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Effects of Soil Acidification on Growth and Nutrient Status of *Pinus densiflora* Seedlings[1]

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土壤酸性化가 소나무 苗木의 生長 및 營養狀態에 미치는 影響[1]

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ABSTRACT

This study was carried out to examine the effects of soil acidification on growth and nutrient status of 2 - year - old *Pinus densiflora* Sieb. *et* Zucc. seedlings grown for 120 days in brown forest soils acidified with H_2SO_4 solution with or without leaching cations from the soil.

The concentrations of Al in the acidified soils increased with increasing amount of H^+ added to the soil. The total dry weight of the seedlings was decreased by the addition of the H_2SO_4 solution. The increase of Al concentration in the belowground part resulted from the decreased concentration of essential mineral elements such as Ca and Mg in the aboveground part. In addition, a strong positive correlation(r=0.96, p<0.001) was observed between the dry weight of the seedlings and the molar (Ca+Mg+K)/Al ratio of the soil solution. When the molar (Ca+Mg+K)/Al ratio was approximately 7.0, the dry weight of the seedlings began to decrease compared with that of the seedlings in the control treatment. The seedlings with the molar (Ca+Mg+K)/Al ratio of 1.0 resulted from approximately 40% growth reduction compared with the control value. The results suggest that the molar (Ca+Mg+K)/Al ratio of the soil solution may be a useful indicator for assessing the critical load of acid deposition.

Key words : acid deposition, molar (Ca+Mg+K)/Al ratio, nutrient status, Pinus densiflora, *seedling growth, soil acidification.*

要 約

황산용액을 첨가하여 인위적으로 산성화시킨 갈색산림토양에 2년생 소나무 묘목을 온실내에서 120일 동안 생육시킨 후, 묘목의 생장과 영양상태를 조사하였다.

토양용액의 Al 농도는 토양의 H^+ 부하량이 증가함에 따라 증가하였으며, 또한 소나무 묘목의 건물생장은 토양의 H^+ 부하량이 증가함에 따라 감소하였다. 소나무 묘목 지하부 Al 농도의 증가는 엽내 Ca 및 Mg 등과 같은 식물생장 필수원소 농도의 저하를 초래하였다. 소나무 묘목의 건물생장과 토양용액의 (Ca+Mg+K)/Al 몰비와의 사이에 높은 상관이 있는 것으로 나타났으며(r=0.96, p<0.001), 토양용액의 (Ca+Mg+K)/Al 몰비가 7.0이하로 낮아지면 건물생장이 감소가 발생하고 몰비가 1.0일 때의 건물생장은 대조구에 비하여 약 40% 감소하였다. 이상의 결과를 종합할 때 토양용액의 (Ca+Mg+K)/Al 몰비의 이용은 산성강하물에 대한 임계부하량 평가에 중요한 指標가 될 수 있다고 생각된다.

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INTRODUCTION

Dry and/or wet deposition of acid substances to forest soils may gradually increase soil acidity (Krause *et al.*, 1986 ; Hallbacken and Tamm, 1986), which could lead to serious forest decline (Hinrichsen, 1986 ; Mohnen, 1988). Soil acidification due to acid precipitation is generally associated with increasing leaching of cations such as Ca, Mg, and K from the rhizosphere(Ulrich *et al.*, 1980). Therefore, trees grown in forest soils acidified by acid precipitation may be adversely affected, not only by the resultant nutrient deficiency but also by increased level of phytotoxic Al concentration. Ulich(1989) suggested that a high concentration of Al in soil solution, resulting from the high soil acidity due to acid deposition, is a major contributing factor in the forest decline observed in central Europe. Eldhuset *et al.*(1994) investigated relationships between soil acidification and seed germination or seedling survival for the most common Norwegian forest tree species, and reported that the germination ratio of Scotch pine(*Pinus sylvestris*), Norway spruce(*Picea abies*) or silver birch(*Betula pendula*) was reduced in a podzolic soil adjusted to pH 3.9 by adding H_2SO_4 solution. The mortality of the three species during the first 7 weeks increased with decreasing from pH 4.8 to pH 3.9. Izuta *et al.*(1990) investigated the growth and nutrient status of 2-year-old Japanese cedar (*Cryptomeria japonica*) seedlings grown in an andisol artificially acidified by adding H_2SO_4 solution to the surface of the potted soil at one-day interval for 80 days, and reported that the dry weight growth and Ca concentration of the seedlings were significantly reduced by adding the H^+ to the soil.

Although there are several studies about the effects of soil acidification on tree species(Ulrich *et al.*, 1980 ; Izuta *et al.*, 1990 ; Eldhuset *et al.*, 1994), little is known about tree species growing in the East-Asia. The objective of this study was performed to investigate the growth response and nutrient status of *P. densiflora* seedlings grown in brown forest soils artificially acidified by adding H_2SO_4 solution. The brown forest soils used in this study are distributed mostly in the Korean and Japanese forest soils(Jeong *et al.*, 1994 ; The Group of Japanese Pedologists, 1990). *P. densiflora* seedlings selected in this study are typical coniferous species and widely distributed in Korea.

MATERIALS AND METHODS

1. Soil acidification

In March 1995, brown forest soils originated from granite was collected from 0 to 20cm mineral soil layer under a Japanese cedar forest stand in Kusaki, Gumma Prefecture, Japan(Tokyo University of Agriculture and Technology Forest). The collected soil was passed through a 5-mm screen.

In this study, the soil was artificially acidified by two different methods. Without the leaching of cations from the soil, H^+ was added as H_2SO_4 solution to the soil at 10, 30, 60, and 90 meq $H^+ \cdot L^{-1}$ air-dried soil, respectively. Soils without the additional supply of H^+ were used as a control. By addition, dolomite of 5% proportion of weight was supplied to the control soil. The acidified soils by the above-mentioned method were put in the container and deionized water, which consists of three times amounts of the volume of the soil, was poured to the container for the leaching of cations from the acidified soil. After 3 days, the water was gradually drained from the bottom of the container.

I used only H_2SO_4 solution to acidify the soil because SO_4^{2-} is considered to be a major component of acid precipitation in Japan(Japan Environment Agency, 1990).

2. Plant growth

2-year-old seedlings of *P. densiflora* were transplanted into the 1/10000a pots filled with the acidified or the control soils. The seedlings were grown for 120 days, from June 2nd to September 29th, 1995, in greenhouse located in Fuchu, Tokyo, Japan. The average of daily cumulative solar radiation, daily air temperature, and relative air humidity in the greenhouse during the growing period was 7.7 MJ · m^{-2} · day^{-1}, 26.8℃, and 76%, respectively. The seedlings were irrigated with deionized water applied to the potted soil surface without leakage of the water from the bottom of the pot. No nutients were added to the potted soil during the growing period. The seedlings were harvested for determination of the dry weights of the needle, trunk, and root on 29th, September. The plant tissues were dried 70℃ for 5 days and weighed.

3. Soil solution analysis

I collected soil solution up to about pF 3.8 by the method of centifuge(Kato *et al.*, 1985) before the *P. densiflora* seedlings were transplanted to the potted soil. The pH of the soil solution was measured with a pH meter(Toa Co., HM - 5B). The soil solution was filtered through filter paper(Tokyo Co., No. 5B). The concentrations of Ca, Mg, K, Mn, and Al in the filtrate were determined with an atomic absorption spectrophotometer(Shimadzu Co., Model AA - 670).

4. Mineral element concentrations of plants

The dried plant tissues were grounded into a fine powder with the vibrating sample mill(Heiko Co., TI - 100). The resultant powders were mixed with 98% of H_2SO_4 solution and the mixtures were heated at 440℃ on a digestion apparatus (Hach Co., Digesdahl 23130 - 20). The digests were diluted with 30% of H_2O_2 solution. The concentrations of Ca, Mg, K, Mn, and Al in the sample solutions were determined as mentioned above.

RESULTS

Table 1 shows the result of soil solution analysis conducted immediately before the *P. densiflora* seedlings were transplanted to the potted soils. The soil solution pH decreased with increasing amount of added H^+ in the all treatments. However, soil solution pH were 0.2~0.7 units higher in the leaching than without leaching treatment. The concentrations of Ca, Mg, and K in soil solution increased with increasing amount of added H^+. The concentrations of Ca and Mg markedly increased below about pH 4.0 in soil solution. The concentrations of Al and Mn in the soils acidified with or without leaching cations increased with increasing amount of added H^+. The concentrations of Al and Mn markedly increased below about pH 4.0 in soil solution.

The dry weight and top/root ratio(T/R) of the

Table 1. The results of soil solution analyses conducted before transplanting *P. densiflora* seedings to the potted brown forest soils.

Soil treatment	pH	Element concentration of soil solution (mmol · L^{-1}) Ca	Mg	K	Al	Mn	(Ca+Mg+K)/Al (mol · mol^{-1})
Without leaching							
Cont+D0.5%	4.93(0.03)	0.26(0.08)	0.17(0.07)	0.149(0.005)	0.06(0.00)	0.005(0.002)	9.56
Control	4.90(0.00)	0.11(0.02)	0.04(0.01)	0.086(0.004)	0.03(0.00)	0.002(0.000)	8.05
10meqH^+	4.33(0.02)	0.56(0.01)	0.32(0.00)	0.185(0.011)	0.14(0.00)	0.020(0.000)	7.55
30meqH^+	4.03(0.01)	0.95(0.00)	0.46(0.01)	0.222(0.007)	1.02(0.09)	0.049(0.001)	1.60
60meqH^+	3.78(0.01)	2.44(0.21)	1.19(0.13)	0.447(0.020)	4.92(0.57)	0.155(0.010)	0.83
90meqH^+	3.57(0.01)	2.96(0.36)	1.28(0.06)	0.381(0.036)	9.55(0.70)	0.188(0.003)	0.48
With leaching							
Control	5.18(0.02)	0.11(0.01)	0.10(0.00)	0.188(0.019)	0.04(0.02)	0.003(0.000)	10.00
10meqH^+	5.03(0.02)	0.21(0.01)	0.22(0.04)	0.166(0.010)	0.06(0.03)	0.009(0.001)	10.61
30meqH^+	4.23(0.01)	0.50(0.06)	0.34(0.04)	0.184(0.018)	0.34(0.00)	0.030(0.000)	2.98
60meqH^+	3.92(0.00)	0.82(0.04)	0.43(0.02)	0.239(0.001)	1.79(0.13)	0.047(0.001)	0.83
90meqH^+	3.78(0.00)	0.67(0.03)	0.39(0.00)	0.226(0.018)	3.83(0.34)	0.043(0.005)	0.34

Value in parenthesis shows standard deviation. The control seedlings were grown in the soil without supply of H^+. The amount of H^+ added to the soil was 10, 30, 60 or 90 meq · L^{-1} air-dried soil. Cont+D0.5%, control soil+0.5% dolomite.

Table 2. Effects of soil acidification on dry weight and its top/root ratio (T/R) of *P. densiflora* seedlings. Each value is the mean of 6 determinations.

Soil treatment	Dry weight (g)				T/R
	Needle	Trunk	Root	Whole-plant	
Initial	1.92	1.04	1.16	4.12	2.55
Without leaching					
Cont+D0.5%	5.48c	2.33b	3.37b	11.18c	2.31a
Control	4.73bc	2.42b	3.04b	10.19bc	2.34ab
10meqH$^+$	4.68bc	2.54b	3.08b	10.30bc	2.36ab
30meqH$^+$	2.87ab	2.04ab	2.08ab	6.99ab	2.38ab
60meqH$^+$	2.57a	1.58a	1.73a	5.87a	2.67b
90meqH$^+$	-	-	-	-	-
With leaching					
Control	6.33b	3.08b	4.50b	13.91b	2.09a
10meqH$^+$	6.82b	3.11b	4.53b	14.47b	2.21ab
30meqH$^+$	3.65a	1.82a	2.28a	7.74a	2.45ab
60meqH$^+$	2.47a	1.70a	1.74a	5.91a	2.54b
90meqH$^+$	-	-	-	-	-

-, the measurement of dry weight was not conducted, because all the seedlings died during the growing period of 120 days. Values followed by the different letters within a column of each soil are significantly different according to the Duncan's new multiple range test($p<0.05$). The control seedlings were grown in the soil without supply of H$^+$. The amount of H$^+$ added to the soil was 10, 30, 60 or 90 meq · L^{-1} soil. Trunk, stem+branch.

P. densiflora seedlings at the end of the 120-day growing period are shown in Table 2. In this study, the seedlings in the case of 90 meq H$^+$ of with or without leaching from the soil died during the growing period. The tissues and total dry weight per plant(TDW) of the seedlings grown in the acidified soil with or without leaching generally decreased compared with the control value except for 10 meq H$^+$ treatment. However, the T/R ratio of the seedlings increased with increasing amount of added H$^+$ in the soil with or without leaching. Additionally, the T/R ratio of the seedlings grown with leaching of cations from the soil was significantly higher in the case of 60 meq H$^+$ than in the control value.

The concentrations of mineral elements in the seedlings after the harvest are shown in Table 3. Addition of H_2SO_4 solution to the soil tended to lower the concentrations Ca and Mg in needle of the seedlings without leaching from the soil. In the acidified soils with leaching from the soil, the concentrations Ca and Mg of needle significantly lower in the case of 60 meq H$^+$ than in the control value. The concentrations of Ca and Mg were reduced in the root grown in the acidified soils with or without leaching. The concentration of K in the needle of with leaching of cations was significantly higher in the case of 60 meq H$^+$ than in the other treatment. However, the concentration of K in the trunk and root with or without leaching was not statistically significant. The concentration of Al in the root was significantly higher in the seedlings grown in the acidified soils than in the control. The concentration of Al in the case of 60 meq H$^+$ in the needle of without leaching higher than in the control value. No significant differences were found in the concentrations of Mn in all of tissues between the seedlings grown in the acidified soil and the control.

DISCUSSION

In general, the most important limiting factors for normal plant growth, physiological functions, and nutrient status of plants grown in acid soil are considered to be in the soil acidity itself,

Table 3. Element concentrations of needle, trunk, and root of *P. densiflora* seedlings after the growing period of 120 days. Values are expressed on the basis of dry weight.

Plant organ	Soil treatment	Ca ($mg \cdot g^{-1}$)	Mg ($mg \cdot g^{-1}$)	K ($mg \cdot g^{-1}$)	Al ($mg \cdot g^{-1}$)	Mn ($mg \cdot g^{-1}$)
Needle	Without leaching					
	Cont+D0.5%	4.40a	1.29a	4.11a	0.51a	0.482a
	Control	3.98a	1.24a	4.28a	0.50a	0.589ab
	10meqH$^+$	3.84a	0.96a	4.00a	0.57a	0.523ab
	30meqH$^+$	3.60a	0.99a	4.10a	0.65ab	0.630ab
	60meqH$^+$	3.37a	1.09a	4.69a	0.79b	0.975b
	90meqH$^+$	-	-	-	-	-
	With leaching					
	Control	4.08b	1.31b	3.36a	0.57a	0.719a
	10meqH$^+$	4.06b	1.11ab	3.62a	0.56a	0.489a
	30meqH$^+$	3.68ab	0.96a	3.31a	0.57a	0.593a
	60meqH$^+$	3.02a	1.00a	5.00b	0.77a	0.597a
	90meqH$^+$	-	-	-	-	-
Trunk	Without leaching					
	Cont+D0.5%	3.31a	0.90ab	2.80a	1.27a	0.156a
	Control	3.20a	0.90ab	3.23a	1.51a	0.197a
	10meqH$^+$	2.95a	0.70a	3.08a	1.28a	0.239a
	30meqH$^+$	2.73a	1.06b	2.87a	1.83a	0.247a
	60meqH$^+$	2.48a	0.82ab	3.41a	1.74a	0.229a
	90meqH$^+$	-	-	-	-	-
	With leaching					
	Control	3.18b	0.98a	2.88a	1.12a	0.229a
	10meqH$^-$	2.90ab	0.85a	2.60a	1.10a	0.206a
	30meqH$^+$	2.82ab	0.78a	2.59a	1.56ab	0.267a
	60meqH$^+$	2.67a	0.79a	3.20a	1.85b	0.237a
	90meqH$^+$	-	-	-	-	-
Root	Without leaching					
	Cont+D0.5%	3.06b	0.85b	3.12a	3.32a	0.066a
	Control	3.11b	0.78ab	3.28a	5.00b	0.095ab
	10meqH$^+$	2.43ab	0.61ab	3.15a	5.16b	0.124b
	30meqH$^+$	2.36ab	0.54ab	3.21a	5.46bc	0.088ab
	60meqH$^+$	1.87a	0.45a	2.35a	6.52c	0.082ab
	90meqH$^+$	-	-	-	-	-
	With leaching					
	Control	3.07b	0.71b	2.83a	4.36a	0.086a
	10meqH$^+$	3.05b	0.83c	3.07a	5.04ab	0.117a
	30meqH$^+$	2.76ab	0.61ab	3.58a	5.14ab	0.110a
	60meqH$^+$	2.51a	0.56a	3.52a	6.17b	0.112a
	90meqH$^+$	-	-	-	-	-

-, the measurement of dry weight was not conducted, because all the seedlings died during the growing period of 120 days. Values followed by the different letters within a column of each soil are significantly different according to the Duncan's new multiple range test($p<0.05$). Each value is the mean of 4 determinations

The control seedlings were grown in the soil without supply of H^+. The amount of H^+ added to the soil was 10, 30, 60 or 90 $meq \cdot L^{-1}$ soil. Cont+D0.5%, control soil+0.5% dolomite. Trunk, stem+branch.

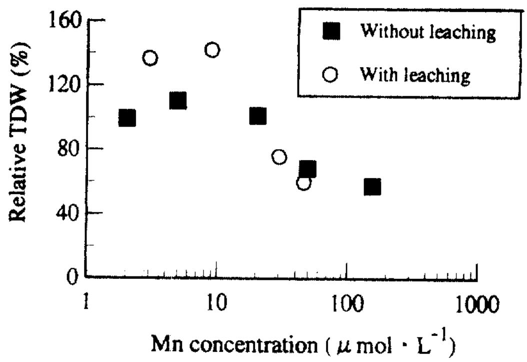

Fig. 1. The relationship between the concentration of Mn in brown forest soils and relative total dry weight(TDW) of *P. densiflora* seedlings. Relative TDW was calculated as followed : relative TDW(%)={(average TDW of the seedlings grown in the soil acidified with H_2SO_4 solution)/(average TDW of the seedlings grown in the control of without leaching)}×100.
The control seedlings were grown in the soil without supply of H^+. The amount of H^+ added to the soil was 10, 30, 60 or 90 meq · L^{-1} air - dried soil.

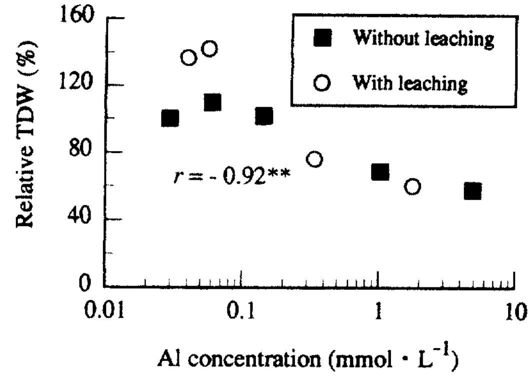

Fig. 2. The relationship between the concentration of Al in brown forest soils and relative total dry weight(TDW) of *P. densiflora* seedlings.
** indicates significant correlation on the 1% level.

the level of phytotoxic metals such as Al and Mn dissolved in the soil solution, and reduced availability of certain essential mineral elements (Adams, 1981). Fig. 1 shows the relationship between the relative total dry weight(TDW) of *P. densiflora* seedlings and Mn concentration in soil solution. As shown in Fig. 1, there was no correlation between the Mn concentration in soil solution and the relative TDW of the seedlings. Therefore, the reduced growth response of the seedlings in acidified soils cannot be explained by the increased Mn concentration.

Although the clear negative correlation(r= -0.92, p<0.01) was found between the relative TDW of the seedlings and Al concentration in the soil solution(Fig. 2), the relative TDW of the seedlings showed a great variation below approximately 0.1mmol · L^{-1} of Al concentration. This result suggests that the growth response of the seedlings in acidified soils cannot be explained completely by Al concentration alone in the soil solution.

In the last decade, the molar ratios of cations such as Ca, M, and/or K to Al in soil solution have been regarded as an important limiting factor for the growth and nutrient status of woody plants(Kruger and Sucoff, 1989 ; Hecht - Buchholz *et al.*, 1987 ; Sverdrup *et al.*, 1994 ; Cronan and Grigal, 1995). Sverdrup *et al.*(1994) reported that there was a positive correlation between the molar (Ca+Mg+K)/Al ratio in the soil solution and the growth of European species such as Norway spruce(*Picea abies*). On the other hand, Cronan and Grigal(1995) proposed the molar Ca/Al ratio of the soil solution as the most useful indicator of stress in forest ecosystems. In this study, a positive correlation was observed between the dry weight growth of the seedlings and the molar of Ca to Al(molar Ca/Al ratio) in the soil solution(Fig. 3). However, when the molar Ca/Al ratio was approximately 3.5, there was a slight variation in the relative TDW of the seedlings(Fig. 3). As shown in Fig. 4, a strong positive correlation(r=0.96, p<0.001) was found between the molar (Ca+Mg+K)/Al ratio in the soil solution and the relative TDW of the seedlings. Therefore, the growth response of the seedlings grown in the acidified soil is considered to be determined by the balance between Al and essential mineral elements for plant growth, such as Ca, Mg, and K in the soil solution.

It is well known that relative high concentra-

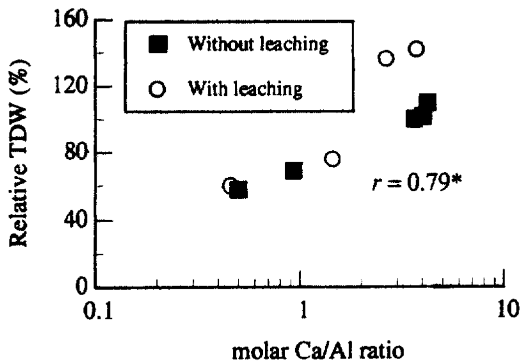

Fig. 3. The relationship between molar Ca/Al ratio in brown forest soils and relative total dry weight(TDW) of *P. densiflora* seedlings.
* indicates significant correlation on the 5% level.

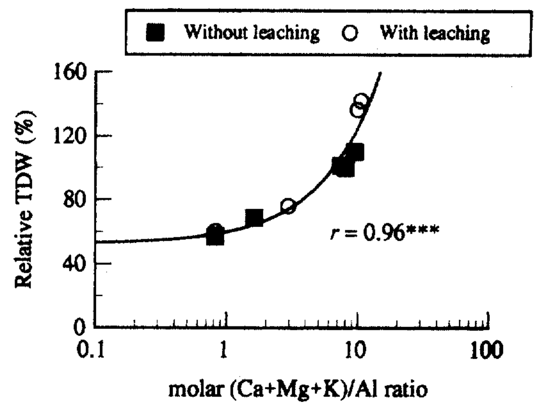

Fig. 4. The relationship between molar (Ca+Mg+K)/Al ratio in brown forest soils and relative total dry weight(TDW) of *P. densiflora* seedlings.
*** indicates significant correlation on the 0.1% level.

tions of Al in soil and nutrient solutions cause a disturbance of the nutrient status of crop and plants(Foy *et al.*, 1978). As shown in Table 3, the concentrations of Ca and Mg in the seedlings grown in the acidified soils were significantly reduced by the addition of H^+ to the soil. Similar results were observed in *P. densiflora* and Japanese cedar seedlings grown in nutrient solutions containing Al at 10 ppm or above(Göransson and Eldhuset, 1987 ; Lee *et al.*, 1997 ; Izuta *et al.*, 1996 ; Miyake *et al.*, 1991). The high Al concentration induced the inhibition of Ca and Mg uptake is thought to result from competition between this metal and these element essential for plant growth at their binding sites on the roots surface(Wagatsuma and Ezoe, 1985). Also, increase of Al concentration in the belowground part of the seedlings decreased the concentration of essential mineral elements for plant growth such as Ca and Mg in the aboveground part(Table 3). This result indicates that the reduction in the dry weight growth of the seedlings grown in the acidified soils was mainly due to the high Al concentration induced by the inhibition of uptake of elements essential for growth through the roots.

The results obtained from this study, the molar ratios of cations such as Ca, Mg, and/or K to Al in the soil solution, particularly the molar (Ca+Mg+K)/Al ratio, are considered to be a useful indicator for evaluating the critical load of acid deposition. When the molar (Ca+Mg+K)/Al ratio was approximately 7.0, the dry weight growth of the seedlings began to decrease compared with that of the seedlings in the control treatment. The seedlings with the molar (Ca+Mg+K)/Al ratio of 1.0 resulted from approximately 40% growth reduction compared with the control value.

The critical load of acid deposition to forest ecosystems in Europe was evaluated based on a molar (Ca+Mg+K)/Al ratio in the soil solution of 1.0, which was determined mainly from the data of many experimental studies on seedlings of European trees such as Norway spruce(Sverdrup *et al.*, 1994). It is necessary to study whether it is possible to use a molar (Ca+Mg+K)/Al ratio of 1.0 as the criterion for assessing the critical load of acid deposition. Future studies are needed on the relationship between the molar ratios of cations to Al in different forest soils and the dry weight growth of many tree species.

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