Research paper

Impact Four Years after Thinning on the Growth and Stand Structure of Taiwania Plantation in the Liukuei Experimental Forest

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【Summary】

This paper examines the impact of thinning 4 yr after it took place on the growth and stand structure of *Taiwania cryptomerioides* plantations in Liukuei Experiment Forest in Southern Taiwan. Thinning to 3 residual levels in basal area were carried out in 1999, and three 0.09-ha plots were set up in each treatment for stand monitoring purposes.

The results showed that partially due to the stand density, the enhancements in the increments of basal area and volume by heavy thinning were less than those by medium thinning. However, enhancement of the growth rate was in a reverse order. The contagion index, which measures the spatial structure of a stand indicated that the regular pattern of individual trees in spatial locations in plantations was shifted toward a random or clumped one through individual tree thinning. The diameter differentiation index describing the spatial distribution of tree sizes indicated that the range of the difference in size of neighboring trees in the plantation was reduced through the thinning operation, with an increase in the proportions of trees having DBH differentiation of a small level (0.83) and a decrease in the average level (0.17). Due to variations in growth probably caused by competition among residual trees, 4 yr after thinning, the proportions of trees with a small difference level and average difference level were reduced (0.81) and increased (0.19), respectively.

Key words: plantation thinning, spatial distribution, structure index, stand growth.

Wang DH, Tang SC, Chiu CM. 2006. Impact four years after thinning on the growth and stand structure of Taiwania plantation in the Liukuei Experimental Forest. Taiwan J For Sci 21(3):339-51.

研究報告

六龜試驗林台灣杉人工林疏伐四年後對生長和林分結構影響之分析

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Received March 2006, Accepted August 2006. 2006年3月送審 2006年8月通過。

摘　要

本研究探討不同疏伐策略對林業試驗所六龜試驗林台灣杉人工林疏伐四年後對林木生長和林分結構之影響。調查結果顯示因受林分密度影響，強度疏伐對單位面積台灣杉斷面積和材積絕對生長量生長之促進效果較中度疏伐效果為低，但就相對生長來說，強度疏伐之促進效果較中度疏伐效果為高；傳播指數顯示，台灣杉人工林的林木位置之規整狀態會隨著下層疏伐作業之實施有所改變，而轉化成有朝向逢機分佈或群狀集合之趨勢；胸徑分化程度指標之分佈顯示疏伐作業縮短了其在林木胸徑差異空間上分佈之範圍，增加其差異屬於小階段之比例(0.83)，和減少位於程度中等階段之比例(0.17)。然疏伐4年後，因保留木間胸徑生長之速率不一，減少了差異位於程度小階段之比例(0.81)，並增加了差異屬於中等階段之比例(0.19)。

關鍵詞：林分結構、空間分佈、結構指標、林分生長。

汪大雄、湯適謙、邱志明。2006。六龜試驗林台灣杉人工林疏伐四年後對生長和林分結構影響之分析。台灣林業科學21(3):339-51。

INTRODUCTION

On plantations, the effects of juvenile spacing do not last long because of the competition of the roots and crowns of the younger trees beginning at the onset of crown closure. Crowded tress have to compete for light, water, and nutrients, resulting in slower growth or even death of some trees (Oliver and Larson 1996). Moreover, some weak trees also become vulnerable to insects and disease. To avoid overcrowding and competition, trees are often thinned to increase the growing space available to the remaining trees. Enhancing growth on final crop trees by removing other trees has long been recognized and practiced in commercial thinning (Abbott and Loneragan 1983).

The forest structure is of interest to many disciplines and is regularly discussed in the context of ecosystem management. Spies (1998) pointed out that the forest structure encompasses many meanings and can be described in many ways. At the stand level, measurements of tree size, age, foliage, biomass, and spatial distribution in the overstory and ground vegetation layers are commonly viewed as components of stand structure. The structure of tree crowns, for example, is a characteristic of stand structure that influences the growth of both trees and understory vegetation (Latham et al. 1998). Changes in the structural attributes of stands also affect stand functions such as photosynthesis and respiration (Waring and Schlesinger 1985), tree growth (O'Hara 1988), the suitability of the stand for wildlife (Morrison et al. 1992), and understory plant diversity (Latham et al. 1998). Therefore, structural diversity has become an important facet within forestry, especially for countries (e.g., Central Europe) with a rather low level of tree species diversity (Neumann and Stalinger 2001). Increasing horizontal and vertical heterogeneity of the stand structure often leads to a higher number of species and contributes to higher stand stability (Latham et al. 1998). Thinning practices can modify the stand structure and therefore have an important potential role in determining stand diversity and ecological stability (Pretzsch 1997, Spies 1998, Humphrey et al. 2000).

In ecology and forestry, finding the patterns of distribution of forests is a prerequisite to understanding the function of forest ecosystems. The quadrat method and distance method are 2 widely used ways to measure the dispersion patterns of populations. In the former, quadrat sampling is used to collect counts of the number of events in subsets of the study region. The disadvantage of the quadrat approach is that such data are strongly influenced by the size of the quadrat used for data collection. In the latter, distances between events are calculated to provide a variable for the measurement of spacing that avoids the use of quadrats, and therefore, eliminates the effect of quadrat size (Cressie 1991). Use of the distance to the nearest neighbor in the detection of randomness in spatial patterns has been advocated by many studies for a long time (Upton and Fingleton 1989). The horizontal pattern of tree locations is typically classified into regular, random, and clustered patterns. Usually, this information may provide valuable insights into the overall structural condition of a stand and, therefore, should be incorporated into the description of the forest structure.

Taiwania (*Taiwania cryptomerioides*) is the major plantation species in the Liukuei Experimental Forest. An inventory showed that, by the end of 1991, there were 1560 ha of plantation accounting for 16.22% of the total area of the experimental forest. Approximately 51.6% of the plantation area was covered by Taiwania, therefore, its silviculture practice is of great importance (TFRI 1992). The purpose of this study was to investigate the influence of alternative thinning regimes on the growth and stand structure of a Taiwania plantation 4 yr after a commercial thinning in Liukuei Experimental Forest.

MATERIALS AND METHODS

This study was conducted in an even-aged Taiwania plantation in Compartment #3 of Liukuei Experimental Forest, Taiwan Forestry Research Institute, located in the Southern Taiwan. The plantation with a 2*2 m spacing was established in 1972 with an area of 78 ha at elevations ranging from 1500 to 1700 m. The mean annual precipitation is 3800 mm, which mostly falls from May to September. The mean annual temperature is 17.5℃. In this plantation, a thinning from below with 3 residual levels in basal area (i.e., 40 m^2 ha^{-1}, 50 m^2 ha^{-1}, and control) was carried out in 1999. The area for each treatment was 3~5 ha. In each treatment, 3 square monitoring plots with an area of 0.09 ha each were set up at random. Within the plot, each tree was mapped, and stand characteristics associated with timber growth and stand structure were measured immediately before and annually after the thinning in 2000~2003.

Since there is an increasing demand for information on alpha diversity, particularly on the spatial distribution of trees and their attributes (Ferris and Humphrey 1999, Pommerening 2002), structural indices describing certain horizontal aspects of the stand structure, such as mean values or a distribution pattern, therefore, have been developed accordingly in the past (Upton and Fingleton 1989). From a mathematical point of view, the majority of indices measuring forest structure can be categorized into 2 major groups: distance-independent and distance-dependent ones. In the former, no spatial information is needed to calculate the indices. The Shannon index is an example of a distance-independent algorithm to describe species mingling (Magurran 1988). However, for the latter group, the coordinates of tree locations are required.

In this study, indices measuring stand structure horizontally associated with distance-dependent measurements were used to evaluate the impact of thinning regimes on the stand structure in a Taiwania plantation. The indices used are briefly described below.

Aggregation Index of Clark and Evans (1954)

The aggregation index, a single value describing aspects of variability of tree locations in forest stands, is defined as:

$R = r_A / E(r);$ (1)

where r_A is the average distance from a tree to its nearest neighbors in a given stand and E(r) is the mean nearest neighbor distances in a stand with completely random tree locations (i.e., a "Poisson forest") of intensity lamda (λ) = N/A. In the case of the first nearest neighboring distance, $E(r) = 1/2*(N/A)^{1/2}$, where N is the: number of trees and A is the area of the forest stand.

The ratio, R, is used to measure the degree to which the observed distribution approaches or departs from random expectations. Generally, the R value is interpreted as follows: for R > 1, the pattern has a tendency to regularity, for R = 1, it is completely random (Poisson process), and for R < 1, there is a clustering in the pattern.

If the value of R indicates that a given population is not randomly distributed, the significance of the departure of r_A from E(r) can be tested by a normal curve with the following equation:

$Z = (r_A - E(r)) / \sigma_{E(r)};$ (2)

where Z is the standard variate of the normal curve and $\sigma_{E(r)}$ is the standard error of the mean distance to the nearest neighbor in an random distribution of the same density as that of the observed population. The value of $\sigma_{E(r)}$ for a population of density ρ for the first nearest neighboring distance is $0.26136 / (N^* \rho)^{1/2}$ where N is the number of measurements of distance made (Clark and Evans 1954).

Contagion Index

Instead of using the aggregation index, Gadow et al. (1998) (cited by Pommerening 2002) developed a contagion variable, W*i*, for each tree to define the degree of regularity of the spatial distribution of tree positions in a forest. The conceptual basis behind the contagion index is described briefly here.

Assume in a forest with a complete regularity of the positions of the n nearest neighbors around a reference tree, *i*, the expected standard angle, α°, between two neighbors would be equal to 360°/n. In a constellation involving 4 neighbors, for example, α° equals 90°. Contagion is defined as the proportion of the actual angle, α, between 2 neighbors which are smaller than the standard angle, α^o

$W = 1/n \, \Sigma \, w_{ij};$ (3)

where w_{ij} = {1, the α angle between tree *i* and neighbor tree j is smaller than α°; 0, otherwise}.

The point pattern of tree positions in a forest can be evaluated by the distribution of W_{ij}. The average contagion (W) value can be used to classify the point pattern into the categories of 'regular', 'random', or 'clumped' (Gadow et al. 1998 cited by Pommerening 2002). The results of Albert's study (1999) showed that trees with a contagion value greater than 0.6 can be considered as clumped, those with values between 0 and 0.5 are regular, and those between 0.5 and 0.6 are random (cited by Pommerening 2002). However, Albert (1999) also pointed out that these distinctions might not be so sharp (cited by Pommerening 2002).

Diameter Differentiation Index

The single tree diameter differentiation variable, T_{ij}, gives the size difference of neighboring trees on a continuous scale and describes the spatial distribution of tree sizes (Pommerening 2002). For a reference tree, *i*, and its n = 3 nearest neighboring j (j = 1, n), the diameter differentiation index T_{ij}, is defined as:

$T_{ij} = 1 - \{\min (DBH_i, DBH_j) / \max (DBH_i,$

$DBH_j)\}$; (4)
where DBH is the diameter at breast height (cm).

The value of T_{ij} increases with an increasing average size difference between neighboring trees. The diameter differentiation index value (T_{ij}) can be classified into 4 levels of differentiation: a small level ($0.0 \leqq T_{ij} < 0.3$), an average level ($0.3 \leqq T_{ij} < 0.5$), a big level ($0.5 \leqq T_{ij} < 0.7$) and a very big level ($0.7 \leqq T_{ij} \leqq 1.0$) (Pommerening 2002).

Based on the concepts mentioned above, a computer program SPAPET coded in FORTRAN was written by the senior author to calculate these indices.

RESULTS AND DISCUSSION

While part of the plantation surveyed in this study had received precommercial thinning in 1991, the report by Wang et al. (2003) showed that due to a decline in the stimulating effect on Taiwania growth, the stand differences had become trivial 7 yr after the previous thinning. Generally, timber variations in growth and stand structure among plots were trivial at the time of implementing the commercial thinning, therefore, the forest state prior to thinning can be used as a baseline to investigate the effect of thinning on factors considered in this study.

Thinning operations are characterized by thinning intensity and thinning method. The latter is often expressed as low, high, or through thinning, depending on whether or not the removal is selective for size (Pienaar 1979). In general, if the thinning is not selective for size, the percentage of thinning in terms of the number of trees removed is equivalent to the percentage of thinning in terms of the basal area or volume removed and vice versa. However, when thinning is selective for size, the percentage of trees removed by the thinning does not equal the percentage of the basal area or volume removed. Field et al. (1978) demonstrated that in such a case, one item's percentage could be estimated from the other. Usually in low thinning, a larger percentage of trees are removed than those of the basal area or volume. As shown in Table 1, the figures are consistent with those of a low-thinning operation.

The characteristics of the Taiwanina plantation immediately before and after, and 4 yr following thinning are presented in Table 1. Hamilton Jr. (1986) mentioned that the most obvious influences of thinning on stands were a reduction in the basal area and an increase in the DBH increment. Both of these effects result in a decrease in mortality rates. The mortality rate of unthinned stands (13.3%) during the 4 yr is higher than those of thinned stands (3.2% with heavy thinning and 5.6% with medium thinning) as shown in Table 1, confirming that mortality was reduced through thinning practice. As the annual increments in 2000~2003 were quite small in both thinned and control plots (Table 2), due to potential measurement errors, no annual analysis was done in this study. However, 4-yr increments were used to assess the effect of thinning on stand growth. A rather-rapid increase in the 4-yr DBH increment occurred in thinned stands, with heavy thinning ranked first, followed by medium thinning in terms of both increment and growth rate (Table 2). Partially due to the density of residual trees in 2003 for the control and that at 4 yr after thinning for the thinned treatment (Table 1), the enhancements in the increments in basal area and volume by heavy thinning were less than those by medium thinning. However, the enhancement in their growth rate was in a reverse order (Table 2). In terms of the DBH distribution, the DBH was truncated and skewed to the right with thinning operations,

Table 1. Characteristics of a Taiwania plantation among alternative thinning regimes

Treatment	Age (yr)	Density (no. of stems ha^{-1})	DBH (cm)	Height (m)	BA (m^2 ha^{-1})	Volume (m^3 ha^{-1})
Heavy thinning		49%[1]			35%[2]	34%[3]
Immediately before thinning	27	1167±400[4]	25.32±1.23	14.61±0.34	61.37±15.69	383.4±95.2
Immediately after thinning	27	593±23	29.13±0.31	15.57±0.15	39.60±0.15	241.43±11.06
After 4 yr	31	574±28	31.93±0.66	16.47±0.47	45.63±2.02	292.67±13.48
Medium thinning		24%[1]			15%[2]	12%[3]
Immediately before thinning	27	1022±220	26.78±1.23	14.94±0.31	61.06±4.05	385.3±27.8
Immediately after thinning	27	778±22	28.63±1.15	15.47±0.32	51.77±2.01	342.23±20.95
After 4 yr	31	734±69	31.30±1.66	16.3±0.30	59.57±3.73	401.93±29.45
Control						
1999	27	1533±243	24.97±1.46	14.51±0.46	80.45±6.78	503.5±42.7
2003	31	1329±170	27.03±1.66	15.27±0.42	85.03±3.88	547.57±19.75

[1] The percentage of trees removed by thinning.

[2] The percentage of basal area removed by thinning.

[3] The percentage of volume removed by thinning.

[4] Mean±standard deviation. DBH, diameter at breast height; BA, basal area.

Table 2. Four-year increments among different regimes of thinning intensity

Treatment	DBH (cm)	Height (m)	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})
Control	2.06	0.76	4.58	44.07
	(8.25%)*	(5.23%)	(5.69%)	(8.75%)
Medium	2.67	0.83	7.80	59.70
	(9.33%)	(5.36%)	(15.06%)	(17.44%)
Heavy	2.81	0.90	6.03	51.24
	(9.61%)	(5.78%)	(15.23%)	(21.22%)

* Figures in parenthesis are the growth rates.
DBH, diameter at breast height; BA, basal area.

and is getting closer to a bell-shaped curve over the years (Fig. 1).

While probability distribution functions (e.g., Weibull) are widely used to describe the distribution of stem size (i.e., DBH), they do not take into account the distribution in space, and thus, largely ignore the spatial character of forest structures (Zenner and Hibbs 2000). Since the competition stress suffered by individual trees is largely related to the tree size and distances between competitors, the information on the spatial distribution of tree sizes, therefore, is desirable (Biging and Dobbertin 1992).

Distances among individual trees used in this study were obtained based on the coordinates of trees. The first nearest neighboring distance is the set of the distances between a subject tree and its first nearest neighboring tree for all subject trees. The nearest neighbor concept can be expanded from the first nearest neighboring tree to the second nearest neighboring tree, and so on.

The regularity test in equation 2 indicated that the plantation had a tendency toward regularity both before and after thinning as a whole. But the regularity of tree locations in forest stands measured based on the first

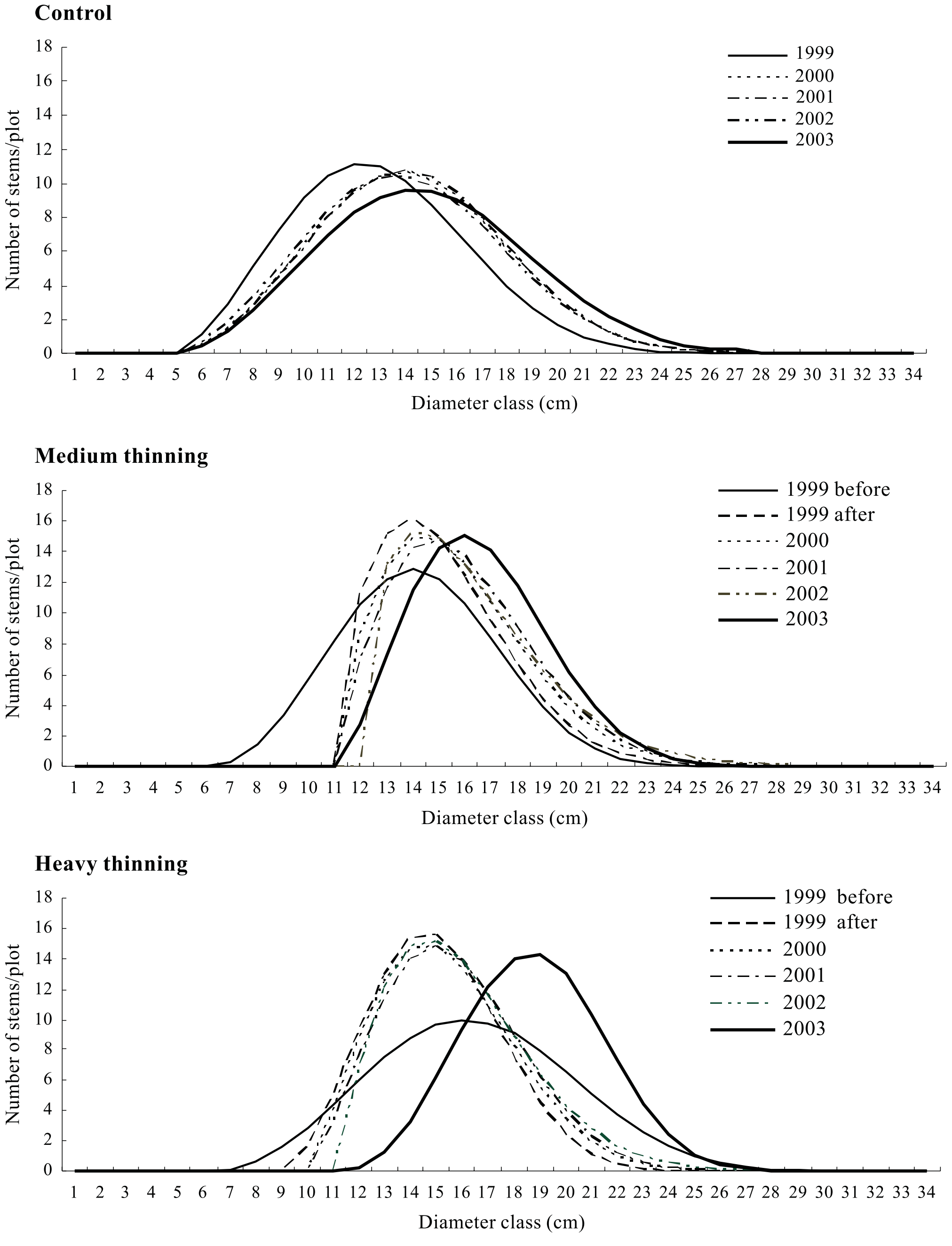

Fig. 1. The Weibull diameter distribution for alternative thinning regimes from 1999 before and after thinning to 2003.

nearest neighboring distance decreased after the thinning operation (Table 3). Moreover, the regularity of tree locations was also affected by alternative nearest neighboring distances used. The trend of weakening the regularity of tree location (i.e., the value dropped from the first to the third nearest neighboring distance) through an increase of neighboring distance both before and after thinning is indicated in Table 4. The consistency of evaluating the regularity between the aggregation index (R) and the average contagion index (W) through thinning practice is demonstrated in Fig. 2.

The pattern of the plant population distribution is not only a fundamental characteristic, but also a feature extremely difficult to describe in precise and meaningful terms. Any improvement in the quantitative analysis of the distribution, therefore, is desirable and would surely facilitate the interpretation of dispersion patterns (Clark and Evans 1954). The aggregation index was proposed by Clark and Evans over half a century, but because of the simplicity in calculation and the readiness in interpretation, it is still widely used today to measure the spatial pattern of stands (Zenner and Hibbs 2000).

Table 3. Changes in the aggregation index before and immediately after the thinning practice based on the first neighboring distance for alternative thinning intensities

Treatment	Before thinning	After thinning
Medium thinning	1.267**	1.224**
Heavy thinning	1.273**	1.199**

** Significant difference at α = 0.01 in regularity testing based on equation (2).

Table 4. Aggregation index before and immediately after thinning practice for a particular plot with heavy thinning based on the first, second, and third nearest neighboring distances

Distance	Before thinning	After thinning
First nearest neighbor	1.273	1.199
Second nearest neighbor	1.082	1.141
Third nearest neighbor	1.049	1.126

Figure 3 displays the change in the contagion index distribution based on the first nearest neighbor tree caused by thinning practice. Before thinning, 72% of trees showed a regular distribution (0.0~0.25), 18% showed a random distribution (0.25~0.5), and 10% showed a clumped distribution (0.75~1.0). However, the proportion of trees at the regular level was dramatically reduced (28%), accompanied by a substantial increase in the proportion of trees in a random (44%) or clumped distribution (28%) after the thinning operation. In other words, the regular pattern of individual trees in spatial locations commonly occurring in plantations was shifted toward a random or clumped pattern by the thinning practice.

Figure 4 displays the change in the DBH differentiation index distribution by the thinning practice based on the first nearest neighboring tree comparison. Before thinning, owing to the greater variation in tree size probably caused by competition, it covered a broad range of DBH differences in size from a small to a big difference level. Among them, regarding DBH difference with respect to the first nearest neighboring tree, 32% of trees were ranked as having a average difference level and 2% of trees were ranked as having a big difference level. In control area, some trees were even ranked as having a very big difference level (Table 5). In thinning operations, the removal of less-competitive trees can narrow down the DBH difference in residual trees, thereby, it increased the proportion of trees which had a small DBH difference (0.83) and decreased the proportion of trees on average difference level (0.17). Four years later, because of variations in growth rates among residual trees, the difference in DBH again became larger, resulting in a small decline in the small level (0.81) and an expansion of the average level (0.19)

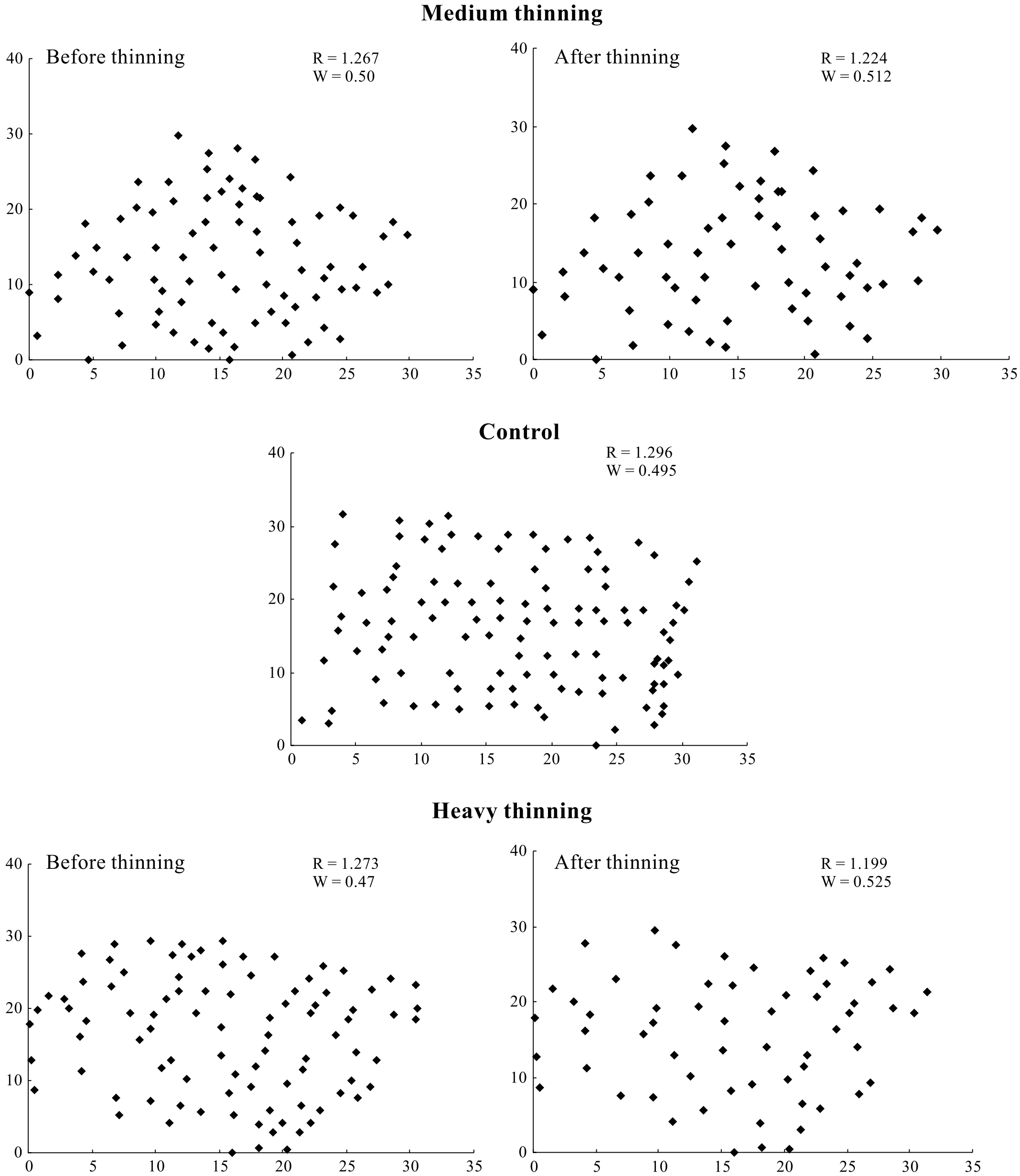

Fig. 2. Tree location patterns in the tree maps revealed by the aggregation index (R) and average contagion index (W) for alternative thinning regimes. Horizontal axis and vertical axis represents the X and Y coordinates of the tree locations in meters, respectively.

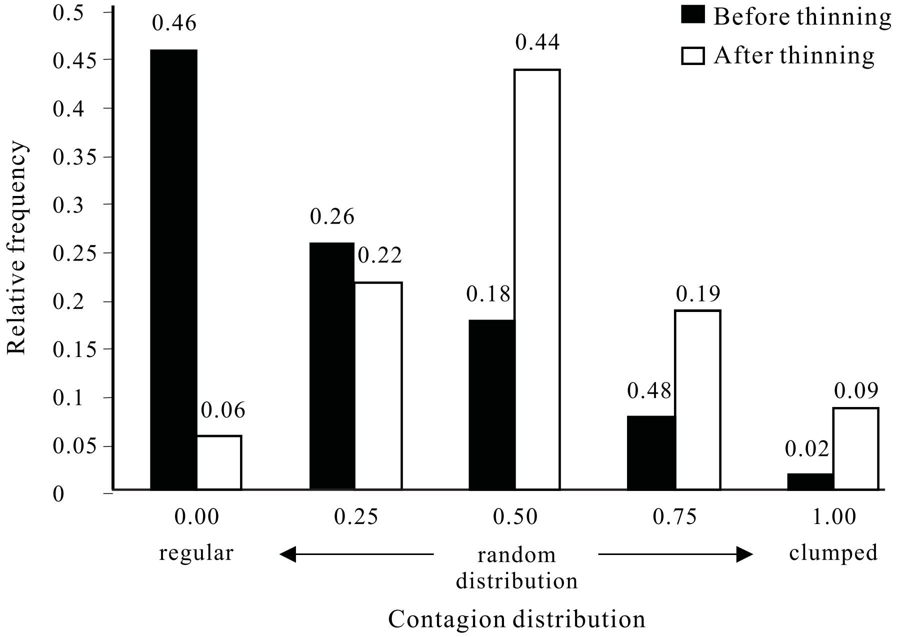

Fig. 3. Distribution of the contagion index before and immediately after thinning for a particular plot in the heavy thinning practice.

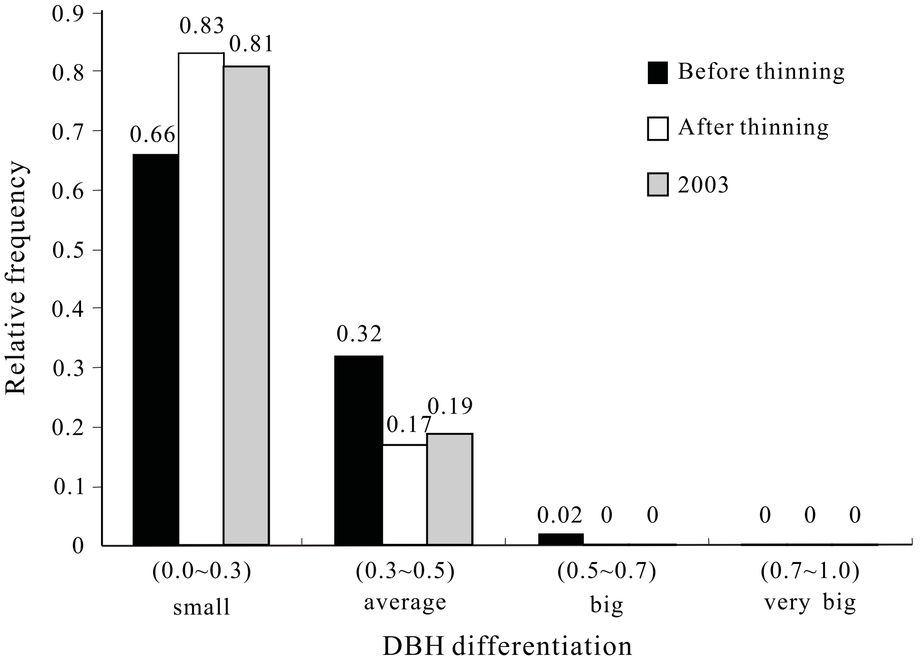

Fig. 4. Distribution of the diameter at breast height (DBH) differentiation index based on the first nearest neighboring distance for a particular plot in the heavy thinning practice.

Table 5. Proportion of the diameter at breast height (DBH) differentiation level based on the first, second, and third nearest neighboring distances for a given control plot in 1999 and 2003

DBH differentiation level*	1999			2003		
	First distance	Second distance	Third distance	First distance	Second distance	Third distance
Small	0.62	0.61	0.54	0.59	0.53	0.52
Average	0.20	0.31	0.33	0.21	0.40	0.30
Big	0.15	0.07	0.11	0.18	0.07	0.18
Very big	0.03	0.01	0.02	0.02	0	0

* Small level, $0.0 \leqq T_{ij} < 0.3$; average level, $0.3 \leqq T_{ij} < 0.5$; big level, $0.5 \leqq T_{ij} < 0.7$; very big level, $0.7 \leqq T_{ij} \leqq 1.0$; T_{ij}, the diameter differentiation index described in equation (4).

Table 6. Proportion of the diameter at breast height (DBH) differentiation level based on the first, second, and third nearest neighboring distances for a given heavily thinned plot in 1999 and 2003

DBH differentiation level*	1999 Before thinning			1999 After thinning			2003		
	First distance	Second distance	Third distance	First distance	Second distance	Third distance	First distance	Second distance	Third distance
Small	0.66	0.71	0.66	0.83	0.81	0.87	0.81	0.80	0.89
Average	0.32	0.23	0.26	0.17	0.19	0.09	0.19	0.20	0.07
Big	0.02	0.06	0.08	0	0	0.04	0	0	0.04
Very big	0	0	0	0	0	0	0	0	0

* Small level, $0.0 \leqq T_{ij} < 0.3$; average level, $0.3 \leqq T_{ij} < 0.5$; big level, $0.5 \leqq T_{ij} < 0.7$; very big level, $0.7 \leqq T_{ij} \leqq 1.0$; T_{ij}, the diameter differentiation index described in equation (4).

(Fig. 4). This pattern of DBH differentiation also held true for comparisons based on the second, and the third nearest neighboring tree as well (Table 6).

The diameter differentiation index is based on pairs of reference trees with first, second or third nearest neighboring trees. Consequently, the size difference of neighboring trees can be described based on the first, second and third nearest neighbors, respectively. This study showed that the effect of measuring distance on diameter differentiation seemed to be correlated with the stand density. In a dense stand (e.g., the control), due to the closer spacing among trees, the increase in distance among neighboring trees intensified the differentiation among tree sizes. If we combine the average, big, and very big levels into one category called the non-small level, a decrease in the proportion of trees at the small level and an increase of trees at the non-small level are noted when the distance used is increased from the first to the second and to the third nearest neighboring trees in both 1999 and 2003 (Table 5). However, there was a lack of consistency observed in the lower-density stand such as the thinned plots (Table 6).

The choice of appropriate sampling schemes is a relevant issue when conducting forest inventories. The relative efficiency of a given sampling method depends on the spatial distribution of the elements in the population surveyed. In a study of the relative efficiency of 3 sampling methods (systematic, stratified, and simple random sampling), Payandeh (1970) pointed out that systematic sampling is equally as precise as the other 2 sampling methods when applied to a randomly distributed population. However, for uniformly spaced populations, systematic sampling is the least precise among the 3 sampling methods. As a result, understanding the spatial pattern of elements of a survey is a prerequisite for the selection of the appropriate sampling method. The spatial stand structure index discussed in this paper should provide a good way to assess the spatial distribution patterns of elements being investigated.

CONCLUSIONS

Through thinning practice, a forest is considered to be "improved" because the remaining trees can grow healthier, and are less susceptible to disease and other disturbances.

The distance method provides a good way to detect the randomness in spatial patterns of stand structure. This paper provides a useful approach for assessing the spatial structure of a Taiwania plantation in Taiwan. However, the same approach can be applied to studies of natural forest as well. The collected data only show the effect in a short term, and data of monitoring for more years are required to investigate the long-term effects of thinning on the topics examined in this study.

ACKNOWLEDGEMENTS

This study was supported by Taiwan Forestry Research Institute grants under the projects 91AS-1.4.1-FI-G1(02) and 92AS-2.3.2-FI-G1(02).

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