Journal of Global Environment Engineering, Vol. 5, pp. 127-137, 1999

INFLUENCE OF VEGETATION DISTRIBUTION ON THE MASS BALANCE OF TOTAL NITROGEN IN A FORESTED MOUNTAIN WATERSHED

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Abstract

A mathematical model of total nitrogen balance in a watershed ecosystem was developed by deriving a time evolution equation for total nitrogen stored in the soil layer. The distribution of the forest tree species was characterized by the growth rate and the stem volume of the trees in this model. To evaluate the influence of the vegetation distribution on the total nitrogen balance, this model was applied to a forested mountain area (Aoya River basin; 4,500 ha) located in the central part of Japan. Total nitrogen loading in the stream water was generally small and the assimilation of nitrogen in trees became active in the forested watershed in which the growth rate and the stem volume of trees were large.

KEYWORDS: *stream water chemistry, forest ecosystem, total nitrogen balance, assimilation of nitrogen, growth rate and stem volume of trees*

1. Introduction

Beside the fixation of carbon dioxide, the absorption of nitrogen is one of the more important functions of forests in the preservation of the environment. For instance, it has been reported that the amount of nitrogen fixed by forests is 1-150kg/ha per year and the amount of nitrogen accumulated in the forest soil is more than 100 times the annual absorption (Granhall, 1981; Tsutsumi, 1987). A considerable amount of nitrogen oxide or nitrous oxide, which is known to contribute to air pollution, acid rain and possibly global warming, is also absorbed in the forest. Clearly, it is crucial to quantify the absorption of nitrogen by the forest in order to put this preservative function in its proper perspective.

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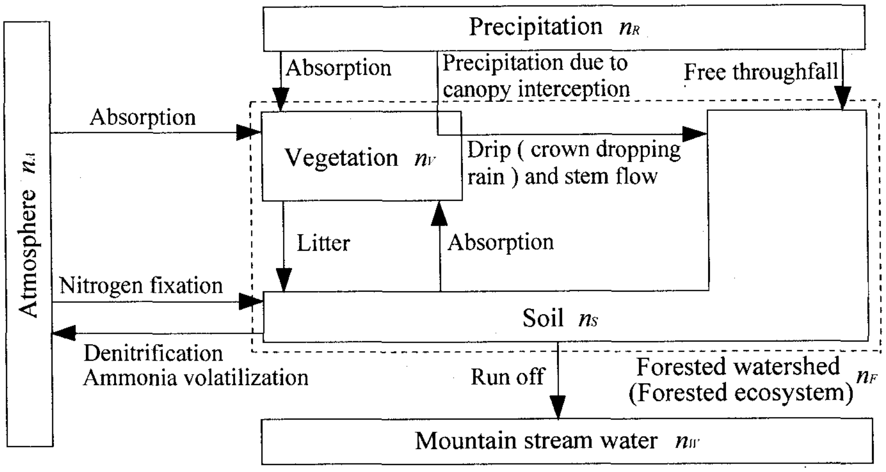


Figure 1. Metabolism of TN in the forested watershed.

The absorption of nitrogen depends on the state of the forest such as the distribution of tree species, the growth rate of trees, the stem volume of trees, the forest age, and so on. The material balance or the mass circulation process in the forest has been studied in the field of agriculture and fundamental knowledge about the role of soil microorganisms and vegetation has been accumulated (Vitousek, 1997; Ohrui and Mitchell, 1997; Magill et al., 1997; Mitchell et al., 1997; Kim, 1998). Although the situation is gradually changing (e.g. Fan et al., 1998), to date most studies on forest soils and soil microbes have been carried out locally, and little research has focused on the total material balance over larger forested areas.

Since May 1996 field observations have been carried out in a large forested watershed (circa 4,500 ha) to evaluate the nitrogen balance in a forest, which has a diversity of tree species and soil types. In an earlier paper (Tsuduki et al., 1998), it has already been shown that the total nitrogen (TN) concentration of a mountain stream water in the forest is a function of the growth rate and the stem volume of the trees. In the present paper, a model is proposed to describe the time evolution of TN in the forested ecosystem and the influence is investigated of the vegetation distribution on the fixation and absorption of nitrogen. Specially, in this study an attempt is made to evaluate the relationship between the mass balance of TN and characteristics of the vegetation distribution by using short term data instead of long term data.

2. Modeling of the TN balance in the forested watershed

2.1 Metabolism of nitrogen in the forest

The metabolism of TN per unit time and unit area of the forested ecosystem is illustrated in Figure 1. The forest is assumed to be composed of a soil part and a vegetation part. In this figure, n_R is the flux of TN transferred by precipitation to the forest. n_A represents the net flux of TN transported from the atmosphere to the forest as a result of absorption of nitrogen oxide to the soil surface, nitrogen fixation, denitrification, volatilization of ammonia, and so on. The flux of TN flowing into the mountain stream water is given as n_W. In the forest, nitrogen is exchanged between the soil and the vegetation. The inorganic nitrogen in the soil is absorbed and assimilated by the vegetation, which supplies back the organic nitrogen as litter falls to the soil. n_V represents the net accumulation rate of TN in the vegetation part. The net accumulation rate of TN in the soil part n_S is described as follows,

$$n_V + n_S = \frac{d}{dt}(N_V + N_S) = n_R + n_A - n_W, \tag{1}$$

where N_S and N_V is TN existing in the soil and the vegetation, respectively. This equation should be applicable to the mass balance for a long period such as the annual change of TN in the forest.

2.2 Time evolution equation for TN in the soil and its solution

It is known that for the past several millennia enormous amounts of nitrogen have accumulated in the forest soils (Kawada, 1989). Before deriving a time evolution equation for TN present in the forest soil N_S, the following three assumptions were added to Eq. (1) describing the mass balance for the rate of change of TN.

1) The flux of TN flowing into the mountain stream water $n_W(t)$ is proportional to the amount of TN in the soil $N_S(t)$ and the coefficient β is constant in time,

$$n_W(t) = \beta N_S(t), \quad \beta = \text{const.} \quad \text{in } t. \tag{2}$$

2) The annual fluxes of TN supplied from the precipitation and the atmosphere are constant,

$$n_R(t) = \text{const.} \quad \text{in } t, \quad n_A(t) = \text{const.} \quad \text{in } t. \tag{3}$$

3) Though the demand of nitrogen for growth depends on the age of the trees, the vegetation is assumed to be in a state of equilibrium so that the net accumulation rate of TN in the vegetation part n_V is constant in a limited period over the period of interest,

$$\frac{dN_V}{dt} = n_V(t) = \text{const.} \quad \text{in } t. \tag{4}$$

Using the assumptions 2) and 3), we can combine the first, the second and the third terms in the right side of Eq. (1) as follows,

$$n_{RAV} = n_R + n_A - n_V = \text{const.} \quad \text{in } t. \tag{5}$$

Substitution of Eqs. (2) and (5) into Eq. (1) gives the following expression,

$$\frac{dN_S}{dt} = n_S(t) = n_{RAV} - \beta N_S(t). \tag{6}$$

The amount of TN in the soil $N_S(t)$ at time t is represented as the sum of the amount of TN in the soil $N_S(t-\Delta t)$ at time $(t-\Delta t)$ and the increment of TN in the soil $n_S(t)\Delta t$ during the period Δt,

$$N_S(t) = N_S(t-\Delta t) + n_S(t)\Delta t. \tag{7}$$

Considering a limit of the above equation when Δt approaches zero, we obtain an ordinary differential equation describing the change of the amount of TN in the soil with time,

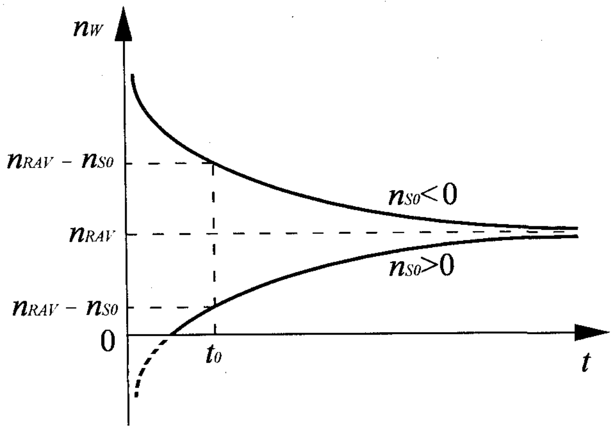


Figure 2. Change in the flux of TN flowing into the mountain stream water n_W with time.

$$\frac{dN_S}{dt} = n_S = n_{RAV} - \beta N_S . \tag{8}$$

The solution of Eq. (8) under the condition that $N_S = N_{S0}$ at $t = t_0$ can be written as follows,

$$N_S = \frac{n_{RAV}}{\beta} + \left(N_{S0} - \frac{n_{RAV}}{\beta} \right) e^{-\beta(t-t_0)} . \tag{9}$$

2.3 Changes in the flux of TN flowing into the stream water with time

The net accumulation rate of TN in the soil at the initial time, n_{S0} is defined as follows,

$$n_{S0} \equiv n_S(t_0) = n_{RAV} - \beta N_S(t_0) = n_{RAV} - \beta N_{S0} . \tag{10}$$

Substitution of Eqs. (9) and (10) into Eq. (2) gives the following equation, which represents the change of the flux of TN into the mountain stream water with time,

$$n_W(t) = n_{RAV} - n_{S0}\ e^{-\beta(t-t_0)} . \tag{11}$$

The value of n_W increases monotonically and approaches n_{RAV} asymptotically with time t under the condition $n_{S0}>0$ as shown in Figure 2. On the other hand, under the condition $n_{S0}<0$, n_W decreases monotonically and approaches n_{RAV} asymptotically with time t. Since n_{S0} can also be expressed as follows,

$$n_{S0} = n_R + n_A - n_V - \beta N_{S0} = (n_R + n_A) - (n_V + \beta N_{S0}) , \tag{12}$$

the condition under which the flux of TN into the stream water n_W decreases with time t is given by the following relationship,

$$n_R + n_A < n_V + \beta N_{S0} . \tag{13}$$

In order that n_W reaches a small value, it is necessary to keep the value n_{RAV} small. For this purpose, it is important to maintain the value of n_V at a high level, because it is almost impossible to control the value of n_R+n_A at a low level. In other words, the presence of vegetation that is capable of assimilating more nitrogen through an active forestry management could bring about a smaller runoff of TN into the mountain stream water.

These theoretical discussions are based on the above-stated assumption 3). Although this assumption may be invalid over longer periods of several decades, it may still hold for a shorter term. This means that Eq. (11) should only be applied to a period $(t-t_0)$ in which t_0 is specified as a point of time when the assumption 3) no longer holds. Thus, as long as t_0 is renewed according to the state of afforestation, the growth of trees and the felling, Eq. (11) should allow realistic estimates of the flux of TN into the stream water n_W.

2.4 Flux of TN into the stream water and the vegetation distribution

The difference of the flux of TN into the stream water n_W from location to location is characterized by the distribution of the net accumulation rate of TN in the vegetation, provided that the runoff coefficient β, the amount of TN in the soil N_{S0}, the net flux of TN transported from the atmosphere n_A and the flux of TN transferred by the precipitation n_R are spatially uniform in the watershed.

Eq. (11) combined with Eqs. (5) and (10) gives the following equation,

$$n_W(t) = -\{1-e^{-\beta(t-t_0)}\}\, n_V + \{1-e^{-\beta(t-t_0)}\}\,(n_R+n_A) + \beta N_{S0} e^{-\beta(t-t_0)} \tag{14}$$

or, more concisely,

$$n_W = -\kappa n_V + c\,, \tag{15}$$

where

$$\kappa \equiv 1-e^{-\beta(t-t_0)}, \quad c \equiv \{1-e^{-\beta(t-t_0)}\}(n_R+n_A) + \beta N_{S0}\, e^{-\beta(t-t_0)}\,. \tag{16}$$

The parameters κ and c are independent of location. The rate of accumulation of TN into the vegetation part is generally affected by the growth rate $\overline{\alpha}$ and the stem volume v_i of each tree species. $\overline{\alpha}$ is an average growth rate defined as

$$\overline{\alpha} = \frac{\sum_i \Delta v_i}{\sum_i v_i}, \tag{17}$$

where Δv_i is the annual growth amount of the stem volume of the i-th species and v_i the stem volume of the i-th species. If the effect of the growth amount $\overline{\alpha}\, v_i$ of the i-th species and the effect of the stem volume v_j of the j-th species are evaluated by the coefficient a'_i and the coefficient b'_j, respectively, the rate of accumulation is expressed as follows,

$$n_V = \sum_i a'_i\, \overline{\alpha}\, v_i + \sum_j b'_j\, v_j\,. \tag{18}$$

Substitution of Eq. (18) into Eq. (15) gives the following equation, in which the flux of TN into the stream water is expressed as a function of the growth rate and the stem volume of trees,

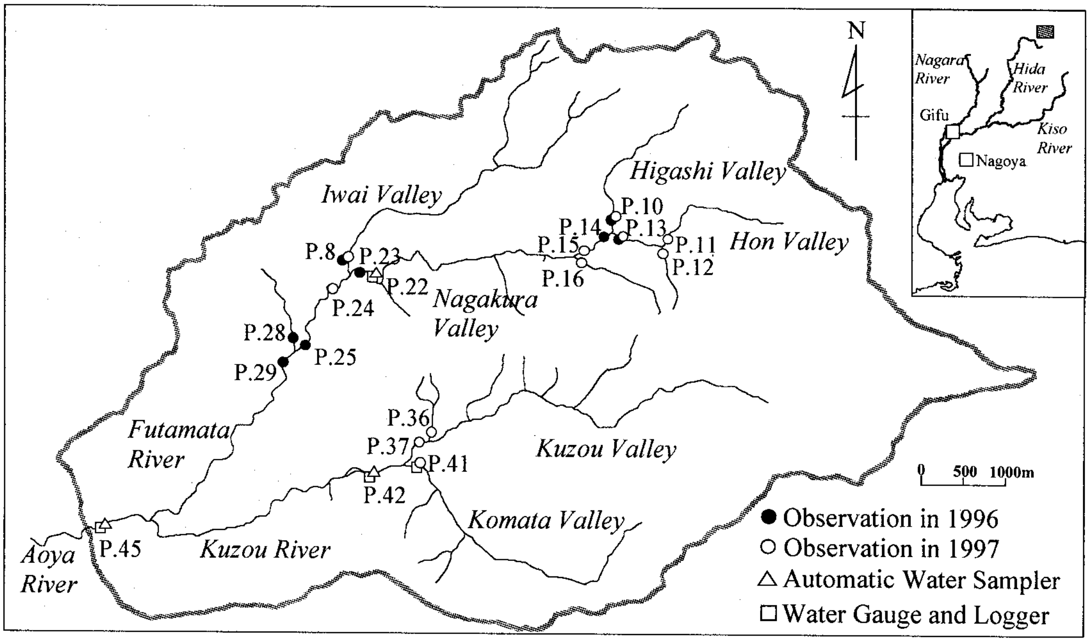


Figure 3. Experimental area and observation points for the discharge and the water quality at the mountain stream.

$$n_W = \sum_i a_i \overline{\alpha} v_i + \sum_j b_j v_j + c, \quad a_i \equiv -\kappa a'_i, \quad b_j \equiv -\kappa b'_j. \tag{19}$$

3. Field observations

To examine the applicability of Eq. (19), field observations were carried out in a forested mountain area located in Asahi Village in Gifu Prefecture, Japan. The observation area is within the Aoya River basin, which comprises the extreme upper reaches of the Hida River and which has undergone little influence by human activities in the neighborhood. The area of this watershed is about 4,500 ha. The elevation is in the range of 800.7 and 2117.1 m and the mean slope is 0.53. The watershed has a natural forest cover of 74.7 % and an artificial forest cover of 21.6 %; the forest is composed of evergreen conifers such as Japanese cypress (*Chamaecyparis obtusa* Endlicher; 20.3 %), deciduous conifers such as Japanese larch (*Larix leptolepis* Gordon; 20.3 %) and broad leaved deciduous trees such as Japanese red birch (*Betula maximowicziana* Regal) and Japanese oak (*Quercus crispula* Blume; 35.7 %). The major types of soil in the watershed are moderately moist brown forest soil (BD; 40.2 %), granular and nutty structure type brown forest soil (BB; 24.8 %) and wet humus podzolic soil ($PW(h)_3$; 15.8 %).

Figure 3 shows the field observation area and the points where the discharge and water quality of the mountain stream were measured. The mark of each point in this figure corresponds to the observation period;

1) Observations in 1996: The stream water was sampled and the discharge was measured at 3 hour intervals at 8 points (marked with ●) for 4 days from September 6 to 9 in 1996. The total amount of rainfall in this period was 75 mm averaged over the whole watershed.

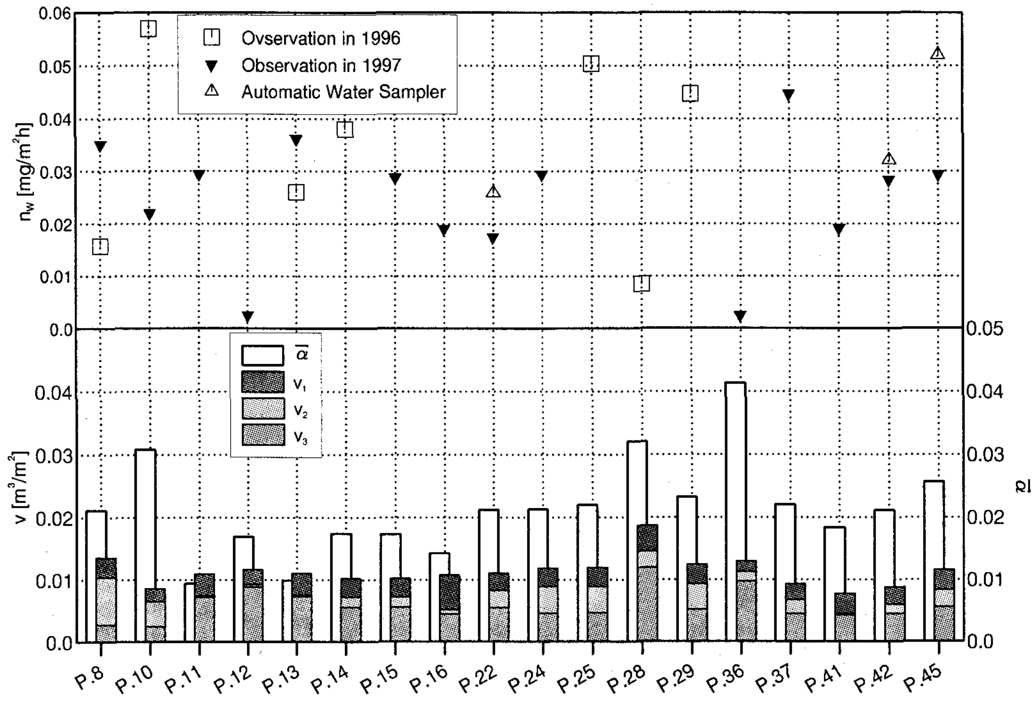
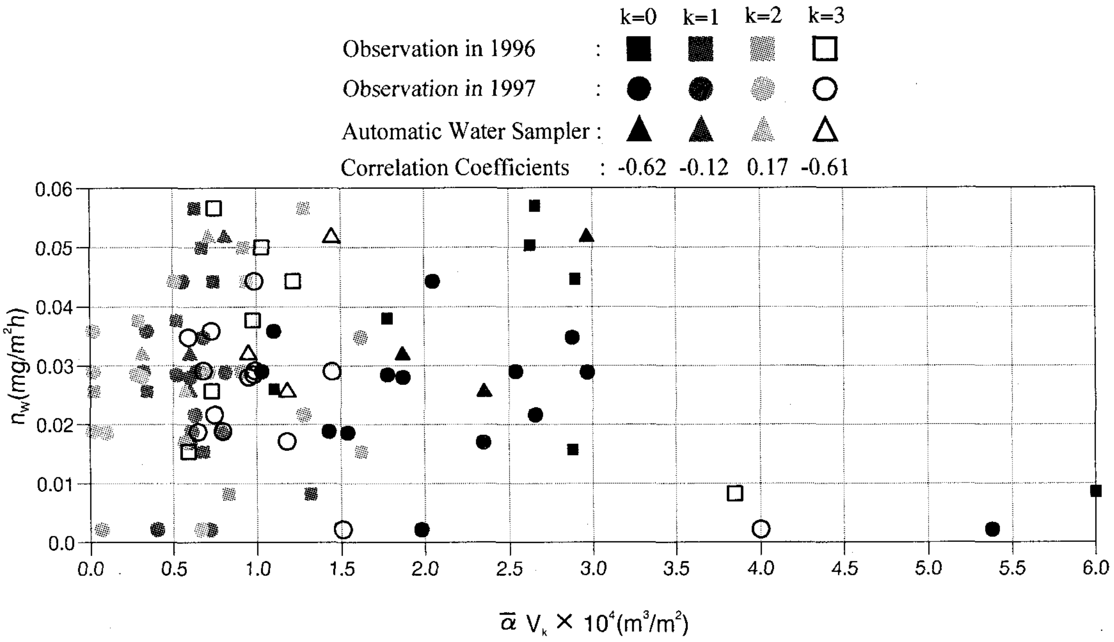


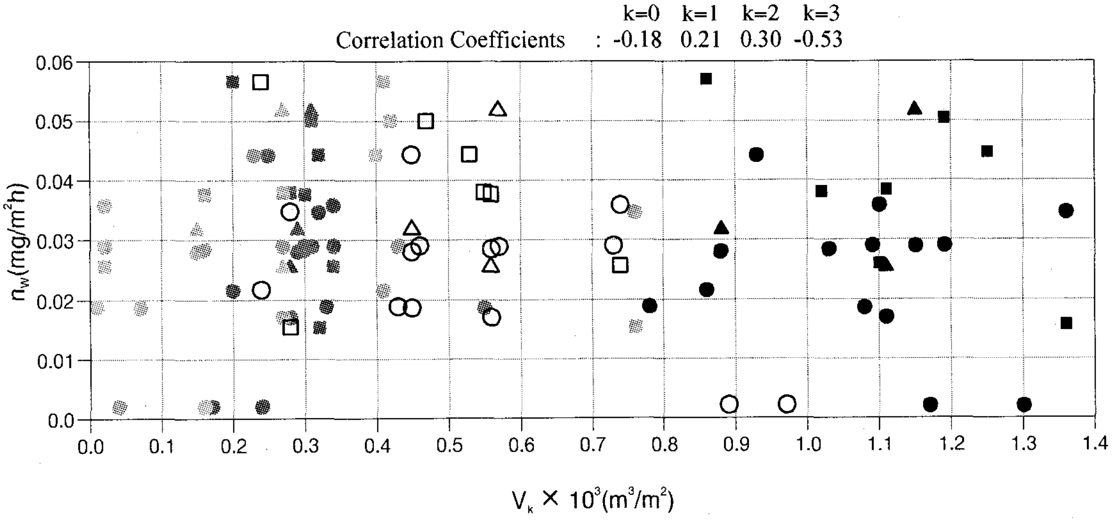
Figure 4. The net flux of TN into the stream water at each observation point n_w, the average growth rate $\overline{\alpha}$ and the stem volume of the k-th species of trees v_k (k=1: broad leaved deciduous tree, k=2: deciduous conifer, k=3: evergreen conifer).

2) Observations in 1997: The stream water was sampled and the discharge was measured at 2 or 3 hour intervals at 11 points (marked with ○) for 6 days from September 21 to 26 in 1997. The total amount of rainfall in this period was 32 mm.
3) Automatic water sampler: Continuous observations were carried out at 3 points (marked with △) for 26 days from September 26 to October 9 in 1997. The stream water was sampled with automatic water samplers at 3 or 12 hour intervals and the discharge data were obtained with current meters and water gauges at 20 minute intervals at these points. The total amount of rainfall in this period was 98 mm (average). The water gauges were installed at 4 points (marked with □) for 75 days from September 13 to November 27 in 1997.

The flux of TN into the stream water n_w at each observation point in each observation period is shown in the upper part of Figure 4. The lower part of Figure 4 shows the average growth rate $\overline{\alpha}$ and the stem volume of the k-th tree species v_k; the vegetation data were obtained from the forest lists provided by the Kuguno-Takayama District Forestry Office. The vegetation data extracted from the lists were converted into a digital data set in the same mesh as the 50 m DEM (digital elevation map) issued by the Geographical Survey Institute. Values of $\overline{\alpha}$ and v_k at each observation point were derived from the vegetation data in the catchment area.



(a) Relationship between n_W and the average amount of growth $\overline{\alpha}\ v_k$.



(b) Relationship between n_W and the stem volum of the trees v_k.

Figure 5. Relationship between the flux of TN into the mountain stream water n_W and the vegetation characteristics $\overline{\alpha}\ v_k$ and v_k (k=0 : all tree species, k=1: broad leaved deciduous trees, k=2: deciduous conifers, k=3: evergreen conifers).

4. Influence of the vegetation distribution on TN in the stream water

Although the above-mentioned Eq. (18) should be applied to the mass-balance data of TN obtained over a long period, it may be of some interest to use Eq. (18) to investigate the spatial difference of the TN flux into the stream even in a short observation period. If the observation period is the same, the spatial difference of the TN flux into the stream water is likely due to the difference of the vegetation distribution.

The influence of the vegetation characteristics such as $\overline{\alpha}\, v_i$ and v_j on the flux of TN into the stream water n_W can be evaluated from the values of the parameters in Eq. (18) through a simple multiple linear regression. However, the amount of the collected data is insufficient for a multiple regression analysis even if the classification of the tree species is restricted to only three species namely broad leaved deciduous trees, deciduous conifers and evergreen conifers. Therefore, a simple linear regression analysis was used to find which of the tree species had the greatest influence on n_W. The TN data and the vegetation characteristics at the observation point in the lower reaches and the upper reaches may be independent each other. But, it was found that the influence of the upper stream to the lower stream can be ignored by the statistical analysis in our previous study (Tsuduki et. al, 1998). In the following regression analysis, we use the data at all of the observation points.

Figure 5 shows the relationships of the flux of TN into the mountain stream water n_W with the growth amount $\overline{\alpha}\, v_k$ and the stem volume of the trees v_k. In the case of $k=0$, v_0 equals to $v_1+v_2+v_3$. In Figure 5 (a), the correlation in the case of $k=0$ is stronger than other cases and n_W increases monotonically with the increase of $\overline{\alpha}\, v_0$; this indicates that the flux of TN into the stream water probably depends on the growth amount of all tree species. Actually, it can also be seen that the effect of the evergreen conifers ($k=3$) is much larger than that of the others. This is confirmed in Figure 5 (b), which shows again that it is mainly the stem volume of the evergreen conifers which has an effect on the flux of TN into the stream water, because the correlation between n_W and v_k in the case of $k=3$ is so much stronger than for the other cases.

Although the plot of data shows considerable scatter, the available data can still be used to provide a rough estimate of the TN flux into the stream water in spite of the short observation period. Adopting the growth amount of all the tree species $\overline{\alpha}\, v_0$ and the stem volume of the evergreen conifer v_3 as the factors influencing to n_W, we obtain the following equation as an example of Eq. (18),

$$n_W = a\,\overline{\alpha}\,v_0 + b\,v_3 + c\,. \tag{19}$$

The parameters *a*, *b* and *c* estimated from the data observed in 1997 were -35 mg/m^{3}h, -2.5 mg/m^{3}h and 0.046 mg/m^{2}h, respectively. Similarly, with the data observed in 1996, both *a* and *b* were also negative. Although the lack of data does not permit a further discussion about the absolute values of the coefficients *a*, *b* and *c*, it can be expected that the flux of TN into the stream water decreases with the increase of the growth amount of all tree species (but mainly evergreen conifers) and with the increase of the stem volume of the evergreen conifer. Since the net accumulation rate of TN in the vegetation depends on the flux of TN into the stream water as shown in Eq. (1), the fixation and absorption of nitrogen can be improved by the growth and the existence of evergreen conifers promotes the ability of this function.

Several investigators such as Vitousek (1977) have already pointed out that the fixation function of nitrogen in the forest is related with the activity of the vegetation. Although the above results are definitely consistent with earlier findings, more data will be needed for a more detailed examination of the relationships between the mass balance of TN and the characteristics of the vegetation distribution.

5. Conclusions

In this study, a mass balance model of TN for mountain watersheds was proposed by deriving a time evolution equation of TN accumulated in the soil to evaluate the influence of the diversity of the tree species on the TN balance in the forested ecosystem. This model can represent the relationships among the flux of TN into the stream water, the net accumulation rate of TN in the vegetation and the characteristics of the trees. It was found that the fixation and absorption of nitrogen by the trees were related to the growth rate and the stem volume of trees by applying the model to the field data observed in a large forested watershed. The fixation and absorptive capability of forests can be improved by the growth of evergreen conifers and by the stem volume of evergreen conifers, although the growth rate of all trees also appears to be a strong determining factor.

Acknowledgment

The authors wish to express their sincere gratitude to the Kuguno-Takayama District Forestry Office for providing them with the forest lists and for permission to observe in the national forest. Special thanks are also due to the Asahi Village Office and the resident for their kind cooperation. The authors would like to thank their colleagues, Wilfried Brutsaert (Visiting Professor, Gifu University) and Onwona-Agyeman SIAW for their helpful suggestions during the preparation of this paper. This study was performed partly under the sponsorship of Grant-in-Aid for Scientific Research by the Japanese Ministry of Education, Science, Sports and Culture.

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Nomenclature

n_A	Net flux of TN transported from the atmosphere to the forest.	[g/m^{2}yr]
n_F	Net accumulation rate of TN in the forested ecosystem.	[g/m^{2}yr]
n_R	Flux of TN transferred by precipitation to the forest.	[g/m^{2}yr]
n_{RAV}	Net flux of TN transported to the soil part.	[g/m^{2}yr]
n_S	Net accumulation rate of TN in the soil part.	[g/m^{2}yr]
n_{S0}	Net accumulation rate of TN in the soil at the initial time.	[g/m^{2}yr]
n_V	Net accumulation rate of TN in the vegetation part.	[g/m^{2}yr]
n_W	Flux of TN flowing into the mountain stream water.	[g/m^{2}yr]
N_S	TN existing in the forest soil.	[g/m^3]
N_{S0}	TN existing in the forest soil at the initial time.	[g/m^3]
N_V	TN existing in the vegetation.	[g/m^3]
β	Runoff coefficient.	[m/h]
$\overline{\alpha}$	Average growth rate of trees.	[1/yr]
v	Stem volume of trees in the unit area.	[m^3/m^2]
$\overline{\alpha}\,v$	Average amount of growth.	[m^3/m^2]
a_i	Coefficient evaluating the effect of the growth amount of the i-th species.	[g/m^{3}yr]
b_j	Coefficient evaluating the effect of the stem volume of the j-th species.	[g/m^{3}yr]
c	Constant coefficient.	[g/m^{2}yr]
i	i=0 : all tree species, i=1: broad leaved deciduous tree, i=2: deciduous conifers, i=3: evergreen conifers	
j	j=0 : all tree species, j=1: broad leaved deciduous tree, j=2: deciduous conifers, j=3: evergreen conifers	