mH} - X - P_H,$$

$$\frac{dN_N}{dt} = X - U_N - D - P_N - L,$$

$$\frac{dN_{iH}}{dt} = E_{mH} - E_{iH},$$

$$\frac{dN_U}{dt} = -H.$$

In this model, fertilization is given as an initial condition, because in the test field only ground fertilizer was applied for barley cultivation.

3) Reaction rate

(1) Barley uptake

The logistic equation is applied to barley growth here, and the growth rate is converted into nutrient uptake rate from the field. The logistic equation can be expressed by Eq. (2).

$$P = \frac{dp}{dt} = \lambda p\left(1 - {p}/{p_\infty}\right),$$

where, $P = P_H + P_N$.

It is assumed that barley takes up NH_4-N or NO_X-N depending on the proportion of both nitrogen forms in the field.

(2) N discharge

For fields where an underdain system was constructed, nutrient leaching can be considered to reflect the nutrient discharge because the leached N is discharged through underdrain pipes or surface drain. When the N concentration of the drainage water is calculated based on the amount of NO_X-N in the field, N discharge rate is expressed in Eq. (3), where N discharge rate is the product of the water drainage rate and N concentration.

$$L = \varepsilon N_N \cdot Q.$$

(3) Other reactions

Mehran and Tanji[6] suggested that all the microbial reaction rates of nitrogen in the soil, nitrification, denitrification, mineralization and demineralization, etc. followed a first order kinetics. Rachhpal-Singh and Nye[9] and Cabrera[2] expressed the hydrolysis rate of fertilized urea as a first order kinetics. Based on these assumptions, for the reactions between stable org.-N and unstable org.-N, we applied a first order kinetics for all the N reaction rates depicted in Fig. 4.

For temperature dependence, it is considered that the relation proposed by Sugihara et al.[13] to transform the reaction rate at an arbitrary temperature to that at a standard temperature based on Arrhenius law can be applied to the paddy fields cultivated with barley *in situ*. Temperature dependence of the rate coefficient was represented by Eq. (4).

* As for the terminology used in the Equations (Eq. (1)-Eq. (4)), see the list on page 119-120.

$$k_i = k_i'\exp\left[\frac{Ea_i}{R}\left(\frac{T-T'}{TT'}\right)\right]$$
$$\cong k_i'\exp(\theta_i K),$$

where, $\theta_i = \frac{Ea_i}{R}$, $K = \frac{T-T'}{TT'}$.

Here in the test field, based on the water retention curve shown in Fig. 5, each layer is considered to correspond to the usual water content in a narrow range (50–55%). As a result, it is not necessary to consider the soil moisture dependence.

Simulation analysis

1) Initial conditions

Close examination of soil properties after the summer crop was made at Saga Agricultural Experiment Station[3–5,7,14]. The ratio of decomposable org.-N (unstable org.-N and stable org.-N) to total org.-N which ranged from 5 to 40% was 10–25% when the total org.-N content was larger than 0.1%, according to Stanford and Smith[12]. As a result, initial conditions of the calculation are indicated in Table 3.

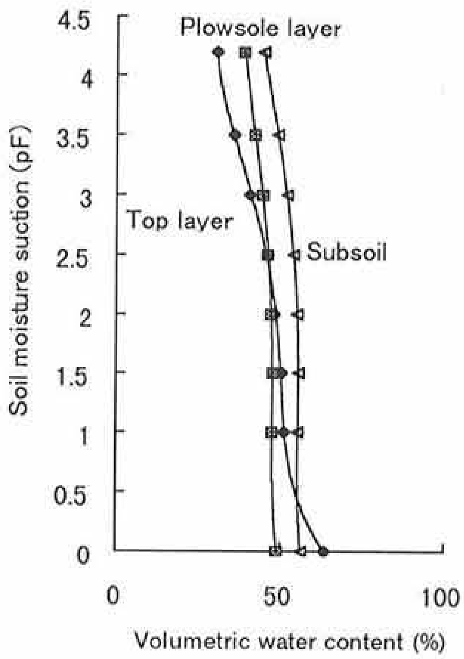

Fig. 5. Relationship between soil moisture suction and volumetric water content

Table 3. Initial conditions for the nitrogen cycle model (Unit: kg)

	1984 Barley	1985 Barley
N_{mO}*	55.9	42.0
N_{iO}	223.7	167.8
N_{mH}	5.0	5.0
N_{iH}	1.4	1.4
N_N	0	0
N_U	5.0	5.0

* See the terminology on page 119–120.

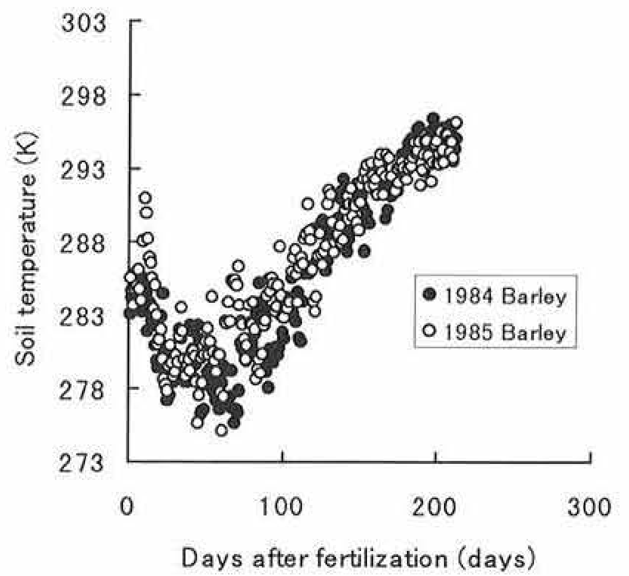

Fig. 6. Estimated soil temperature during the barley cultivation period

2) External conditions

Oba and Sakuratani[8] proposed a statistical model expressed by Eq. (5) in which the mean soil temperature in the top layer (depth of 0.1 m) can be estimated from the atmospheric temperature in the barley field.

$$T_S = -0.01\cdot(T_a - 273.15)^2 + 1.02\cdot(T_a - 273.15) + 276.27 \quad (R^2 = 0.87).$$

Here, the soil temperature deduced by Eq. (5) is given as an external condition. Fig. 6 shows the soil temperature in the barley field deduced by Eq. (5).

3) Simulation analysis

The value of each parameter is given as a mean value in the reference[6,15]. Since the temperature dependence of bio-chemical reactions in the soil is not well documented, parameter values are estimated as optimum values within a considerable range using a genetic algorithm (GA). The shift rate coefficient of unstable org.-N to stable org.-N, nitrification rate and denitrification rate are estimated in the same way.

N concentrations of under-drainage water during the 1985 barley period when a large number of samples were observed and the changes in the pattern of N concentration with time were well defined were used for trial data.

The results of the calculation shown in Fig. 7 (a) indicate the good fit to the observed data, and parameter values used here are listed in Table 4. It was interesting to note that denitrification could be disregarded.

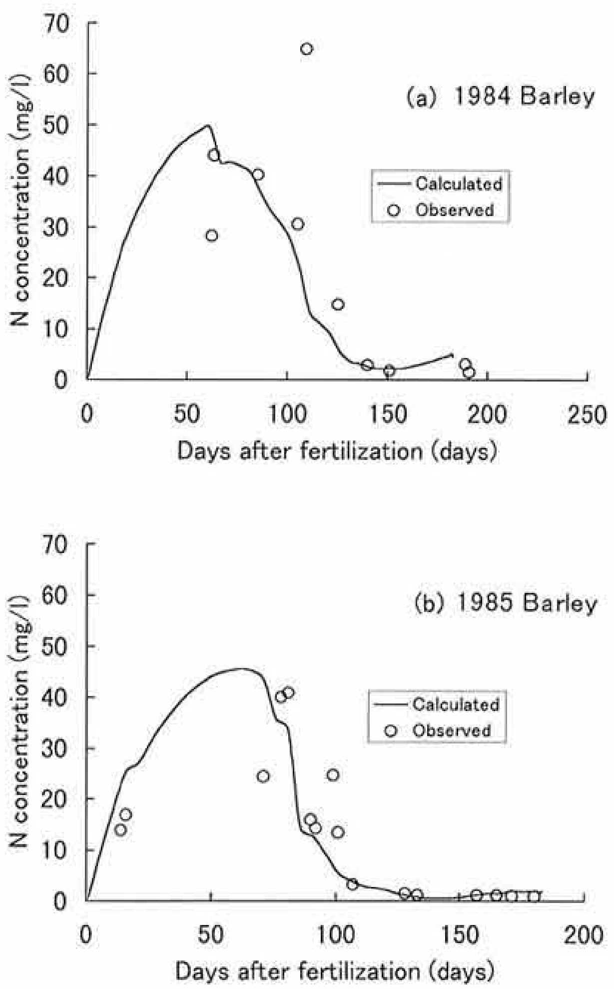

Fig. 7. Observed and simulated N concentration of under-drainage water

Table 4. Parameter values for the calculation

k_1'*	0.15 day^{-1}	θ_1	11,950 K
k_2'	0.15 day^{-1}	θ_2	12,000 K
k_3'	0.5 day^{-1}	θ_3	9,800 K
k_4'	0.51×10^{-2} day^{-1}	θ_4	5,000 K
k_5'	0.17×10^{-3} day^{-1}	θ_5	6,500 K
k_6'	1.0 day^{-1}	θ_6	10,550 K
k_7'	0.44 day^{-1}	θ_7	12,000 K
k_8'	0.94×10^{-3} day^{-1}	θ_8	8,900 K
k_9'	0.79×10^{-1} day^{-1}	θ_9	5,100 K
k_{10}'	0.0 day^{-1}	θ_{10}	6,800 K
ε	0.12×10^{-1} m^{-3}	λ	0.04 day^{-1}

* See the terminology on page 119–120.

The results of the model applied to the 1984 barley cropping field using the same parameter values are shown in Fig. 7(b). The calculated changes of N concentration of the under-drainage water corresponded to the observed data with a relatively good accuracy. Therefore the N cycle model proposed here enables to simulate well the N concentration of the under-drainage water in the field.

Conclusion

In this study, we estimated the characteristics of nutrient discharge from a paddy field cultivated with barley, and observed that the 1) nutrient discharge through underground drainage accounted for more than 95% of the total nutrient discharge from the field, 2) most of the nitrite in the under-drainage water was in the NO_X-N form, and 3) N concentration in the under-drainage water during the cultivation period changed with time, and also the pattern of change varied with the rainfall distribution during the period.

Then, an N cycle model to estimate the N discharge from a barley field was proposed. The unique features of this model are as follows: 1) N contained in the field occurs in 6 forms; stable org.-N, unstable org.-N, exchangeable NH_4-N, soluble NH_4-N, NO_X-N and urea-N, 2) various transformation processes: nitrification, denitrification, mineralization, demineralization, hydrolysis and ion exchange were assumed to follow a first-order kinetics, 3) Arrhenius law was applied to the temperature dependence of transformation rates, and 4) N concentration of the field drainage was assumed to be directly proportional to the nitrate/nitrite N content in the field. It was possible to trace the observed data of N discharge from the underdrain during 2 periods of barley cultivation in the paddy field.

This model can contribute to the prediction of N discharge from a field in conjunction with a field drainage model.

Terminology

N_{mO}: unstable org.-N (kg).
N_{iO}: stable org.-N (kg).
N_{mH}: soluble NH_4-N (kg).
N_N: NO_X-N (kg).

N_{iH}: exchangeable NH_4-N (kg).
N_U: urea-N (kg).
U_{mH}: demineralization rate of soluble NH_4-N (kg/day).
U_N: demineralization rate of NO_X-N (kg/day).
M_{mO}: mineralization rate of unstable org.-N (kg/day).
M_{iO}: mineralization rate of stable org.-N (kg/day).
S: shift rate of unstable org.-N to stable org.-N (kg/day).
E_{iH}: release rate of exchangeable NH_4-N (kg/day).
E_{mH}: adsorption rate of soluble NH_4-N (kg/day).
H: hydrolysis rate of urea-N (kg/day).
X: nitrification rate of soluble NH_4-N (kg/day).
D: denitrification rate of NO_X-N (kg/day).
k_1': demineralization rate coefficient of soluble NH_4-N to unstable org.-N (day^{-1}).
k_2': demineralization rate coefficient of NO_X-N to unstable org.-N (day^{-1}).
k_3': adsorption rate coefficient of soluble NH_4-N to exchangeable NH_4-N (day^{-1}).
k_4': mineralization rate coefficient of unstable org.-N (day^{-1}).
k_5': mineralization rate coefficient of stable org.-N (day^{-1}).
k_6': release rate coefficient of exchangeable NH_4-N to soluble NH_4-N (day^{-1}).
k_7': hydrolysis rate coefficient of urea-N to soluble NH_4-N (day^{-1}).
k_8': shift rate coefficient of unstable org.-N to stable org.-N (day^{-1}).
k_9': nitrification rate coefficient (day^{-1}).
k_{10}': denitrification rate coefficient (day^{-1}).
P_H: plant uptake rate of soluble NH_4-N (kg/day).
P_N: plant uptake rate of soluble NO_X-N (kg/day).
L: leaching rate of NO_X-N (kg/day).
p: N content in plant (kg).
p_∞: N content in plant at the end of cropping (kg).
λ: growth constant (day^{-1}).
ε: constant (m^{-3}).
Q: under-drainage discharge (m^3/day).
Ea: apparent activation energy (J/mol).
R: gas constant (J/K/mol).
T, T': temperature or standard temperature (K).
T_s: soil temperature (K).
T_a: atmospheric temperature (K).

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