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Responses of Japanese Tree Species to Excessive Nitrogen Load

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Abstract An increase of nitrogen (N) deposition from the atmosphere has been one of the environmental stresses which are affecting forest ecosystems. In some terrestrial ecosystems, the excessive N input induces over-nutrition with N, described as 'N-saturation', which may reduce tree health due to nutrient imbalance accompanied with soil acidification and depression of mycorrhizal symbiosis. Nitrogen deposition in Japan is gradually increasing, and N saturation has already been exhibited in some suburban forests. The experimental studies indicated that the sensitivity to N load differs among Japanese tree species. To evaluate and conserve the future Japanese forest condition, it is necessary to develop the threshold of N load based on the plant responses.

I. Introduction

In general, nitrogen (N) acts as a fertilizer for tree growth when the amount of N input to forest ecosystems is optimal. In some forests, however, current increase of atmospheric N deposition induces over-nutrition with N, described as 'nitrogen saturation', which may reduce tree health due to nutrient imbalance and soil acidification [1, 2]. In Japan, anthropogenic emission and atmospheric deposition of N are gradually increasing, and in some suburban forests around Tokyo Metropolis, N saturation may appear [3, 4]. Although many experimental and field studies on the effects of 'N fertilizer' on the productivity and nutrient status of Japanese forest tree species were conducted since 1960s [5-7], information on the influences of over-nutrition on Japanese forest tree species is limited at the present time.

In this review, we summarize the current trends in the N-induced air pollution in Japan, and introduce several experimental studies on the sensitivity to excessive N load concerning representative Japanese forest tree species.

II. Nitrogen Deposition in Japan

Since the Industrial Revolution, atmospheric deposition of N to terrestrial ecosystems has been increasing with elevated anthropogenic emissions of NO_X and NH_Y [8, 9]. Global emissions of NO_X and NH_Y are estimated to be approximately 33-52 and 50-131 Tg N year^{-1}, respectively, and they are predicted to continuously increase with increments of fossil fuel consumption and livestock breeding [8, 10, 11].

In Japan, emission of SO_x, one of the major gaseous air pollutants produced by fossil fuel combustion, has been reducing from the 1980s as a result of technical and political regulations enforcement (Fig. 1). On the other hand, NO_X emission remains stable level in the 21st century (Fig. 1), indicating that a major acidic air pollutant in Japan will be NO_X rather than SO_X in the near future. The similar trend is found in the results of air quality monitoring which has been carried out since 1970 by the Environment Agency of Japan (the Ministry of Environment). As shown in Fig. 2, annual mean concentration of atmospheric SO_2 has been continuously reducing since 1970s. However,

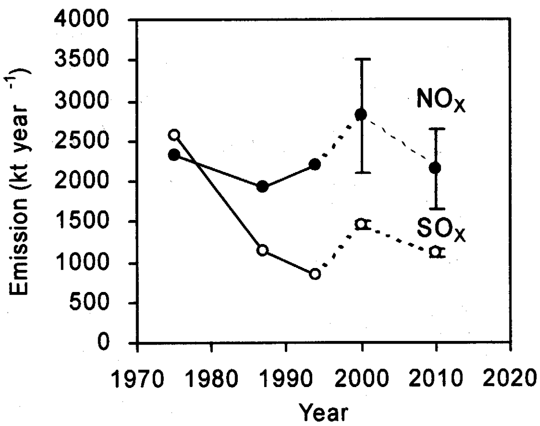

Fig. 1. The trends in the emissions of SO_X and NO_X in Japan. The emissions in 2000 and 2010 are the means projected on the basis of 2-4 emission scenarios, and vertical bars indicate the maximum and minimum values. Data source: Goto *et al.* [12] and Kannari *et al.* [13].

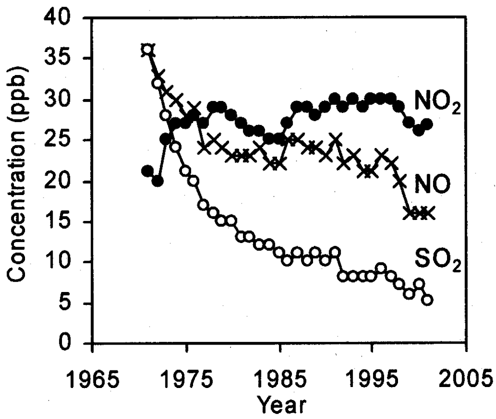

Fig. 2. Long-term trends in annual mean concentrations of atmospheric SO_2, NO and NO_2 in Japan. The concentrations of SO_2, NO and NO_2 are the average at 13, 24 and 14 General Environmental Air Monitoring Stations, respectively. Data source: Ministry of the Environment [14, 15].

annual mean concentration of atmospheric NO_2 barely reduced and it was higher than that of SO_2 in the past three decades. Although information on the emission of NH_y is limited in Japan [16], molar ratio of NH_4^+/NO_3^- in the current precipitation is ranged from 1.2 to 1.4 [17], suggesting that N emission as NH_Y is similar level to that as NO_X in Japan. Table 1 shows the result of acid deposition monitoring which has been carried out by Environment Agency of Japan (the Ministry of Environment) from 1989 to 2000. The wet deposition rate of non-seasalt sulfate (nss-SO_4^{2+}) tended to decrease, but that of NO_3^- was slightly increasing between 1989 and 2001. The mean wet deposition rate of total-N (NO_3^- + and NH_4^+) all over Japan ranged from 4.9 to 7.2 kg N ha^{-1} $year^{-1}$. Because dry N deposition rate is considered to be similar level of wet N deposition rate, the total N load (the sum of wet and dry depositions) in Japan may be approximately 10 kg N ha^{-1} $year^{-1}$.

In general, because N is a limiting nutrient for many temperate forest ecosystems, most of atmospheric N input to the forest is absorbed and assimilated by microbes and plants [18, 19]. In N-limited forests, therefore, N output as NO_3^- in stream water is usually lower than atmospheric N input. However, several researchers observed relatively high N output in stream water as compared to the atmospheric N input, and suggested that N status in some forests of Central Europe and North America are changing from 'N-limited' to 'N-saturated' [20, 21]. In Japan, results of the current field

Table 1. Wet deposition of acidic substance in Japan. Each value is the mean of 24-40 monitoring site, and minimum and maximum values are shown in the parentheses. Data source: Environment Agency of Japan [25, 26] and Ministry of the Environment [27].

Survey period	*n*	nss-SO_4^{2-} (kg S ha^{-1} $year^{-1}$)	NO_3^- (kg N ha^{-1} $year^{-1}$)	NH_4^+ (kg N ha^{-1} $year^{-1}$)	NO_3^-+NH_4^+ (kg N ha^{-1} $year^{-1}$)
Apr.1989-Mar. 1992*	28	8.4 (1.5-16.0)	2.7 (0.4-5.7)	3.6 (0.2-7.8)	6.3 (0.6-11.1)
Apr.1993-Mar. 1994	24	14.4 (3.6-32.0)	2.8 (0.6-5.7)	3.9 (0.4-8.0)	6.6 (1.0-11.1)
Apr.1994-Mar. 1995	32	10.9 (4.6-20.5)	2.2 (0.5-4.4)	2.7 (0.9-6.6)	4.9 (1.4-9.2)
Apr.1995-Mar. 1996	39	16.0 (6.0-28.2)	3.3 (1.2-5.9)	4.2 (1.3-8.8)	7.4 (2.5-12.9)
Apr.1996-Mar. 1997	40	13.4 (6.0-25.8)	3.2 (1.2-6.1)	3.6 (0.3-7.8)	6.8 (1.8-12.8)
Apr.1997-Mar. 1998	41	14.8 (5.5-25.6)	3.4 (1.0-5.4)	4.2 (1.7-7.7)	7.6 (2.9-12.2)
Apr.1998-Mar. 1999	38	7.2 (3.6-13.1)	3.5 (0.9-7.6)	4.1 (1.5-8.0)	7.6 (3.3-14.1)
Apr.1999-Mar. 2000	32	6.5 (2.9-12.7)	3.2 (1.5-5.9)	3.9 (0.8-8.2)	7.1 (2.3-13.9)
Apr.2000-Mar. 2001	40	8.8 (2.4-17.5)	3.3 (0.7-9.0)	3.9 (0.8-9.0)	7.2 (1.5-18.0)

* Average of 5-year investigations.

studies suggested that N-saturation is already occurring in some Japanese forest ecosystems with relatively high N deposition rate over 10 kg N ha^{-1} $year^{-1}$ [3, 22, 23].

Because forested area, where N balance is continuously investigated, is very limited, it is difficult to estimate whether the N-saturation could/will occur in many Japanese forests or not. Wright et al. [24] suggested that the threshold of N load for the appearance of N-saturation in European forest ecosystems is approximately 10 kg N ha^{-1} $year^{-1}$. Because environmental factors which affect N balance in forest ecosystems (ex. climate, vegetation and soil type etc.) are considered to be quite different between Japan and central Europe, the original threshold of N load for the appearance of N-saturation in Japanese forests should be defined. Furthermore, relatively high atmospheric N deposition at approximately 10 kg N ha^{-1} $year^{-1}$ and its upward tendency (Table 1) indicate that the effects of increasing N deposition on Japanese forests should be clarified for evaluating the future forest condition.

III. Hypotheses of Negative Nitrogen Effects on Forest

Over-nutrition of N in N-saturated forests may reduce tree vitality through many N-related processes such as accelerated soil acidification and deteriorated nutrient status (Fig. 3). It is well known that high concentrations of atmospheric NO_2 (several ppm) and NH_3 (hundreds ppb) cause direct damages to plant leaves [28, 29]. In Japan, however, atmospheric concentrations of NO_x and NH_3 are ppb order, it suggests that direct injuries of NO_2 and NH_3 to forest tree species do not occur at the present time. On the other hand, wet deposition of NO_3^- (HNO_3) and NH_4^+ play as acidic substance for forest ecosystems. High load of these N compounds induces soil acidification caused by H^+ originated from HNO_3 and nitrification process of NH_4^+ [30]. Soil acidification leads to leaching of base cations from soil to watershed and increase the solubility of manganese (Mn) and aluminum (Al) in the rhizosphere. Consequently, tree vitality may be declined by nutrient deficiency, imbalance of cations and excessive accumulations of Mn and Al [30-32]. High N deposition to soil may affect the plant-mycorrhiza

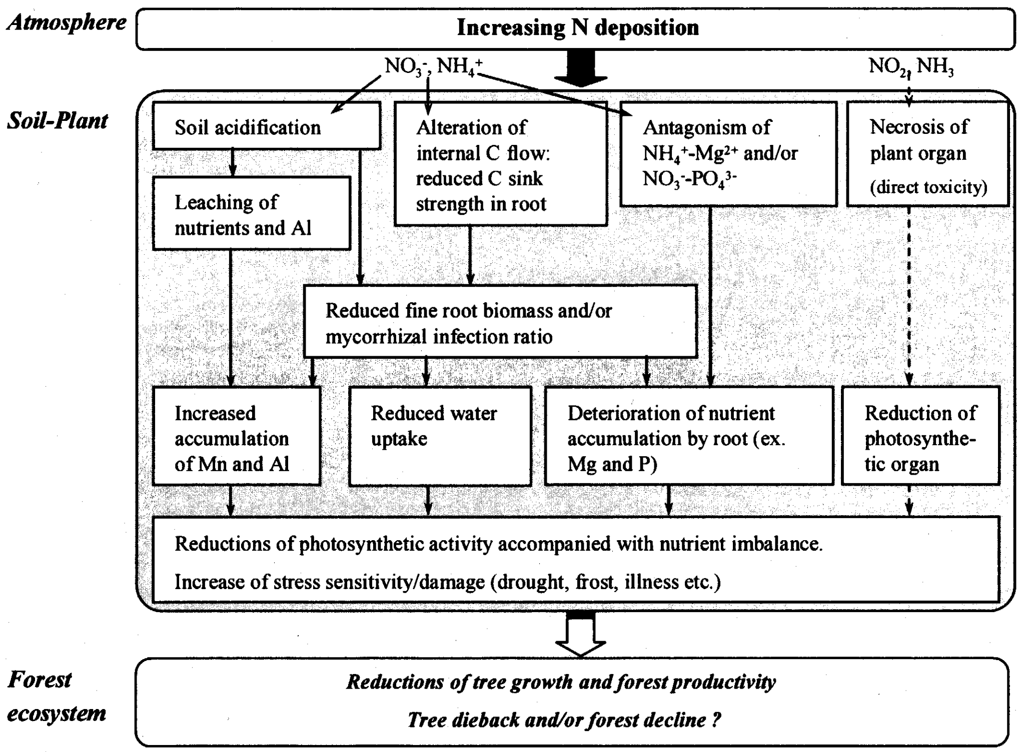

Fig. 3. Schematic images of the negative effects of increasing N deposition to forest trees.

relationships, which causes the imbalance of plant essential elements such as phosphorous (P) and magnesium (Mg) [33, 34]. In some forests with severe N-induced air pollution in Central Europe, therefore, excessive N input is considered to be one of the major environmental stresses possibly causing forest decline [35-37]. In Japan, Tsuchiya and Naemura [38] revealed a negative correlation between air pollution caused by NO_X and decline of Japanese red pine. Recently, relatively high atmospheric N deposition is considered to be a major stress factor which accelerates forest decline of Japanese red pine [39].

IV. Experimental Studies on the Effects of High Nitrogen Load on Japanese Tree Species

It is very important to clarify the responses of trees to increasing N load when we evaluate the future forest conditions. In Central Europe, several experimental studies have been conducted in parallel with field surveys to clarify the effects of excess N load on forest trees, and some of them demonstrate the negative impacts of increasing N deposition [e.g. 40, 41]. In Japan, however, information on the influences of N load on Japanese forest trees are very limited [42]. Furthermore, diversity of plant responses to N load has not yet been clarified.

Difference in the Sensitivity to Nitrogen Load among the 7 Tree Species

From the late 1990s, we started experimental studies on the effects of N load on growth, physiological functions such as photosynthesis and nutrient status of Japanese forest tree species. The growth responses of seven representative Japanese forest tree species to increasing N load were experimentally investigated under semi-natural conditions [43-46]. Table 2 shows the designs of our previous experimental studies. Although there were slight differences in the experimental designs and conditions among the experiments, 1-2 year-old seedlings of two coniferous tree species (*Pinus densiflora* Sieb. et Zucc. and *Cryptomeria japonica* D. Don), four broadleaved-evergreen tree species (*Quercus glauca* Thunb., *Q. acuta* Thunb. ex Murray, *Castanopsis cuspdata* Thunb. and *Pasania edulis* Makino) and one deciduous tree species (*Fagus crenata* Blume) were grown in potted brown forest soil for 1-2 year under N load as NH_4NO_3 solution to the soil at 0 to 340 kg ha^{-1} $year^{-1}$.

The relationships between the whole-plant dry mass of the 7 tree species and N load are shown in Fig. 4. In all the species, the whole-plant dry mass was increased by N load less than 50 kg N ha^{-1} $year^{-1}$. *Quercus* trees showed continuous stimulation of the whole-plant dry mass with increasing the amount of N added to the soil. In *Castanopsis cuspdata, Pasania japonica* and *Cryptomeria japonica,* the degree of growth stimulation was approximately 30 % at the N load of 50 kg N ha^{-1} $year^{-1}$ and it was gradually reduced at the N load of $\geq$100 kg N ha^{-1} $year^{-1}$. No N-induced growth inhibition was detected in these five tree species. On the contrary, the whole-plant dry masses of *Fagus crenata* and *Pinus densiflora* tended to be reduced by the increasing N load of $\geq$50 and $\geq$100 kg N ha^{-1} $year^{-1}$, respectively. Although these results were obtained the short-term experiments, it can be concluded that

Table 2. The summary of experimental studies on the effects of N load on seven Japanese forest tree species.

Species	Plant type	Plant age	Experimental term, field	Nitrogen load (kg N ha^{-1} $year^{-1}$)	Method of N addition
Pinus densiflora *	Coniferous, evergreen	1 year old	2 years, open air	0, 28, 57, 113, 340	NH_4NO_3, 1 time/year
Cryptomeria japonica *	Coniferous, evergreen	1 year old	1 year, open air	0, 28, 57, 113, 340	NH_4NO_3, 1 time/year
Quercus glauca **	Broad leaf, evergreen	2 year old	1 year, open air	0, 10, 50, 100, 300	NH_4NO_3, 12 times/year
Quercus acuta **	Broad leaf, evergreen	2 year old	1 year, open air	0, 10, 50, 100, 300	NH_4NO_3, 12 times/year
Castanopsis cuspdata **	Broad leaf, evergreen	2 year old	1 year, open air	0, 10, 50, 100, 300	NH_4NO_3, 12 times/year
Pasania edulis **	Broad leaf, evergreen	2 year old	1 year, open air	0, 10, 50, 100, 300	NH_4NO_3, 12 times/year
Fagus crenata ***	Broad leaf, deciduous	2 year old	1 year, phytotron	0, 10, 50, 100, 300	NH_4NO_3, 6 times/year

Reference: * Nakaji *et al*. [43, 44], ** Tominaga *et al*. [45], *** Nishimi *et al*. [46].

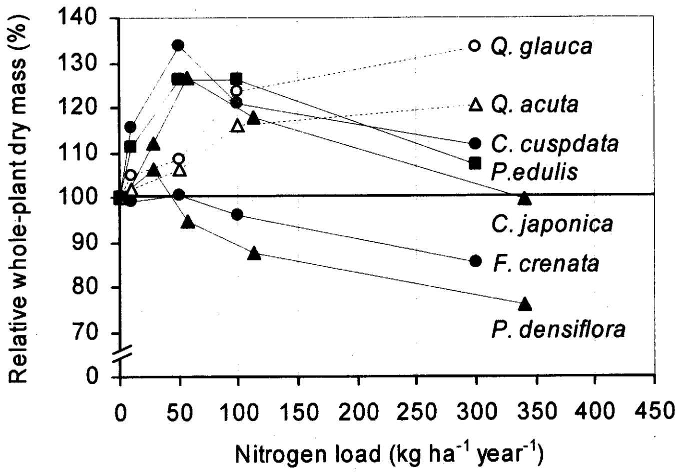

Fig. 4. Relationship between relative whole-plant dry mass of 7 tree species and the amount of N addition to the soil.. The values are re-caluculated from the results of 1-year experiments reported by Nakaji *et al*. [43], Tominaga *et al*.[45] and Nishimi *et al*.[46].

the sensitivity to N load is quite different among the Japanese forest tree species, and the composition of plant species in forests should be important to estimate the future forests conditions such as tree health, productivity and biodiversity in Japan.

Effects of Nitrogen Load on Needle Nutrient Status and Mycorrhizal Infection of Pinus densiflora

We investigated the influences of N loads at 0, 28, 57, 113 and 340 kg ha^{-1} $year^{-1}$ on needle nutrient status and mycorrhizal infection of *Pinus densiflora* seedlings [43, 44]. Figure 5 shows the element concentrations in the needles of *Pinus densiflora* seedlings grown in the 5 different N treatments for 1 year. Needle Mn concentration was significantly increased by N load. The needle concentrations of P and Mg were significantly reduced with the increasing the amount of N added to the soil. There was no significant effects of N load on the needle Al concentration (data not shown). The concentration ratios of N/P and N/Mg in the needles were significantly increased by N load, and those in the highest N treatment were 77 g g^{-1} and 22 g g^{-1}, respectively. Mohren *et al.* [47] reported the critical values of needle P concentration and N/P ratio which induces 10% reduction of the growth of Douglas fir (*Pseudotsuga menziesii*) seedlings are 1.5 mg g^{-1} and 20-30 g g^{-1}, respectively. In *Pinus densiflora* seedlings, nutrient imbalance of P, Mg (deficit) and Mn (excess) in the needles may be caused by the relatively high N load. Leaf nutrient status is generally affected by the chemical property of soil. Also, symbiosis of mycorrhiza strongly contributes to the nutrient uptake of *Pinus* trees [48]. The increase of N load caused little soil acidification, which increased the concentrations of P and Mg in the soil solution [44]. As shown in Fig. 6, N load-induced reductions of needle P and Mg concentrations were accompanied with the lowered mycorrhizal infection ratio. These results indicate that excessive N load induces growth reduction of *Pinus densiflora* with nutrient imbalances of P and Mg due to the reduction of mycorrhizal infection.

V. Conclusion

The long-term monitoring of acidic deposition shows that N deposition is one of the most dominant acidic substances in Japan. Experimental studies concerning Japanese tree species indicated that excessive N load beyond 50 kg N ha^{-1} $year^{-1}$ does not always increase the tree growth, and induces growth inhibition of N-sensitive tree species such as *Pinus densiflora*.

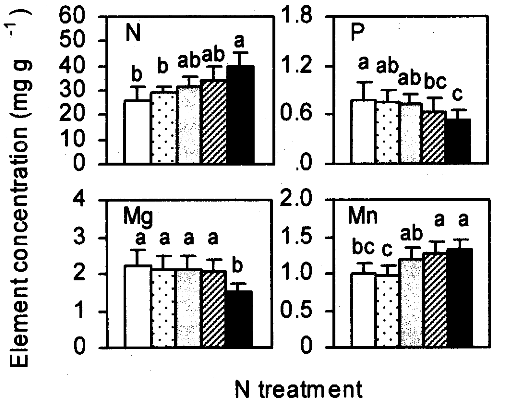

Fig. 5. Needle concentrations of N, P, Mg and Mn in *Pinus densiflora* seedlings. Each value is the mean (+s.d.) of six seedlings. Different letters above bars indicate significant differences among the treatments. N load (kg ha^{-1} $year^{-1}$): □ 0, □ 28, □ 57, ▨ 113, ■ 340. From Nakaji et al.[43].

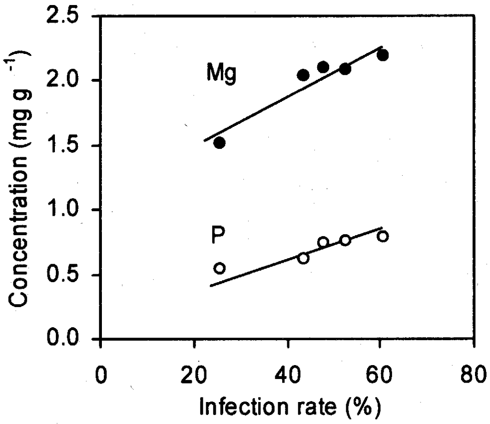

Fig. 6. Rerationship between mycorrhizal infection ratio and needle concentration of Mg (●) or P (○) of *Pinus densiflora* seedlings. From Nakaji et al. [44].

To evaluate the effects of increasing atmospheric N deposition on the entire forests in Japan, information obtained from experimental studies must be linked with field surveys. For example, because we clarified that excessive N load induces nutrient imbalances of sensitive Japanese forest tree species such as *Pinus densiflora*, the foliar concentrations of N, P and Mg, and the ratios of N/P and N/Mg may be useful as an indicator for evaluating the forest conditions under the increase of the N deposition. In Europe, the threshold of foliar nutrient status such as N/P ratio have been defined in major native tree species to evaluate forest health being affected by N deposition and other air pollutants [49, 50]. In Japan, although recently environmental scientists start to show interest in N saturation of forest ecosystem and negative N effects on forest trees, long-term experiments concerning the effects of N load on Japanese forest tree species and long-term monitoring of physiological and nutrient status of trees growing in forests under relatively high N load are not conducted at the present time. We claim that the original criteria based on the plant responses to increasing N load should be developed to conserve Japanese forests in healthy condition in the future.

VI. Acknowledgements

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