論文

Effects of stand structure on growth in selection stands dominated by todo fir (*Abies sachalinensis*)Satoshi TATSUHARA*, Hirokazu YAMAMOTO**,
Norikazu TAKADA** and Hiroshi INUGAI**

TATSUHARA, Satoshi, YAMAMOTO, Hirokazu, TAKADA, Norikazu and INUGAI, Hiroshi : **Effects of stand structure on growth in selection stands dominated by todo fir (*Abies sachalinensis*)**. Jpn. J. For. Plann. 25 : 17~25, 1995 This paper examines the relationship between growth and stand structure in selection forests dominated by todo fir (*Abies sachalinensis* (Fr. Schmidt) Masters). Trees were classified into six classes by their species (conifers or broad-leaved trees) and diameter (small, medium or large trees). A principal component analysis showed that the six class volumes were well summarized by the first two principal components obtained from the class volumes. The first principal component contrasted the volume of small and medium-sized conifers with the volume of large conifers and broad-leaved trees. The second principal component contrasted the volume of medium and large conifers with the volume of large broad-leaved trees. Next, a multiple regression analysis showed that there were correlations of net increment, gross increment and mortality with the principal components; and the relationships between stand volume growth and six class volumes were shown numerically. The first principal component reflected a constant effect (i. e., independent of time since selection cutting) of stand structure on volume growth and the second principal component reflected the effect depending on selection cutting. In conclusion, selection stands with many medium-sized conifers grew more than stands containing fewer medium-sized conifers or than stands containing more trees assigned to other classes; and large conifers suppressed stand volume growth less if the selection cutting cycle was short.

龍原 哲・山本博一・高田功一・犬飼 浩：トドマツ主体の択伐林において林分構造が成長に与える影響 森林計画誌 25 : 17~25, 1995 本研究ではトドマツ主体の択伐林における林分構造と成長の関係を調べた。最初に、林木を樹種と胸高直径によって6つに分類した。樹種は針葉樹と広葉樹に、胸高直径は小径級、中径級、大径級に分類した。主成分分析によって6種類の材積は第一主成分と第二主成分によって表現できることが示された。第一主成分は小中径針葉樹の材積と大径木の材積の差を表しており、第二主成分は中大径針葉樹の材積と大径広葉樹の材積との差を表している。次に、重回帰分析によって林分材積の純成長量、粗成長量、枯損量が二つの主成分と相関を持つことが示され、林分材積の成長と6種類の材積との関係が数量的に示された。第一主成分は林分構造が材積成長に与える影響を安定的に示しており、第二主成分はこの影響が択伐によって変動することを示していた。以上の結果から、中径針葉樹が多い択伐林は材積成長量が大きく、また、回転年が短ければ大径木もあまり材積成長を抑制しないことが導かれた。

I. Introduction

Relationships between growth and stand structure in natural stands are important when managing uneven-aged stands for selective harvesting

(selection stands). However, it is difficult to understand the relationships because the structure of natural stands is complex and their growth process depends on the stands themselves, as analyzed and reported by TAKEUCHI *et al.* (1980, 1981)

* Fac. of Agric., the Univ. of Tokyo. Tokyo 113 東京大学農学部

** University Forest in Hokkaido, the University of Tokyo, Furano, Hokkaido 079-15 東京大学北海道演習林

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and ISHIBASHI (1990). They, however, classified trees in natural stands into two species classes or three diameter classes. Because these factors in natural stands are dependent, a mutual relationship (i.e., if one factor increases, the others decrease) between them should be taken into consideration.

Most of the Tokyo University's Hokkaido Forest is covered with natural forest that is mainly selectively cut. The most important species

for timber products is todo fir (*Abies sachalinensis* (FR. SCHMIDT) MASTERS). Therefore, this paper reports analysis of relationships between growth and stand structure in the selection stands dominated by todo fir. Trees are classified into six classes by their species and diameter.

II. Data

The study area, the Hokkaido Forest, is located in the *Pan mixed forest zone* (43°N, 142°E) between

Table 1. List of experimental plots.

Plot code	Year of plot establishment	Compartment	Subcompartment	Area (ha)
5001	1963	87	a	0.398
5002	1959	86	f	0.360
5004	1959	36	c	0.480
5005	1961	86	b	0.325
5006	1961	36	b	0.348
5007	1963	84	a	0.333
5101	1958	51	a	0.250
5102	1958	51	a	0.250
5103	1958	51	a	0.250
5104	1958	51	a	0.250
5105	1960	57	b	0.418
5107	1959	64	a	0.750
5110	1960	103	b	0.370
5111	1960	103	b	0.436
5113	1959	101	a	0.571
5115	1961	106	b	0.398
5116	1961	102	a	0.415
5124	1963	109	a	0.345
5137	1969	51	a	0.376
5138	1969	51	a	0.242
5139	1970	61	b	0.514
5144	1972	99	a	0.995
5202	1960	24	a	0.286
5204	1958	31	b	0.492
5206	1929	24	c	0.301
5207	1929	24	c	0.295
5208	1929	24	c	0.301
5209	1929	24	c	0.392
5212	1961	26	d	0.351
5213	1961	18	e	0.375
5216	1963	25	b	0.324
5219	1969	25	a	0.146
5220	1969	25	c	0.231
5243	1980	25	c	0.300
5304-2	1960	58	a	0.498
5304-3	1960	58	a	0.500

the cool-temperate and the sub-boreal zone. The Hokkaido Forest is divided into two working circles, the "first" and the "second", which differ in management of the selection stands. In the first, the selection cutting cycle is ten years and the ratio of selection cutting is 16% (i. e., 16% of the stand's trees are removed in each selection cut). In the second, the selection cutting cycle is 20 years and the ratio of selection cutting is 20%. Data analyzed in this study were taken on 36 permanent plots in the first circle's selection stands. Years of plot establishment and their areas are shown in Table 1. Generally, they have been measured every four years, plus when the stands containing them were selectively cut. Diameters at breast height (DBH) were measured on all trees whose diameters were ≤ 5.0 cm.

Although the plots contain many species, todo fir predominates and comprises most of conifers. Conifers occupy 40% to 90% in terms of both stocking and stand volume. The main broad-leaved trees in the plots were Japanese linden (*Tilia japonica* (MIQ.) SIMONKAI), painted maple (*Acer Mono* MAXIM. subsp. *marmoratum* (NICHOLSON) KITAMURA), monarch birch (*Betula Maximowicziana* REGEL), white oak (*Quercus mongolica* FISCHER et TUREZ. var. *grosseserrata*), and caster aralia (*Kalopanax pictus* (THUNB.) NAKAI).

III. Analyses

1. Principal component analysis for stand structure

Trees were classified into six classes by their

species and diameter. The species classes were conifers and broad-leaved trees. The diameter classes (small trees, medium trees and large trees), are used for management in the Hokkaido Forest and HIRATA *et al.* (1987) showed validity of this classification for describing stand structure. Size ranges of diameter class are: small (5 to 25 cm), medium (25 to 39 cm) and large (> 39 cm).

Tree volumes were estimated from their DBHs by the following equations:

$$v = d^{2.45935} / 6814.2425, \quad (1)$$

$$v = \begin{cases} d^{2.4189} / 6086.9537 & (d \leq 76) \\ 0.19 d - 8.62 & (d > 76) \end{cases} \quad (2)$$

where v (m^3) is volume and d (cm) is DBH. Eq. (1) is for conifers and Eq. (2) is for broad-leaved trees. These equations were obtained by fitting to local volume tables used in the Hokkaido Forest. Volumes for the six classes were calculated by summing volumes of individual trees. Volumes per hectare were used as original variables in the analysis below.

A principal component analysis for the six original variables yielded Table 2. The first principal component explained 49.0% of the total variance. Together, the first two principal components explained 77.7% of the total variance, well summarizing variation of the original. Eigenvectors corresponding to the eigenvalues of the principal components are shown in Table 3. Values of the first two principal components are given in Fig. 1. The first principal component's values ranged from -133.8 to 129.9 and those of the second from -147.6 to 73.1 . Table 4 shows average

Table 2. Eigenvalues of the covariance matrix.

Principal component	Eigenvalue	Proportion(%)	Cumulative(%)
1	3588.59	49.0	49.0
2	2093.37	28.6	77.7
3	1281.14	17.5	95.2
4	166.84	2.3	97.4
5	132.58	1.8	99.3
6	54.54	0.7	100.0

Table 3. Eigenvectors.

Variable	1	2	3	4	5	6
Small conifers	-0.2180	0.0847	-0.2198	0.8339	-0.4017	0.2006
Medium-sized conifers	-0.6487	-0.2037	-0.6413	-0.3491	-0.0672	-0.0051
Large conifers	0.3126	-0.9352	-0.0904	0.1358	-0.0261	0.0187
Small broad-leaved trees	0.0771	-0.0007	0.0975	-0.2898	-0.2382	0.9186
Medium-sized broad-leaved trees	0.1446	0.0160	0.0965	-0.2809	-0.8806	-0.3394
Large broad-leaved trees	0.6380	0.2764	-0.7165	-0.0378	0.0356	0.0200

Table 4. Average values of the principal components.

Attribute	Number of measurements	1	2	3	4	5	6
Just after cutting	35	-1.215	5.435	12.253	2.501	-0.411	-0.891
Others	81	0.525	-2.349	-5.294	-1.081	0.177	0.385

Table 5. Results of multiple regression analysis concerning effect of the first two components on net increment.

Attribute	Term	Regression coefficient	F-ratio	Partial correlation coefficient	Correlation coefficient	Multiple correlation coefficient
Just after cutting	a_1	-0.02562	9.94**	-0.487	-0.447	0.519
	a_2	-0.01728	3.06	-0.295	-0.207	
	a_0	6.24936				
Others	a_1	-0.03302	17.27**	-0.426	-0.414	0.445
	a_2	0.01732	2.60	0.179	0.143	
	a_0	5.34455				
Total	a_1	-0.03026	23.65**	-0.416	-0.415	0.422
	a_2	0.00714	0.88	0.082	0.075	
	a_0	-5.55810				

** Significant at the 0.01 level of probability.

Fig. 1. Relationships between values of the first two principal components.

Fig. 2. Relationships between value of the first principal component and net increment.

values of the principal components for data collected from open stands just after cutting and data from other stands whose canopies were closing (data collected a few years after selection cutting).

2. Multiple regression analysis for growth and the principal components

Mean annual net increment, mean annual mortality and mean annual gross increment were calculated in terms of volume from each stand's data. To analyze the relationship between stand growth and stand structure, the linear regression model

$$Y = a_0 + a_1 C_1 + a_2 C_2 \quad (3)$$

was selected, where Y is response, C_1 is value of the first principal component, C_2 is value of the second principal component, and a_i ($i=0, 1, 2$) are coefficients. The model was fitted to three groups of data: data collected just after selection cutting, other data collected a few years after selection cutting (from stands whose canopies were closing) and both combined.

Fitting the model to the net increment and values of the principal components data yielded Table 5. Net increment correlated negatively with the first principal component's value in all three groups. Fig. 2 shows their relationships. However, there was low negative correlation between net

increment and the second principal component's value in the data collected just after selection cutting, low positive correlation in the other data and, consequently, little correlation in the combined data. That is to say, the first principal component affected net increment constantly (i. e., independent of time since selection cutting), while the second principal component had less effect on net increment than the first principal component and affected net increment differently in stands just after selection cutting and other stands a few years after selection cutting.

Fitting the model to the mortality and principal components data yielded Table 6. There were positive correlations between mortality and the first principal component's value in all three groups. Fig. 3 shows their relationship. However, there was little correlation between mortality and the second principal component's value in the data collected just after selection cutting, low negative correlation in the other data and, consequently, low negative correlation in the combined data. That is to say, the first principal component affected mortality constantly while the second principal component had less effect on mortality than the first principal component and had little effect in stands just after selection cutting.

Fitting the model to the gross increment and

Table 6. Results of multiple regression analysis concerning effect of the first two components on mortality.

Attribute	Term	Regression coefficient	F-ratio	Partial correlation coefficient	Correlation coefficient	Multiple correlation coefficient
Just after cutting	a_1	0.008426	2.88	0.288	0.275	0.297
	a_2	0.004081	0.46	0.119	0.079	
	a_0	1.45121				
Others	a_1	0.01819	7.83**	0.302	0.288	0.345
	a_2	-0.01564	3.16	-0.197	-0.175	
	a_0	2.41953				
Total	a_1	0.01522	9.51**	0.279	0.276	0.308
	a_2	-0.009939	2.37	-0.143	-0.138	
	a_0	2.16328				

** Significant at the 0.01 level of probability.

principal components data yielded Table 7. Gross increment correlated negatively with the first principal component's value in all three groups. Fig. 4 shows their relationships. However, there was a low negative correlation between gross increment and the second principal component's value in the data collected just after selection cutting, little correlation in the other data and, consequently, little correlation in the combined data. That is to say, the first principal component affected gross increment constantly while the second principal component had less effect on gross increment than the first principal component and affected gross increment only in stands just after selection cutting.

Fig. 3. Relationships between value of the first principal component and mortality.

A third principal component, C_3 , was added, yielding the linear regression model

$$Y = a_0 + a_1 C_1 + a_2 C_2 + a_3 C_3 \quad (4)$$

which was applied to the three data group. However, correlation coefficients of the model improved little.

IV. Discussion

Variation of the selection stands' six class volumes is well summarized by the two principal components, C_1 and C_2 as follows:

$$\begin{aligned} C_1 = & -0.2180 V_{sc} - 0.6487 V_{mc} + 0.3126 V_{lc} \\ & + 0.0771 V_{sb} + 0.1446 V_{mb} + 0.6380 V_{lb} \end{aligned} \quad (5)$$

Fig. 4. Relationships between value of the first principal component and gross increment.

Table 7. Results of multiple regression analysis concerning effect of the first two components on gross increment.

Attribute	Term	Regression coefficient	F-ratio	Partial correlation coefficient	Correlation coefficient	Multiple correlation coefficient
Just after cutting	a_1	-0.01719	13.88**	-0.550	-0.492	0.595
	a_2	-0.01325	5.56	-0.385	-0.272	
	a_0	7.70253				
Others	a_1	-0.01483	14.16**	-0.392	-0.392	0.392
	a_2	0.001666	0.10	0.035	0.013	
	a_0	7.76430				
Total	a_1	-0.01504	23.30**	-0.414	-0.413	0.417
	a_2	-0.002822	0.48	-0.065	-0.059	
	a_0	7.72207				

** Significant at the 0.01 level of probability.

$$C_2 = 0.0847 V_{sc} - 0.2037 V_{mc} - 0.9352 V_{lc} + 0.0007 V_{sb} + 0.0160 V_{mb} + 0.2764 V_{lb} \quad (6)$$

where V_{sc} , V_{mc} , V_{lc} , V_{sb} , V_{mb} , and V_{lb} were volumes of small, medium and large conifers and broad-leaved trees, respectively. The first principal component, C_1 , contrasts the volume of small and medium-sized conifers with the volume of large conifers and broad-leaved trees. The second principal component, C_2 , contrasts the volume of medium and large-sized conifers with the volume of large broad-leaved trees. Small and medium-sized broad-leaved trees had little effect on the principal components.

This analysis revealed that the first principal component had a constant effect on growth of selection stands dominated by todo fir and its value was negatively correlation with growth. This means that small and especially medium-sized conifers increased selection volume growth while large conifers and broad-leaved trees decreased it. Conversely, the second principal component's effect on selection stand growth changed with time after selection cutting; its value was negatively correlated with growth just after cutting and positively correlated with growth later at canopy closure. The second principal component was affected mainly by large-conifer volume. Open stands with a greater volume of large conifers grew more just after cutting, because in the six classes large conifers grew most and in the open stands shaded small and medium-sized trees less. They did, however, suppressed small and medium-sized trees as their canopies closed. Thus, stands with closing canopies and greater volumes of large conifers grew less than other stands. Fig. 5 shows the largest growth areas in the selection stands. As stand canopies close, the area moves as shown. The effects of stand structure on growth depend on canopy closure, also meaning that large conifers

Fig. 5. The largest growth areas in the selection stands.

Note: The ellipses show the areas where the selection stands reflect the greatest amount of growth.

do not suppress stand volume growth if those stands are allowed to open.

TAKEUCHI *et al.* (1980) reported that conifers grew more than broad-leaved trees in natural forests and the highest growth rates occurred in stands where growth was concentrated in the conifers. ISHIBASHI (1990) reported that stands with high volumes of conifers grew more than stands with low conifer volumes. Furthermore, TAKEUCHI *et al.* (1981) reported that selection stand growth depended mainly on growth of small and medium-sized trees in the first working circle and ISHIBASHI (1990) reported the same in other kinds of natural forests. They observed a relationship between growth and each factor of species and diameter class volume. In this paper the data were analyzed by the principal components of the factors of species and diameter class volumes and our results agree with their reports.

ISHIBASHI and HIROKAWA (1986) stated that gross increment of natural forests varied even though they had the same stand volume, that it had maximum and minimum distribution curve and

that the maximum distribution curve culminated at stand volume of $300 \text{ m}^3/\text{ha}$. They explained forest and stand growth and mortality with a distribution graph. Net increment, however, decreased with the value of the first principal component (Fig. 2); gross increment also decreased with its value, though the difference between minimum and maximum values was less than net increment (Fig. 3). Though mortality was scattered more widely than net increment and gross increment, it tended to increase with the first principal component's value as in Fig. 3. Based on these analyses, general dynamics of the first working circle's selection stands are summarized in Fig. 6. A selection stand moves down and to the right as it grows, which means that growth itself decreases in a selection stand as the number and volume of large conifers and broad-leaved trees increase and the stand canopy closes. It moves up and to the left if it is selectively cut. This means that large trees are harvested mainly by selection cutting, which increases growth in selection stands. It can be moved in any direction by mortality, depending on the resulting change of stand structure. For example, it moves

Fig. 6. General dynamics of selection stands in the Hokkaido Forest.

to the left if large trees die and to the right if medium-sized conifers die.

V. Conclusion

Stand structure of selection stands was explained by two principal components obtained from the volume of six classes by their species and diameter. Growth was observed to correlate with the principal components, i.e., the relationship between stand volume growth and the six class volumes were shown numerically. The first principal component reflected a constant effect of stand structure on volume growth and the second principal component reflected the effect depending on selection cutting. These results led to conclusion that selection stands with more volume in medium-sized conifers grew more than stands containing fewer medium-sized conifers or than stands containing more trees assigned to the other classes; and, that large conifers suppressed stand volume growth less if the selection cutting cycle is short.

In this paper, the relationship between volume growth and stand structure was shown for selection forest management. Lumber value, however, was not concerned. Value growth is important for management, too. Thus, determining optimum stand structure for selection forest management requires additional study to examine relationships between value growth and stand structure.

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