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Soil Nitrogen Dynamics in Two Black Locust Stands Established on Volcano Mt. Showa-Shinzan, Northern Japan[1]

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日本 北部의 昭和新山의 噴火後에 成立한 두 아카시아나무 林分의 土壤中 窒素動態[1]

文 炫 植[2]

ABTRACT

To clarify the soil N dynamics, the relationship between soil N and vegetation recovery after volcanic eruptions was investigated in two stands dominated by black locust(*Robinia pseudo-acacia* L.) on volcano Mt. Showa-Shinzan, northern Japan, from August 1994 to July 1996. No significant differences were observed between the two stands with respect to soil chemical properties and soil extractable N. At both stands, total N concentration were high in spring and declined through the summer and fall. The peaks in concentrations of extractable NH_4^+ and NO_3^- occurred in July at both stands. NH_4^+ mineralization showed a conspicuous peak in June and July throughout the study period. Extractable NO_3^- concentration and nitrification rates at the two stands during the study period were relatively high. Negative values for NH_4^+ mineralization at both stands were found in August. Extractable NH_4^+ and NO_3^- concentrations were correlated positively with soil organic matter, and nitrification rates were controlled by NH_4^+ mineralization and extractable NH_4^+ concentration at both stands.

Key words : Robinia pseudo-acacia, *NH_4^+ mineralization, Nitrification, Nitrogen availability, Vegetation recovery, Volcanic eruption.*

要 約

이 研究는 日本 北部의 昭和新山 噴火後에 成立한 壯齡林과 幼齡林의 두 아카시아 나무 林分에 있어서 土壤中의 窒素動態와 植生回復과의 關係를 究明하기 위하여 1994年 8月부터 1996年 7月까지 2年間 調査하였다. 土壤의 化學的性質과 有效態 窒素는 두 林分 間에 뚜렷한 差異는 나타나지 않았지만, 土壤中 全窒素 含量은 初期生長期인 5月에 높은 數値를 나타낸 後 점차 減少하는 傾向을 나타내었다. 두 調査 林分에서 암모니아態 窒素와 窒酸態窒素는 7月에 뚜렷이 높아지는 傾向을 나타내었다. 窒素無機化는 地溫의 增加로 因해 每年 6月~7月에 높아지는 傾向을 나타내었다. 窒酸態窒素의 含量과 窒酸化作用은 두 調査 林分에서 比較的 높은 數値를 나타내었다. 두 調査 林分의 窒素無機化는 8月에 마이너스의 數値를 나타내었다. 두 調査 林分에 있어서 암모니아態 窒素와 窒酸態窒素는 土壤有機物 含量과, 窒酸化作用은 窒素無機化와 암모니아態 窒素의 含量과 正의 相關을 나타내었다.

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INTRODUCTION

Forest development in a volcanic area is recognized as an example of primary succession (Vitousek *et al.*, 1989). Over the past few decades a considerable number of studies have been made on forest development after volcanic eruption(Tezuka, 1961 ; Wood and Del Moral, 1987 ; Whittaker *et al.*, 1989 ; Tsuyuzaki, 1994), but most of these studies have been concerned with describing the successional sequences and species composition of plant communities that accompany forest development.

Nitrogen(N) cycling within forest ecosystems has received considerable attention because N availability often limits plant productivity and plant communities. Increased biomass production due to the addition of N fertilizers has been widely observed(Keeney, 1980). Robertson *et al.* (1988) suggested that small-scale patterns of N availability within sites may also be important in distribution patterns of succession. Differences in the amounts and forms of available soil N had been shown to be related to the successional positions of species(Westman, 1981 ; Tilman, 1984, 1986) and the plant community(Robertson and Vitousek, 1981 ; Robertson, 1982 ; Titlyanova, 1982).

The early stages of forest development are frequently dominated by symbiotic N-fixing species, since symbiotic N-fixing species are fast growing, accumulate high N concentrations and increase nutrient availability in the ecosystem (Turner *et al.*, 1976 ; Youngberg and Wollum, 1976). Actually, in the 50 year-period after the 1944-45 eruptions, Mt. Showa-Shinzan has recovered with the natural invasions of pioneer species such as black locust(*Robinia pseudo-acacia*), poplar(*Populus maximowiczii*), alder(*Alnus maximowiczii*), and aspen(*Populus sieboldii*). Unfortunately, no studies have been directed towards understanding the process of vegetation recovery after volcanic eruption from the standpoint of soil nutrients. Therefore, it would appear to be important to have an understanding of the soil N dynamics at black locust stands at an early stage in vegetation recovery when we discuss forest development in a volcanic area.

The purpose of the present study was to estimate soil N dynamics such as NH_4^+ mineralization and nitrification rate in mature and immature black locust stands recovering from a volcano, in order to determine the underlying factors that control these processes.

MATERIAL AND METHODS

1. Study area

This study was conducted in Mt. Showa-Shinzan(407m in alt., 42° 33′ N, 140° 52′ E) northern Japan, which was created by volcanic eruptions in the period of 1944-45. Annual precipitation in this area is about 990㎜, with about a half this falling in the summer months. The mean annual temperature is 8.6℃, with mean monthly temperatures ranging from -6.2℃ in January to 23.2℃ in August. This study area is covered by snow for about 4 months, from late December to early April. The soils of this area are lapilli, andesite and pumice stone developed after volcanic eruptions. Black locust stands revegetates covering more than 20㏊ after creation of Mt. Showa-Shinzan. Although black locust is exotic species introduced from native North America, the species is planted extensively in Japan for erosion control. On the upper and lower slopes of volcano Mt. Showa-Shinzan, black locusts form two ecosystems displaying differences between tree age and species composition. In this study, two study stands representing 20 and 48 year-ages after volcanic eruptions were selected. The maximum tree heights at mature and immature stand were 25m and 9m, and their basal areas were 41.3 and 19.1㎡/㏊, respectively. While the immature stand largely consisted of a pure stand of black locust, the mature stand was made up of a mixture of certain deciduous broad-leaved trees such as oak(*Quercus crispula*), maple(*Acer mono*), and prickly castor-oil tree (*Kalopanax pictus*). A dominant feature of the forest floor at each stand was the presence of giant knotweed(*Polygonum sachalinense*) and wormwood(*Artemisia montana*). Characteristics of the study stands are shown in Table 1.

Table 1. Characteristics of the study stands.

Parameter	Mature stand	Immature stand
Altitude(m)	125	260
Plot size(m²)	400	400
Aspect	N	NE
Slope(°)	0–3	6–15
Tree age(yr)	47–50	17–21
Basal area(m²/ha)	41.3	19.1
Coverage(%)	100	100
Mean Height(m)	18	7
Dominant species		
Upper	*Robinia pseudo-acacia*	*Robinia pseudo-acacia*
Lower	*Polygonum sachalinense*	*Artemisia montana*

2. Soil sampling and analysis

Seven samples were randomly collected at mineral soils depth of 0–10cm in each stand. Samples were brought to the laboratory and refrigerated at 4℃. Sampling was carried out every month from August 1994 to July 1996, except when soils were frozen(December–April). Before analysis, soil samples were ground and passed through a 2-mm sieve. Soil moisture content was determined by measuring the loss of weight at 105℃. Organic matter content was determined by loss of weight on ignition at 450℃ for 4hr. Soil pH(H_2O) was measured on 1 : 2.5 soil : deionized water extracts using a glass electrode. Total N content were measured by using a C-N Corder (MT-1600, YANACO). Available P in soil was extracted by 0.002N H_2SO_4 and determined by atomic absorption spectrophotometry(SPCA-626D, SHIMADZU). Exchangeable cations were extracted from soils with 1N CH_3COONH_4 buffered to a pH of 7.0, and then the concentrations of Ca^{2+}, Mg^{2+} and Na^+ were determined by atomic absorption spectrophotometer, and those of K^+ by a flame-photometric procedure(SPCA-626D, SHIMADZU).

The concentrations of extractable NH_4^+ and NO_3^--N were determined. Seven 20g fresh-soil samples were extracted by shaking with 2N KCl. The extracts were filtered and stored. NH_4^+ and NO_3^--N in the extract were determined by an automated colorimetric method using the nitroprusside-catalysed indophenol reaction and analyzed as NO_2-N after reduction in a Cadmium column(UV-260, SHIMADZU), respectively. The concentrations of extractable NH_4^+ and NO_3^--N were expressed as N milligram per kilogram of dry soil.

Net NH_4^+ mineralization and nitrification rate were also determined by 30 day aerobic incubations in the laboratory(Keeney, 1982). At the end of the incubation period, seven samples were extracted and analyzed for NH_4^+ and NO_3^--N as described above. Net NH_4^+ mineralization was taken to be the difference between the initial and incubated samples. Similarly, nitrification rate was taken to be the initial NO_3 concentration minus the concentrations observed after incubation. Nitrogen availability is the sum of net NH_4^+ mineralization and nitrification rate.

3. Statistical analysis

All data from the stands were subjected to analysis of variance, with all data log-transformed to homogenize the variance inherent in measuring chemical parameters. Estimations of contrasts between the different stands were based on Tukey's honest-significant-difference measure. Analysis of variance was performed with the SPSS(Statistical Package for the Social Sciences) version 7.5.

RESULTS

1. Soil properties

Table 2 shows the results of soil properties at both stands. Soil properties were expressed as mean values throughout the study period. There was no significant difference between the mature and immature stands with respect to moisture content, soil pH(H_2O), organic matter, and available P concentrations. The concentrations of exchangeable Ca^{2+} and Mg^{2+} were relatively higher at the immature stand than at the mature stand. No significant differences were found in K^+ and Na^+ between two stands(Table 2). At both stands, total N concentrations was high in spring and declined through the summer and fall(Fig. 1).

Table 2. Soil properties for mineral soils of mature and immature black locust stands on volcano Mt. Showa-Shinzan. The data are mean values during the study period with standard deviations in parenthesis

Stand	Moisture (%)	pH (H_2O)	Organic matter(%)	Available P (mg/100g)	Exch. (me/100g)			
					Ca	Mg	K	Na
Mature	28.2[a]	5.98[a]	4.0[a]	11.7[a]	7.8[a]	1.25[a]	1.49[a]	0.17[a]
	(6.65)	(0.42)	(1.41)	(5.48)	(1.35)	(0.33)	(0.40)	(0.03)
Immature	26.3[a]	6.02[a]	3.7[a]	14.0[a]	13.3[b]	2.01[b]	1.56[a]	0.20[a]
	(4.68)	(0.35)	(1.33)	(2.34)	(2.21)	(0.57)	(0.47)	(0.04)

Same superscript letters within each column indicate no significant difference($p<0.05$) sites based on ANOVA

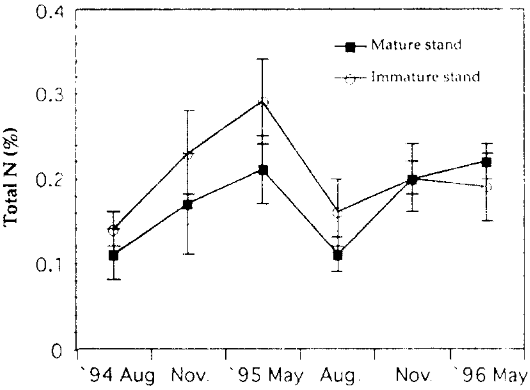

Fig. 1. Seasonal change of total N content for mineral soils of mature and immature black locust stands established on volcano Mt. Showa-Shinzan.

2. Extractable NH_4^+ and NO_3^- -N

Extractable NH_4^+ concentration varied throughout the year and were ranged from 0.6 to 4.7(N ㎎/㎏) at the mature and 0.65 to 5.0(N ㎎/㎏) at the immature stand(Fig. 2A). A conspicuous peak in extractable NH_4^+ concentration occurred in June and July 1995 and declined through the late summer and fall at both stands. The smallest average extractable NH_4^+ concentration occurred during November and May at the two stands. Annual average NH_4^+ concentrations were 1.78 (±1.31) at the mature stand and 2.14(±1.33)(N ㎎/㎏) at the immature stand.

Extractable NO_3^- concentrations were ranged from 5.4 for June 1996 to 10.2(N ㎎/㎏) for July 1996 at the mature stand and 2.6 for October 1994 to 10.8(N ㎎/㎏) for July 1996 at the immature stand(Fig. 2B). A large peak in extractable NO_3^- occurred in July 1996 at both stands. Average extractable NO_3^- concentrations throughout the study period were slightly higher at the mature stand. Compared to the concentrations of extractable NH_4^+ and NO_3^- -N, extractable NO_3^- was relatively higher than NH_4^+ except for June

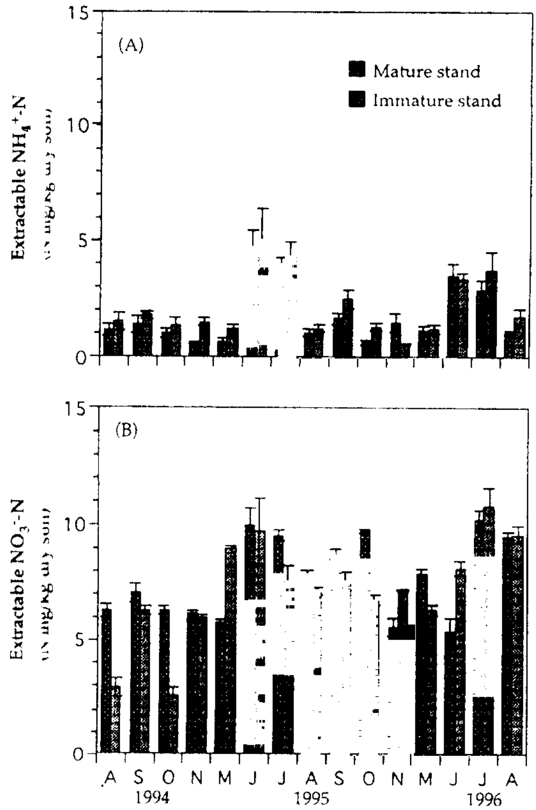

Fig. 2. Seasonal patterns and amounts of extractable NH_4^+ and NO_3^- -N concentrations for mineral soils of mature and immature black locust stands established on volcano Mt. Showa-Shinzan. The data are mean values with standad deviations.

Table 3. The ratio of extractable N to total N in field and nitrification rates relative to N availability

Stand	Sampling month	Extractable N* (N mg/kg)	% of total N	N availability** (N mg/kg)	Nitrification (%)
Mature	'94Aug.	8.32	0.55	—[a]	—[a]
	Nov.	6.87	0.49	2.83	52.3
	'95May	6.78	0.25	4.54	32.2
	Aug.	8.83	0.49	—[a]	—[a]
	Nov.	8.54	0.53	4.61	30.6
	'96May	9.73	0.49	4.27	57.8
Immature	'94Aug.	6.28	0.37	—[a]	—[a]
	Nov.	8.94	0.36	3.77	32.1
	'95May	10.81	0.64	5.28	28.0
	Aug.	10.08	0.63	—[a]	—[a]
	Nov.	7.80	0.52	3.63	36.6
	'96May	8.52	0.57	3.30	59.4

* : Extractable N is sum of NH_4^+ and NO_3^- -N.
** : N availability added up NH_4^+ mineralization and nitrification rate.
a : Net immobilization occurred in the laboratory incubation.

and July at the two stands. The percentage of extractable N relative to total N ranged from 0.25 to 0.55% at the mature stand and from 0.36 to 0.64% at the immature stand(Table 3).

3. NH_4^+ mineralization and nitrification rate

Seasonal patterns in net NH_4^+ mineralization and nitrification rate are shown in Fig. 3. Generally, net NH_4^+ mineralization reflected the amount of organic N and the quality/quantity of soil organic matter available for mineralization. At both of the two black locust stands, net NH_4^+ mineralization was greater in June and July, and decreased in the late summer and fall. No significant difference was observed in NH_4^+ mineralization between the two stands. Negative values for NH_4^+ mineralization at both stands were found in August.

Although the nitrification rates throughout the study period showed no remarkable differences between the two stands, higher values for nitrification rates at the two stands were observed in June and July, and declined in the fall and early spring. The percentage of nitrification to N availability ranged from 31 to 58% at the mature and ranged from 28 to 59% at the immature stand(Table 3).

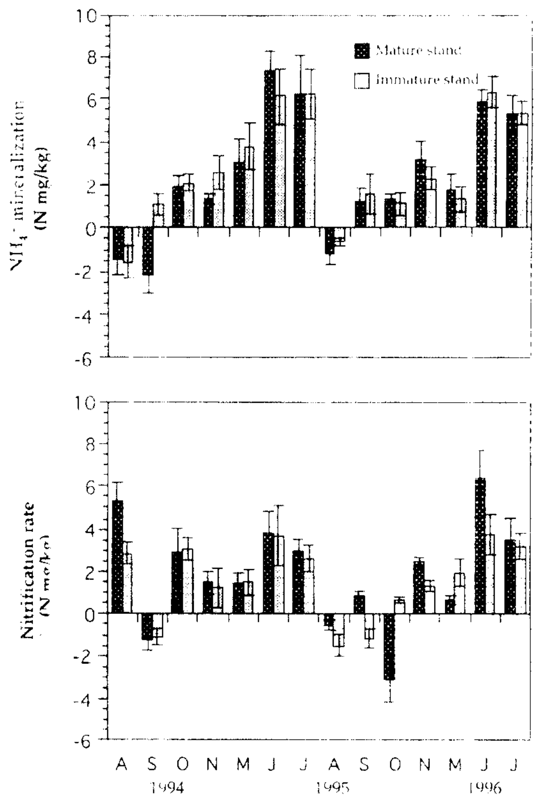

Fig. 3. Seasonal patterns of net NH_4^+ mineralization and nitrification rate for mineral soils of mature and immature black locust stands established on volcano Mt. Showa-Shinzan. The data are mean values with standad deviations.

4. Correlation between soil N and soil properties

The correlation between soil N and soil properties at the two stands is shown in Table 4. Low soil pH(H_2O) had a detrimental effect on NH_4^+ mineralization and nutrient availability in the soil, but the soil pH(H_2O) had no effect on N dynamics in the present study. Extractable NH_4^+ concentration was correlated positively with organic matter($r=0.78$ and 0.71, $p<0.001$ at the mature and immature stand, respectively). Extractable NO_3^- concentration also showed positive correlation with soil moisture content($r=0.48$ and 0.58, $p<0.001$ at the mature and immature stand, respectively) and organic matter($r=0.41$ and 0.57, $p<0.001$ at the mature and immature stand, respectively). Although extractable NH_4^+ concentration was correlated significantly with NH_4^+ mineralization($r=0.76$ and 0.67, $p<0.001$, at the mature and immature stand, respectively), extractable NO_3^- concentration did not show a certain correlation with nitrification rate. At the mature stand, nitrification rates were controlled by NH_4^+ mineralization($r=0.51$, $p<0.001$), extractable NH_4^+ concentration($r=0.54$, $p<0.001$) and organic matter($r=0.54$, $p<0.001$). Similarly, nitrification rates gave significant correlation with NH_4^+ mineralization($r=0.56$, $p<0.001$), extractable NH_4^+ concentration($r=0.49$, $p<0.001$) and organic matter ($r=0.38$, $p<0.01$) at the immature stand.

DISCUSSION

Differences in soil organic matter have been proposed to control N mineralization in various forest ecosystems in Wisconsin(Nadelhoffer *et al.*, 1983 ; Pastor *et al.*, 1984). In contrast to our results these studies showed no relation between N availability and soil N content in a variety of old forests in Wisconsin. The reasons for this difference are not clear, but may be due to variations in the quality and/or quantity of soil organic matter between dominant species and differences in habitat conditions.

Many investigators have examined the relationships between successional sere and nitrification in various forest ecosystems. Robertson and Vitousek(1981) found that rates of nitrification

Table 4. Correlation coefficient between soil N and soil properties

〈Mature stand〉

	Soil pH	Moisture	Organic matter	Extractable NH_4^+	Extractable NO_3^-	NH_4^+ mineralization
Soil pH						
Moisture	-0.03^{ns}					
Organic matter	-0.06^{ns}	0.34^{**}				
Ext NH_4^+	-0.13^{ns}	0.31^{**}	0.78^{***}			
Ext NO_3^-	-0.10^{ns}	0.48^{**}	0.41^{***}	0.39^{**}		
NH_4^+ mine	0.20^{ns}	-	0.70^{***}	0.76^{***}	0.27^{*}	
Nitrification	0.13^{ns}	-	0.54^{***}	0.54^{***}	-0.24^{ns}	0.51^{***}

〈Immature stand〉

	Soil pH	Moisture	Organic matter	Extractable NH_4^+	Extractable NO_3^-	NH_4^+ mineralization
Soil pH						
Moisture	0.11^{ns}					
Organic matter	-0.03^{ns}	0.57^{***}				
Ext NH_4^+	-0.17^{ns}	0.42^{***}	0.71^{***}			
Ext NO_3^-	0.13^{ns}	0.58^{***}	0.57^{***}	0.54^{***}		
NH_4^+ mine	0.01^{ns}	-	0.77^{***}	0.67^{***}	0.63^{***}	
Nitrification	0.10^{ns}	-	0.38^{***}	0.49^{***}	0.08^{ns}	0.56^{***}

$n=70$, ^{ns} : Not Significant, * : $p<0.05$, ** : $p<0.01$, *** : $p<0.001$

appeared to be regulated by the rates of NH_4^+ mineralization in primary and secondary successional seres. In addition, nitrification rates seemed to be regulated by the availability of ammonium at the majority of the primary successional stands and at all sites in the secondary successional sere(Robertson, 1982). In this present study, nitrification rates were controlled by the level of extractable NH_4^+ and NH_4^+ mineralization at the two stands.

The concentrations of extractable NH_4^+ were higher in June and July. Also, higher production of NH_4^+ mineralization was observed in both June and July, and generally declined during midsummer and fall. The higher extractable NH_4^+ concentration and NH_4^+ mineralization in June and July suggests that litters that had sojourned over the winter period, because of low microbial activity, provided a suitable substrate for microbial decomposition with the approach of warmer weather and consequent increase in soil temperatures(Van Cleve *et al.*, 1993 ; Moon, 1998). The negative values for both NH_4^+ mineralization and nitrification rate observed in August and September probably resulted from N immobilization by soil microbes during the incubation period(Nadelhoffer *et al.*, 1984 ; Van Cleve *et al.*, 1993). This suggested that the rates of NH_4^+ mineralization and nitrification rate exceed the rate at which organic N and ammonium-N are mineralized to ammonium-N and nitrate-N during the incubation period.

At the two stands, extractable NO_3^- concentrations were relatively high. The relatively high concentrations of extractable NO_3^- suggested that the nitrification process is active and that NO_3^--N is readily available for other plant uptake. Boring *et al.*(1981) and Montagnini *et al.*(1986) reported that area dominated by black locust had high NO_3^--N concentration and active nitrification rate. Actually, both stands in the present study showed considerable nitrification rate. If one considers the N cycling within a forest ecosystem, black locust ecosystem had greater NH_4^+ mineralization and nitrification rates in the early stages of forest development, resulting in a higher potential for losses of nitrate through leaching from the forest soil, as the nitrate ion is more easily leached from soil and readily exported from forest ecosystems. Beaupied *et al.*(1990) and Binkley *et al.*(1985) stated that N-fixing alder species can rely most of their N requirements on an atmospheric origin, even if mineral N is plentiful in the soil. Compared to understory vegetation between other ecosystems established on Mt. Showa-Shinzan(Moon, 1998), dense understory vegetation within black locust stand presumably due to high retention of extractable NO_3^--N and active N mineralization.

Substantial quantities of N fixation have been reported for black locust(Boring and Swank, 1984), resulting in probably high N input into soils. Boring and Swank(1984) estimated that N input into the forest ecosystem as a result of N fixation by black locust to be 48 N ㎏/㏊/yr for a 4-years-old stand, 75 for a 17-years-old stand, and 33 for a 38-years-old stand. These data for N-fixation by black locust suggest that N fixation increases rapidly and peaks in the early to intermediate stages of forest development and then declines with later forest development. Additionally, these data endorses the notion that N fixing species are well-adapted to nutrient-poor stands such as occur after volcanic eruptions (Vitousek and Walker, 1989), as shown for the vigorous N fixation ability of black locust.

A comparison of individual numbers at the two stands showed that black locust density decreased with tree age. Some overturned trees of black locust were found at the mature stand and inferior individuals had been eliminated from the overstory. This may be an important successional mechanism for the release of sub-dominant species such as maple, oak and prickly castor-oil tree. In addition, the open gaps in the canopy promote growth in the understory of longer-lived individuals such as knotweed. It is well known that the black locust generally has a relative by short life span(McGee and Hooper, 1975), but that its presence results in an increased N accumulation through active N fixation in the primary stage and during early canopy gap formation, conditions which may facilitate plant growth and successional species replacement.

Although 50 years have passed since the creation of Mt. Showa-Shinzan by a volcanic eruption, the author attempted to understand the vegetation recovery, because many studies have stressed the importance of the relationship between nutrient availability and the plant community. On the upper and lower slopes of volcano Mt. Showa-Shinzan, black locust forms two communities displaying differences between tree age and species composition. After the creation of Mt. Showa-Shinzan by a volcanic eruption, the mature black locust stand probably represents an early community that was established as a result of N fixation by black locust. When we consider ecological succession, it is to be expected that the mature stand of black locust will be rapidly replaced by other species as a result of the accumulation of abundant soil nutrients and canopy gap formation compared to immature stand, even though precise estimations of the successive changes remain problematic.

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