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A Simplified Model for Estimating Nitrogen Mineralization in Paddy Soil*

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Abstract : The estimation of available nitrogen in paddy soil is important in order to evaluate rice productivity and to improve fertilizer management. In this study, a simplified model is proposed for estimating nitrogen mineralization in paddy soil based on incubation experiments. The main factors considered are soil moisture percentage on dry weight basis before submergence (θ) and temperature (T). Soil samples were collected from an experimental paddy field (Alluvial, SL) at Kyoto University. Incubation experiments were conducted for wet and air dried soil under four different temperatures of 15°, 20°, 25° and 30°C. To investigate the effect of preflooding soil moisture on N mineralization, we set eight levels of soil moisture before submergence, after which samples were subjected to a similar incubation experiment. Mineralized N in wet soil (N_W) increased linearly, while the drying effect (N_D), defined as a difference in N mineralized between air-dried soil and wet soil, was found to have an equal ceiling value over the incubation temperature conditions, though the rate toward the asymptote varied with temperature. We employed the following equations to express the N mineralization rate :

$dN/dt = dN_W/dt + dN_D/dt$

$dN_W/dt = K_W$

$dN_D/dt = K_D N_O \exp(-K_D t)$

where, K_W and K_D are temperature dependent rate constants expressed by the Arrhenius' equation, of which the apparent activation energy was 24,803 and 14,058 cal • mol^{-1}, respectively. No is the maximum effect of soil drying expressed as a function of θ before submergence as follows :

$N_O = 7.171 - 0.66\theta + 0.015\theta^2, \quad \theta \leq 19.56\%$

$= 0 \quad \theta > 19.56\%$

The present model was able to estimate satisfactorily the amount of NH_4-N mineralized under specific conditions. Increasing the model generality is a subject for further study.

Key words : Drying effect, Model, Nitrogen mineralization, Paddy soil, Soil moisture before flooding, Soil incubation, Temperature.

水田土壌における窒素無機化量の簡易推定モデル：長谷川利拡・堀江　武（京都大学農学部）

要　旨：水田土壌の特性と環境要因から土壌窒素の無機化動向を説明することは，水田の持つ水稲生産ポテンシャルの評価だけでなく，合理的な施肥法の確立のために重要である．そこで本研究では，湛水前の土壌乾燥程度と湛水期間中の温度から土壌窒素の無機化量を推定するモデルを提案した．京都大学実験水田（沖積，SL）の作土から採取したサンプルを 15，20，25，30°C の 4 温度条件下で湿潤細土，風乾細土について恒温湛水培養を行った．また，鳥山ら[12]に従い，湛水前の土壌水分を 8 段階設定し，窒素無機化に及ぼす湛水前の含水比の影響を調査した．湿潤土のN無機化量 (N_W) は時間に対し直線的に増加したのに対し，乾土効果 (N_D) は頭打ちを示し，その上限値はいずれの温度条件においても同様であった．これらの結果に基づき，N無機化速度は，以下のように表すことができる：

$dN/dt = dN_W/dt + dN_D/dt$

$dN_W/dt = K_W$

$dN_D/dt = K_D N_O \exp(-K_D t)$

ここで，t は時間（日），N_O は湛水前の土壌含水比，θ の関数：

$N_O = 7.171 - 0.660\,\theta + 0.0150\,\theta^2, \quad \theta \leqq 19.56\%$

$N_O = 0, \quad \theta > 19.56\%$

として表される．また，K_W, K_D は温度の関数，アレニウスの式で近似され，その活性化エネルギーはそれぞれ 24,803 および 14,058 cal • mol^{-1} であった．この式より求めた N 無機化量は実測値とよく適合することがわかった．

キーワード：温度，乾土効果，水田土壌，湛水前の土壌含水比，窒素無機化，土壌培養，モデル．

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Nitrogen is the most important nutrient in rice (*Oryza sativa* L.) production. It is the element required in a large quantity and the one most commonly limiting to rice yield. Nitrogen is also associated with the quality of environment because the fraction of N lost from the paddy can be a source of environmental pollution. Therefore, a number of studies have been conducted to improve crop productivity and N use efficiency. The conventional approach for the study of N management has been field experiments with different levels and methods of N application. However, results obtained from these experiments are often erratic and difficult to repeat basically because of the complex and variable nature of the rice production system.

Crop simulation models can be powerful tools to study the effects of weather and agronomic practices on rice yield. It also enables us to quantify the energy and nutrient flow in the soil-plant system, which in turn can be used for the evaluation of potential productivity and N efficiency. The imperative part of the model taking into account the effect of N is the estimation of N availability in soil. In paddy rice, a relatively large portion of crop N is derived from mineralization of soil organic matter. In fact, 4-10 g/m^2 of N is absorbed without inorganic fertilizer[5,10,15]. This amount is almost comparable to that of fertilizer usually applied during the whole growing period. As a consequence, accurately estimating the amount of N mineralized from soil organic matter becomes of prime importance. Soil N mineralization is a result of microbial activity influenced by various factors such as weather, soil conditions and types of residues incorporated in the soil. In a simulation model focusing on crop growth and N balance, however, the component of soil N processes should be relatively simple but yet cover major factors that influence mineralization of N with a small number of inputs.

There have been a number of studies concerned with the formulation of the amount of N mineralized in paddy soil. Yoshino and Dei[17] developed a mineralization model using accumulated effective temperature. Sugihara et al.[9], Ando and Shoji[1], an Ando et al.[2] expressed the accumulated nitrogen mineralized by a first order rate equation with Arrhenius' equation. Toriyama et al.[12] found a quantitative relationship between soil moisture before flooding and the amount of N mineralized.

This study attempted to intergrate the findings obtained in those early studies and results of additional experiments on N mineralization into a simplified dynamic model for estimating N mineralization in paddy soil that could be integrated into a rice simulation model for growth, development, yield and N balance. The main factors considered in this study were soil moisture before flooding and temperature during the incubation period.

Materials and Methods

Soil samples were taken from the plow layer of four randomly chosen plots at an experimental paddy field at Kyoto University (Alluvial, SL, CEC=15.6 meq/100g dry soil, C=3.09%, N=0.224%, C/N=13.8, Phosphate Absorption Coefficient=500 mg P_2O_5/100g dry soil) in May of 1989 by a cylindrical soil sampler (ϕ30 cm). In this field 1.2 kg/m^2 of stable manure was applied annually after harvest. The sample was mixed for uniformity and passed through a 2 mm seive in order to remove the debris and stones. The soil moisture percentage on a dry weight basis was 44% at sampling.

Experiment 1

A 14.4 g of wet soil (10 g on the dry wight basis) was weighed, put into the test tubes (ϕ18 mm, 150 mm depth) and mixed by adding 20 ml of distilled water, after which the test tubes were covered by a rubber cap and incubated for 8 weeks under four temperature conditions of 15, 20, 25, and 30°C. NH_4-N was measured at 0, 3, and 7 days after flooding, then at one week interval till days 56.

Experiment 2

The same sample as in Experiment 1 was air dried, then flooded and incubated in the same way as in the previous case. The soil weight in each tube was 10 g on a dry weight basis.

Experiment 3

The same sample was gradually air dried to eight preset levels of soil moisture[12]. The samples were then subjected to the same procedures as Experiment 1. The test tubes were kept at 30°C. NH_4-N was measured after 21 days.

Each treatment in all the experiments consisted of four replications.

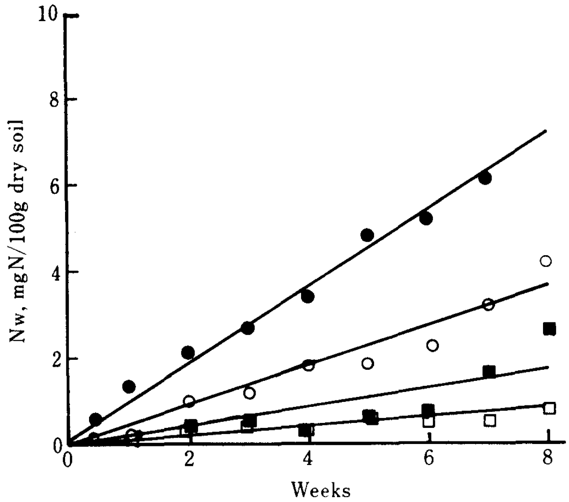

Fig. 1. Temporal changes of nitrogen mineralization in wet soil, N_W, at different incubation temperatures.
●: 30°C ○: 25°C ■: 20°C □: 15°C

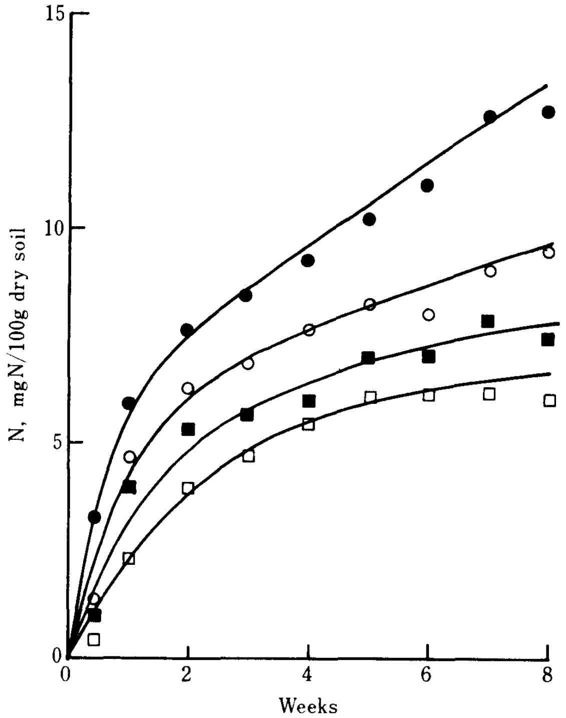

Fig. 2. Temporal changes of nitrogen mineralization in air dried soil, N.
●: 30°C ○: 25°C ■: 20°C □: 15°C
The lines indicate the estimated N by Eqs. (7) & (8).

NH_4-N determination

The sample was washed into a 250 m*l* sample vial with 30 m*l* of distilled water. Then 50 m*l* of 20% KCl was added. After 1 hour vibration, the sample was left for settling overnight. The sample was then centrifuged to provide a sample for analysis by the indo-phenol colorimetric method[6].

Results

Figure 1 shows the time course of NH_4-N release from the wet soil (N_W) under four different temperature conditions. N_W increased linearly with time at each temperature; the slope was highly dependent on temperature. In this experiment, we did not observe a saturating response during the 8 week incubation.

Figure 2 presents the temporal change in mineralized nitrogen from the air dried soil under four different temperature conditons. Mineralization rate at each temperature was initially very high during the first 2 weeks but steadily levelled off to reach a constant value depending on the temperature.

The constant rates obtained after the rapid increase phase were very similar to those in wet soil at respective temperatures. In fact, the accumulative drying effect (N_D), defined as the difference between the nitrogen mineralized in wet soil and the one in dried soil, reached an asymptote, which was about the same value for all the temperatures studied (Fig. 3), though the rate towards the asymptote varies with temperature. Unlike N_W, N_D seems to have an upper limit which was determined by soil moisture conditions before submergence.

The relationship between the effect of drying and soil moisture percentage on .dry weight basis (θ) was studied in Experiment 3 and the results are presented in Fig. 4. Above 19.56% of θ, no soil drying effect was observed under the incubation temperature 30°C. Below the threshold θ at 30°C, the drying effect increased as the initial θ decreased.

The above observations indicate that the nitrogen mineralization process consists of two different responses with respect to time: a linear response with no upper limit (N_W) and an asymptotic response with a preset upper value determined by the soil moisture conditions before submergence (N_D). This can be written as:

$$\frac{dN}{dt}=\frac{dN_W}{dt}+\frac{dN_D}{dt} \qquad (1)$$

dN_W/dt is expressed as a function of temperature as follows:

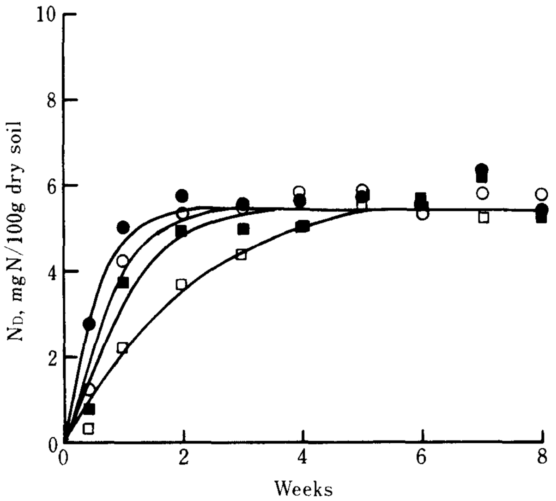

Fig. 3. Temporal changes of N_D at the different incubation temperatures, where N_D is the effect of drying on N mineralization measured as the N increment in air dried soil before flooding over wet soil.
● : 30°C ○ : 25°C ■ : 20°C □ : 15°C
The lines indicate the estimated N_D by Eq. (4).

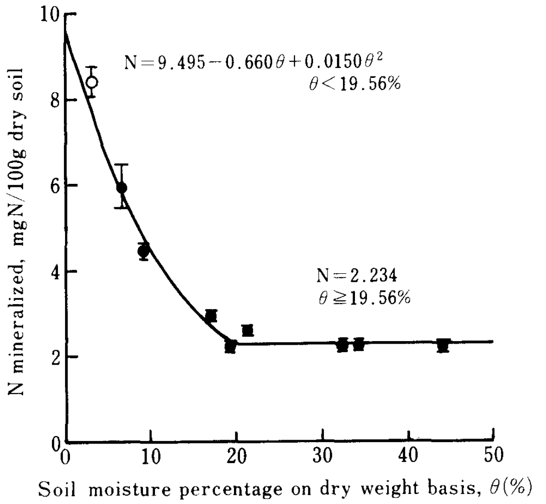

Fig. 4. Relationship between mineralized N after 21 days of incubation at 30°C and soil moisture percentage on dry weight basis before submergence.
● : values obtained in Experiment 3.
○ : a value in Experiment 2.
The line was fitted to the data of Experiment 3.

$$\frac{dN_W}{dt}=K_W \quad (2)$$

$$K_W=A_W\exp(-Eaw/(R(T+273))) \quad (3)$$

where, A_W is a constant for wet soil, Eaw is apparent activation energy for K_W, T is temperature in °C, and R is a gas constant (1.986 cal • deg^{-1} • mol^{-1}), respectively. Fitting the Arrhenius' formula to the data shown in Fig. 1 gave the parameter values of $A_W=1.07\times10^{17}$ mg N/100 g dry soil/day and Eaw=24,803 cal • mol^{-1} (Fig. 5).

The time course of N_D at different temperatures shown in Fig. 3 can be summarized by a set of saturation curves with respect to time :

$$\frac{dN_D}{dt}=K_DN_O\exp(-K_Dt) \quad (4)$$

in which, N_O is the maximum (or asymptotic) effect of soil drying and K_D is a rate constant. The relationship between N_O and soil moisture percentage on dry weight basis (θ) before flooding, obtained from Experiment 2, can be well approximated by the following equation (Fig. 4) :

$$N_O=7.171-0.664\times\theta+0.015\times\theta^2 \qquad \theta<19.56\% \quad (5)$$

$$N_O=0 \qquad \theta\geq19.56\%$$

By fitting the integrated form of Eq. (4) to the mineralization curves at different temperatures given in Fig. 3, the relationship between K_D and temperature T was obtained and presented in Fig. 6. This is well approximated by :

$$K_D=A_D\exp(-Ead/(R(T+273))) \quad (6)$$

where A_D is a constant and Ead is the apparent activation energy for K_D. The estimated values were 3.01×10^9 d^{-1} for A_D and 14,058 cal • mol^{-1} for Ead, respectively.

Integrating Eq. (2) and Eq. (4), we obtain the following equations, respectively :

$$N_W=N_I+K_Wt \quad (7)$$

$$N_D=N_O\{1-\exp(-K_Dt)\} \quad (8)$$

where, N_I is the initial available N.

The estimated values of N_D by Eq. (8) with N_O calculated by Eq. (5) are indicated by the lines in Fig. 3. They are in good agreement with the measured data. The time course of total N mineralization can be estimated by adding Eqs. (7) and (8). The curves presented in Fig. 2 are the calculated time courses of total N mineralization for the condition of Experiment 2, which also agreed well with the measurements.

Discussion

In this study, a constant rate function (Eq. (2)) with respect to time was employed for

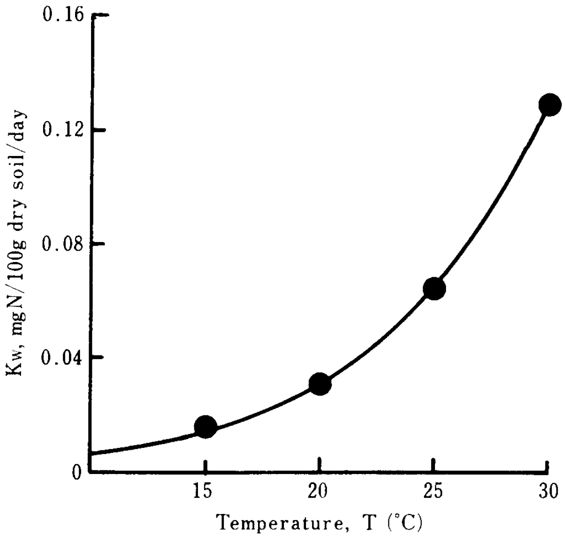

Fig. 5 Nitrogen mineralization rate of wet soil as a function of temperature.

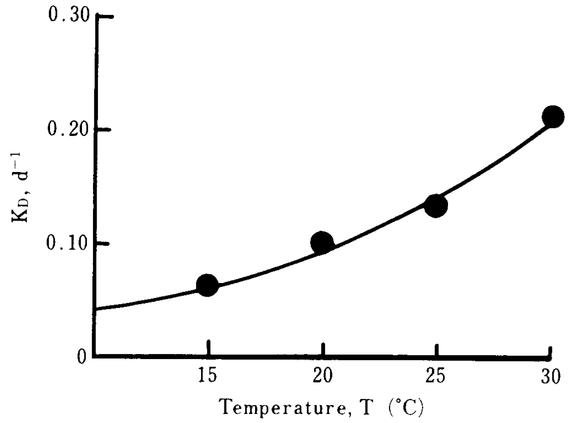

Fig. 6 Temperature dependence of K_D, the rate constant for soil drying effect (N_D).

N_W. Other studies used the first order rate equation with a preset upper limit or mineralization potential, based on the saturating response in the incubation experiments[9,15]. The first order rate equation explains well the pattern of N mineralization from various kinds of soil and organic matter, where no N recovery is expected. In actual field conditions, however, paddy soil recovers much nitrogen during the flooded period[7,11,14,16]. This suggests that the upper limit for N_W is likely to increase during submergence, so that the rate of N_W in an actual paddy field is mostly limited by microbial activities which are represented by the rate constant. From a practical point of view, a constant rate function as Eq. (2) can be used to estimate N mineralization from wet soil under field conditions, which provides a great simplicity in the model.

Most models so far developed have dealt with air dried soil and wet soil separately. This has limited the applicability of such models for the estimation of N mineralization dynamics in various preflooding moisture conditions. In this study, we employed Eq. (1) to express nitrogen mineralization for soils with different moisture before submergence, based on the observation that a constant rate of N mineralization after the initial rapid phase in air dreid soil is quite similar to the rate in wet soil at each temperature. Yoshino and Dei[17], Inubushi et al.[4], Toriyama et al.[12] and Ando et al.[3] found a similar relationship between N_W and N (air dried) in many kinds of soil types under the temperature range of 15°C to 30°C, suggesting the assumption underlying the present model is valid in this temperature range. However, it was also found that this relationship dose not hold for the temperature exceeding 30°C[4,17]. Therefore, the application of this model has to be confined to the temperature range of 15 to 30°C.

The relationship between the effect of drying (N_D) and θ obtained in Experiment 3 was consistent with what was found by Toriyama et al.[12] and Ueno et al.[13], although Toriyama et al.[12] used a 1st degree linear function under the threshold θ. Because threshold θ as well as other parameters is specific for a given soil type, experiments with several soil moisture levels have to be conducted. We also need to take into consideration the effect of the drying history of soil before submergence to improve the model applicability.

In this study, the temperature functions (Eqs. (3) and (6)), were obtained from constant temperature conditions. Stanford et al.[8] and Yoshino and Dei[17] have reported that the temperature function determined from constant temperature experiments can be applied to fluctuating temperature conditions. On the other hand, Ando and Shoji[1] suggested that the apparent activation energy estimated from the field incubation (soil temperature ranging from 10 to 24°C) was higher than that obtained from the constant temperature incubation (20, 25, and 30°C). The model validation would be necessary under fluctuating temperatures to apply the model to field conditions. It should also be noted that because we had only 1 temperature treatment for the relationships between N_D and θ (Experiment 3), the temperature function for K_D (Eq. (6)) was assumed to be independent of the level of θ or N_0.

In conclusion, the present simplified model can successfully explain the amount of NH_4-N mineralized for a specific soil type with a given θ that was attained by a specific drying process. In order to increase the generality of the model, however, it is necessary to determine the effects of soil properties and drying history before flooding on the mineralization rate parameters.

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