

Research paper

Three-year Patch Thinning Effects on the Stand Structure in Overstory Trees of a Japanese Cedar Plantation in Taiwan

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【 Summary 】

Stand structure plays an important role in forest ecosystem management. In this study, we examined the immediate and 3-yr effects of patch thinning treatments on the stand structure of overstory trees in a 35-yr-old Japanese cedar (*Cryptomeria japonica*) plantation located in the Zenlen area, central Taiwan. Among twelve 1-ha plots, 4 plots were randomly assigned to 1 of 3 patch thinning intensities in a randomized complete block design: no removal (control), and 25 and 50% tree removal in the area. The stand structure of the residual overstory trees was examined immediately after thinning and again after 3 yr using non-spatial stand structural indices (vertical evenness and the diameter at breast height (DBH) distribution), a pair correlation function (G function), and spatial stand structural indices (diameter differentiation index and structural complexity index). The vertical evenness of the overstory tree canopy was reduced after thinning. Unlike the left-truncated Weibull DBH distribution commonly caused by thinning from below, no notable left-truncated Weibull distribution caused by patch thinning was detected. The change in the spatial point pattern expressed by the G function with scale-up at a distance scale was influenced by the intensity of the thinning. The stand structural complexity was affected by the spatial scale used and stand attributes surveyed, and it was reduced immediately after thinning but had varying impacts on the DBH and tree height.

Key words: vertical evenness, pair correlation function, stand structural complexity, Weibull function, diameter differentiation index.

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研究報告

塊狀疏伐對柳杉上層林木林分結構三年之影響

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摘 要

林分結構在森林生態系經營中承擔重要之角色。本研究探討人倫地區35年生柳杉人工林在塊狀疏伐後三年內對上層林木林分結構之影響。試驗地內設置12個1公頃樣區，進行上層林木之每木調查和樣木位置之量測。以逢機區集方式逢機進行三種疏伐強度(疏伐面積25、50%和對照)之塊狀疏伐，每一處理重複4次。使用垂直均勻、胸徑分佈、組對空間相關函數(G函數)、胸徑分化指標和結構複雜度指標來推估疏伐後立即和前三年對林分上層木結構之影響。結果顯示上層林木之垂直均勻度在疏伐後降低；和下層疏伐不同，塊狀疏伐在疏伐後不會造成胸徑分佈之明顯左截；尺度變化導致林木空間點分佈，因疏伐強度之不同有所差異；林分結構複雜度隨者空間尺度和林分屬性有所變異，塊狀疏伐在疏伐後立即降低林分結構複雜度，但對胸徑和樹高則有不同之影響。

關鍵詞：垂直均勻、組對空間相關函數、林分結構複雜度、胸徑分化指標。

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INTRODUCTION

In plantations, competition in the roots and crowns of trees occurs at the onset of crown closure. Crowded trees compete for light, water, and nutrients, resulting in the slow growth or even death of some trees (Oliver and Larson 1996). To avoid overcrowding and minimize negative effects of competition, trees are often thinned to increase the growing space available for residual trees. Therefore, thinning is one of the most commonly employed forest silvicultural treatments used to enhance the growth of final crop trees (Abbott and Loneragan 1983).

Traditionally, the objective of thinning was to create more space or redistribute the resources available for residual trees, thereby, producing higher-quality sawlogs (Smith 1986, Mäkinen and Isomäki 2004). Recently, issues regarding biodiversity, environmental health, recreation, competing land use objec-

tives, carbon sequestration, and wildlife habitats have affected public attitudes towards forest management, and thinning has also been viewed as an important treatment for addressing some of these issues (Sheriff 1996, Chambers et al. 1999).

In addition to effects on individual tree and stand growth (Marquis and Ernst 1991, Mäkinen and Isomäki 2004), thinning affects soil water availability (Donner and Running 1986), ecophysiology (Gauthier and Jacobs 2010), plant physiology, nutrient contents (Ginn et al. 1991, Bauhus et al. 2001), understory plant communities (Dodson et al. 2008, Fahey and Puettmann 2008), the microclimate environment (Della-Bianca and Dils 1960, Wang et al. 2003, Weng et al. 2007, Rambo and North 2009), and long-term tree mortality trends (Powers et al. 2010).

Tappeiner II et al. (2007) listed 5 types

of thinning that vary in the way trees are removed: (1) thinning from below; (2) thinning from above; (3) crown thinning; (4) free thinning; and (5) strip or row thinning. The resulting average diameter at breast height (DBH) and crown size of residual trees differ with each type. For example, thinning from below is the most widely used type, where the average DBH and crown size of the residual trees increase due to the removal of suppressed, intermediate, and smaller co-dominant trees. In contrast, when thinning from above, the average DBH and crown size of residual trees decrease because of the removal of dominant and co-dominant trees. Even if the residual stocking levels are the same among the 5 types of thinning, different tree- and stand-level responses to thinning will result because attributes of the residual tree populations differ (Weiskittel et al. 2011). Patch thinning, is actually thought to be thinning that does not account for tree size. It is similar to the row thinning method with the only difference being in the shape and usually creates more gaps than those methods of thinning from below.

The forest structure is of interest to many disciplines and is often discussed in the context of ecosystem management. The forest structure encompasses many meanings and can be described in many ways (Pommerening 2002). Measurements of trees size, age, foliage distribution, biomass, and spatial distribution in the overstory and ground vegetation layers are commonly viewed as components of stand structure (Spies 1998). At the stand level, the stand structure appears to be a good surrogate measure for biodiversity in forest ecosystems (Barbeito et al. 2009). The structure of tree crowns, for example, is a characteristic of the stand structure that influences the growth of both trees and the understory vegetation (Latham et al. 1998). Changes in structural attributes of stands also affect

stand functions such as photosynthesis, respiration (Waring and Schlesinger 1985), tree growth (O'Hara 1988), suitability of a stand for wildlife (Morrison et al. 1992, Mountford and Peterken 1999), and understory plant diversity (Latham et al. 1998). Moreover, stand structure is also considered an important element of stand biodiversity (MacArthur and MacArthur 1961, Freemark and Merriam 1986, Staudhammer and LeMay 2001). Thus, in terms of ecosystem service and biodiversity, stand structural diversity has become an important facet within forestry, especially for countries with a rather low level of tree species diversity, such as those of the Central European Region (Neumann and Stalinger 2001).

The spatial forest structure influences growth processes, and all biotic and abiotic impacts modify the spatial structure (Zenner 2000). Several structural indices have been developed to quantify the spatial forest structure and are used as surrogate measures for quantifying biodiversity (Zenner and Hibbs 2000, Gandow and Hui 2002, Pommerening 2002, Barbeito et al. 2009). A good understanding of the spatial forest structure is crucial for the sustainable management for economic and environmental purposes (Pommerening 2006).

Taiwan is a mountainous island with an area of about 36,000 km² in the South China Sea. The forests of Taiwan cover 58% of the island's area, of which about 73% are considered natural forests (TFB 1995). Japanese cedar (*Cryptomeria japonica*), also called sugi, was introduced to Taiwan by the Japanese government in 1921 based on its successful experiences in plantation establishment in Japan (Chao 2005). In 2000, sugi plantations were the second most common plantation species in Taiwan, with an area of 47,000 ha, accounting for about 22% of the total conifer

plantations in Taiwan (World Forest Institute 2001).

In the past, sugi plantations were planted as monocultures mainly for timber production in Taiwan. Nowadays, with the emphasis on forest ecosystem management, the concern has become how to apply thinning practices to existing sugi plantations to enhance the heterogeneity of the stand composition and structure so as to meet the goals of biodiversity conservation and promote land productivity and stability of ecosystems for sustainable plantation management in Taiwan.

While there are studies investigating the thinning effects on sugi plantations in the past in Taiwan, they all used the approach of thinning from below to solely increase timber production (Weng et al. 2007, 2011, Yen et al. 2008). No patch thinning was examined in the field. As the overstory stand structure influences a wide range of ecosystem process, including wildlife abundance (Lehmkuhl et al. 2006), understory vegetation composition, and biomass (Collins et al. 2007), and being that patch thinning is a new approach adopted in Taiwan, the purpose of this study, therefore, was to investigate the immediate and 3-yr influences of alternative patch thinning strategies on the structural diversity of overstory trees in a sugi plantation in the Zenlen area of central Taiwan.

MATERIALS AND METHODS

Site description

The experiment site was in the 74th and 75th compartments of the Nan dai national working circle of the Taiwan Forestry Bureau, in the Zenlen area of central Taiwan. The sugi plantation was planted in 1971–1972 with an area of 78 ha at elevations of 1500–1700 m. Based on records from the nearby Sun-Moon Lake Weather Station (120°54'29"E,

23°52'53"N, elevation 1018 m), the mean annual precipitation at the study site is 3800 mm mostly in May to September. The mean annual temperature is 17.5°C. The average slope of the study area is 20° ~ 22°. The soil has a loamy sand (LS) type texture composed of 78.2% sand and 9.3% clay on average (Wang 2010, pers. comm).

Experimental design and thinning treatments

A randomized block design was used that had 3 thinning intensities, replicated 4 times on 1-ha plots. All 12 plots were uniform in topography and aspect. A buffer strip, 20–30 m in width, separated each plot. The total area of the sugi plantation for the experiment was about 25–30 ha.

In each plot, stems of all woody plants with a DBH of > 1 cm were tagged, identified by species, and measured for DBH. Stem location was recorded on a Cartesian coordinate system. Height was measured on trees sampled across the range of DBH to develop a DBH-height curve for sugi.

Thinning was accomplished by removing all overstory trees within patches 10×10 m in size. The patches were systematically located to cover 25 or 50% of the total area of a plot. For the 25% thinning intensity, 1 patch located in the lower-left corner was cut within each of 25 quadrants with dimensions of 20×20 m (Fig. 1). For the 50% thinning intensity, 2 patches connected southwest to northeast diagonally were cut within each quadrant (Fig. 1).

Functions and indices of the stand structure

In this study, both spatially implicit and spatially explicit functions and stand structural indices were used to assess the impacts of patch thinning on the stand structure.

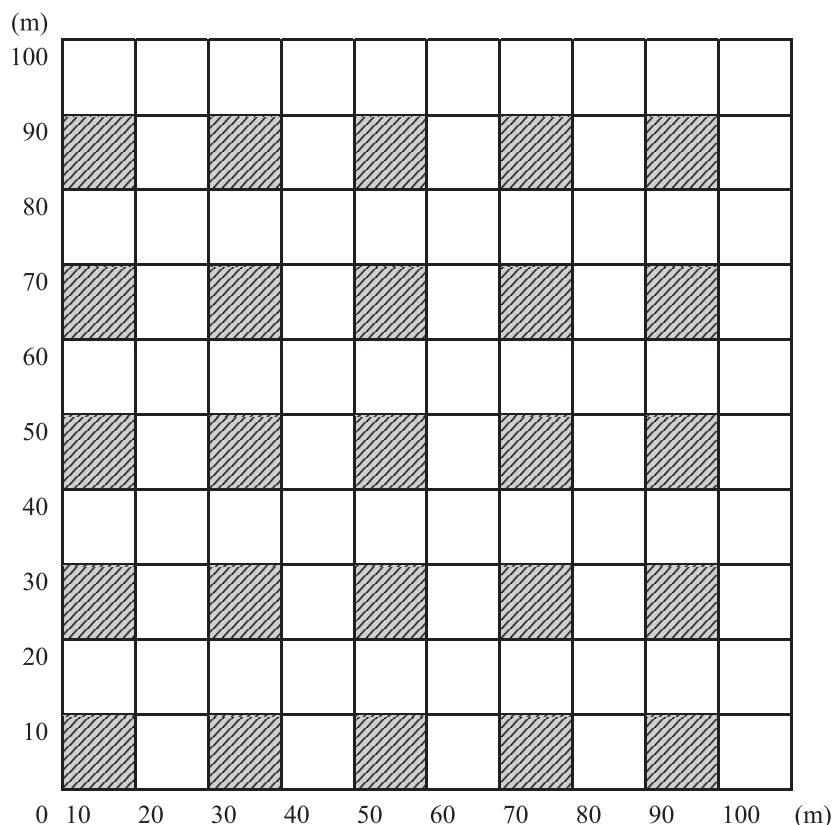


Fig. 1. Allocation of cutting areas indicated by dark slashes for a thinning intensity of 25% in area. Two 1/4 quadrants (10×10 m) diagonally connected southwest to northeast within a 20×20-m block were set up as the cutting area for a thinning intensity of 50%.

Spatially implicit stand structural indices

Indices were developed to assess the vertical and horizontal components of the stand structure. Five canopy layers of sugi tree heights (< 13, 13~15, 15~17, 17~19, and > 19 m) were used to calculate the vertical evenness (VE; Equ. 1). The 3-paramater Weibull function (Bailey and Dell 1973) was used to estimate the DBH distribution among tress because of its modeling flexibility and easy computation (Lynch and Moser 1986, Zhang et al. 1993):

$$VE = (-\log p) \times p / \log 5; \tag{1}$$

where p is the ratio of the number of trees for a given class i to the total number of trees.

Function and spatially explicit stand structural indices

In addition to indices or empirical distributions, functions are also used to model point processes in statistics (Penttinen et al. 1992). The pair correlation function used in this study was the G function (Zhukov 2010). The G function in this study measures the distribution of distances from an arbitrary tree to its nearest neighbors :

$$\hat{g}(r) = \frac{\sum_{i=1}^n li}{n}; \tag{2}$$

where

$$li = \begin{cases} 1 & \text{If } di \in \{di : di \leq r, \forall i\} \\ 0 & \text{otherwise} \end{cases}$$

di is the distance between the subject tree i

to its nearest neighbor tree j ; r is a given distance; and n is the number of subject trees.

Unlike the aggregation index, R (Clark and Evans 1954), the pair correlation function $g(r)$ does not result in 1 number, but in a function which can be plotted on a graph. The comparability of point processes with complete spatial randomness (CSR) can be assessed by plotting the empirical function (i.e., observed value) against the theoretical expectation, $G(r)$. For a regular pattern, values of the empirical function are below envelopes, and a contrast exists for a cluster pattern (Zhukov 2010).

The diameter differentiation index (Pommerening 2002), based on the nearest neighboring tree distance, was applied to spatially express size differences of neighboring trees on a continuous scale. For the i th reference tree and its $n = 3$ nearest neighboring trees j ($j = 1 \dots n$), the diameter differentiation index T_{ij} is defined as:

$$T_{ij} = 1 - [\min(\text{DBH}_i, \text{DBH}_j) / \max(\text{DBH}_i, \text{DBH}_j)]; \quad (3)$$

where DBH is the diameter at breast height (in cm).

To calculate the diameter differentiation of an entire stand, all T_{ij} values are summed and divided by the number of trees to obtain a single number, T . Diameter differentiation values can be classified as follows. (1) A small differentiation comprises the class 0.0~0.3 indicating that the tree with the smallest DBH is $\geq 70\%$ of the neighboring tree's size. (2) An average differentiation comprises the class 0.3~0.5 which means that the tree with the smallest DBH is 50~70% of that of the neighboring tree. (3) A big differentiation comprises the class 0.5~0.7 indicating that the tree with the smallest DBH is 30~50% of the neighboring tree's size. (4) A very big differentiation comprises the class 0.7~1.0 which means that the tree with the smallest DBH is

< 30% of the neighboring tree's size (Pommerening 2002).

Based on vertical gradients and distances of neighboring trees, Zenner and Hibbs (2000), using the triangular irregular network (TIN) (Fig. 2), created an index called Structural Complexity Index (SCI) to measure structural variability among stands.

The SCI is defined as the sum of the surface areas of the TINs for a stand (SAT) divided by the ground area covered by all triangles:

$$\text{SCI} = \text{SAT} / \text{AT}; \quad (4)$$

where AT is the sum of the projected areas of

all triangles and $\text{SAT} = \sum_{i=1}^N \frac{1}{2} |a_i \times b_i|$, $i = 1, \dots, N$, N is the number of triangles in the plot, $|a_i \times b_i|$ is the absolute value of the product of the vector AB with coordinates $a_i = (x_{ib} - x_{ia}, y_{ib} - y_{ia}, z_{ib} - z_{ia})$ and the vector AC with coordinates $b_i = (x_{ic} - x_{ia}, y_{ic} - y_{ia}, z_{ic} - z_{ia})$ (Fig. 2). The sum of 1/2 the vector products gives a surface area in 3 dimensions by connecting the z-coordinates of trees with spatial coordinates x and y . When all trees in a stand have the same z (e.g., height), the value of SCI equals 1, giving the lower limit of the SCI (i.e., when all trees in a stand have the same height).

In order to investigate the scale impact on the SCI, 2 scales were used in this study. One scale regarded the entire plot as a unit (i.e., 100 × 100 m), and calculated 1 value for each plot. The other divided the entire plot into 100 subunits of 10 × 10 m in size, then calculated the SCI for each subunit, and averaged the subunit SCI values to obtain 1 value for each plot.

Edge correction

Indices accounting for tree positions require an edge correction process (Pommerening and Stoyan 2006) to avoid an edge bias in index calculations. In this study, we used

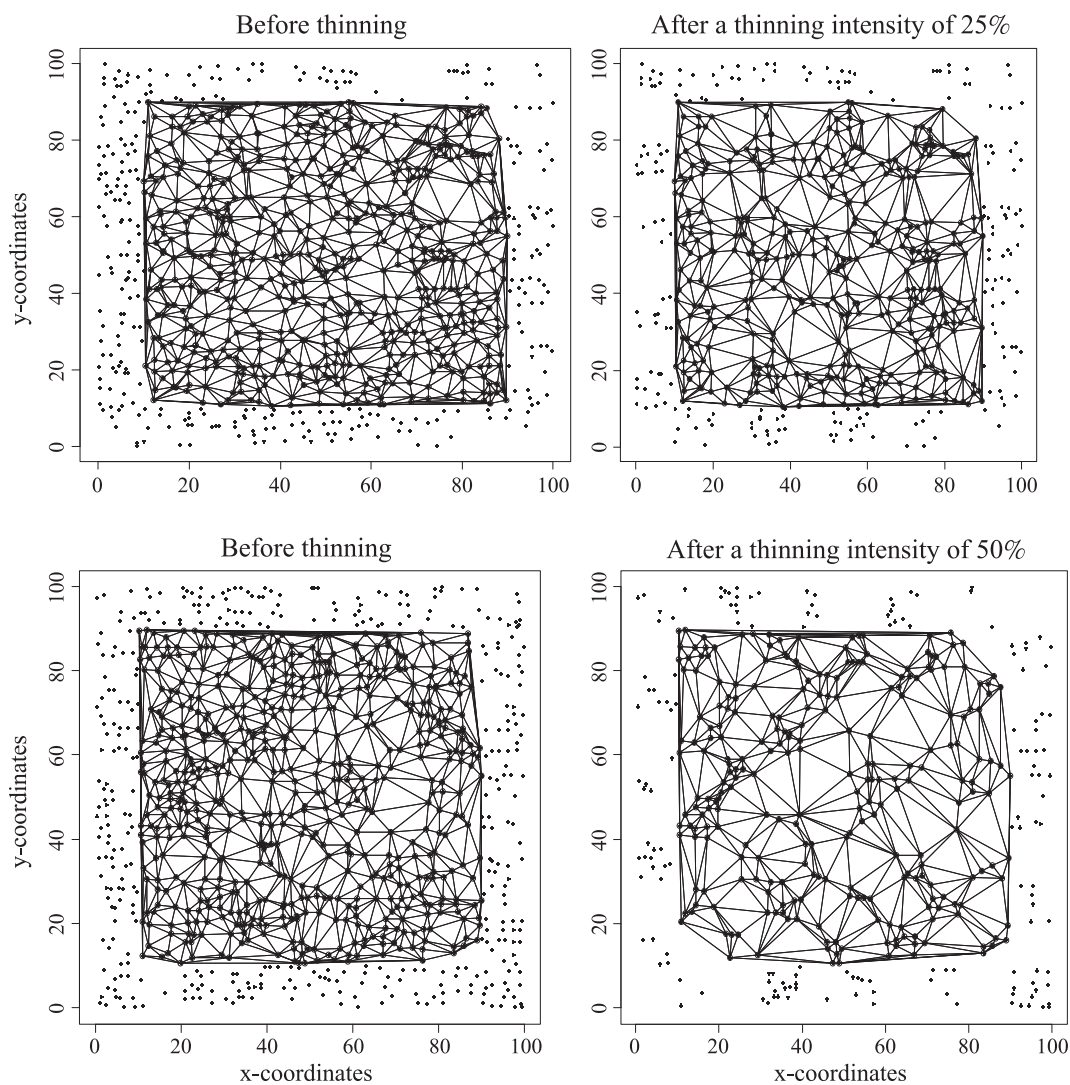


Fig. 2. Structural Complexity Index Delaunay triangulation for plots 1 (above) and 2 (below) before (left) and after thinning (right) on the 80×80 -m scale.

the buffer method (Diggle 2003) for which only trees within a buffer strip of 10 m along the plot boundaries (i.e., the inner part of size 80×80 m) were used to calculate the SCI on both small and large scales.

RESULTS

Stand structural characteristics

The stand density of overstory trees

ranged from 893–1285 trees/ha, and the average DBH varied 24.1–27.8 cm among plots (Table 1). Competition among trees and other factors may account for the heterogeneity among plantations. Computation of the species composition in basal area showed that sugi and China fir (*Cunninghnia lanceolata*) were the dominant overstory trees in the stand. Because the basal area of sugi was $> 80\%$ of the total basal area in the overstory

Table 1. Characteristics of stand attributes for overstory trees surveyed on a 1-ha basis in the study area

Plot	Density (no. of stems)	DBH (cm) ^{a)}	Height (m) ^{a)}	Basal area (m ² ha ⁻¹)	Volume (m ³ ha ⁻¹)
1	893	27.0 ± 7.3	17.48 ± 1.99	54.77	461.45
2	944	27.6 ± 7.5	17.62 ± 1.70	60.63	512.10
3	1055	26.0 ± 6.3	17.37 ± 1.45	58.39	488.86
4	939	27.8 ± 6.9	17.72 ± 1.63	60.57	511.86
5	895	25.2 ± 6.9	17.15 ± 1.85	47.88	400.10
6	1114	26.5 ± 6.6	17.49 ± 1.56	65.32	548.84
7	1285	24.1 ± 6.3	16.98 ± 1.61	62.79	520.77
8	1019	25.6 ± 5.8	17.37 ± 1.41	55.24	461.92
9	1184	24.2 ± 6.4	16.98 ± 1.59	58.32	484.17
10	964	27.5 ± 7.1	17.64 ± 1.57	61.01	514.90
11	1074	24.3 ± 6.3	17.00 ± 1.70	52.92	439.60
12	896	26.3 ± 7.2	17.38 ± 1.66	52.28	439.05

^{a)} Mean ± standard deviation.

DBH, diameter at breast height.

layer, the plantation was still considered a pure sugi plantation.

Thinning effects on the stand structure

Comparisons of stand attributes showed that the thinning intensity in terms of the area treated can be roughly applied to the number of trees, basal area, and volume removed (Table 2). The Weibull DBH distribution of each plot approximated a normal distribution, and its shape did not change after thinning regardless of the thinning intensity, as shown, for example, by plots 11 and 5 (Fig. 3). In the control plot, the shape of Weibull distribution gradually shifted downwards revealing the increasing mortality of trees over time (Fig. 3).

In each plot, the DBH differentiation index was compared before and 0–3 yr after thinning. Before thinning, using plot 11, where removal of trees within 25% of the area, was scheduled, as an example, we found that most trees expressed a DBH difference with their neighbors that varied spatially in the ‘small level’ (0.0–0.3), meaning that DBH differences among neighboring trees were <

30%. Only a few trees differed in DBH by > 50% from their neighbors, i.e., at the ‘big level’ of differentiation (Fig. 4). However, the percentage of trees with a DBH differentiation index at the ‘small level’ increased after thinning (65 to 72%). On the contrary, the percentage of trees with a DBH differentiation index of an ‘average level’ decreased after thinning (27 to 23%). The same pattern of the DBH differentiation index was observed in plot 5 with the 50% thinning intensity (Fig. 4).

The spatial pattern of plots can be observed using the G function. The G function measures the distribution of distances from an arbitrary event to its nearest events (Ripley 1988). In this study, under the relative distance (i.e., distance observed / distance of the plot boundary) framework, for a given relative distance (e.g., 0.2), we calculated the proportionality of trees in a plot which had a distance to their nearest neighbors of less than or equal to a given relative distance, and then we judged the spatial point pattern based on a comparison of the empirical function G(r) to its G function under the CSR. The resulting G

Table 2. Comparisons of stand attributes between before and after thinning by plot

plot	Treatment area (ha)	Number of trees (ha)			Basal area (m ² ha ⁻¹)			Volume (m ³ ha ⁻¹)		
		Before thinning	Removed	Percent removed	Before thinning	Removed	Percent removed	Before thinning	Removed	Percent removed
1	0.25	893	264	29.6	54.77	15.28	27.9	461.45	128.28	27.8
4	0.25	939	239	25.4	60.57	15.02	24.8	511.86	126.43	24.7
7	0.25	1285	253	19.7	62.79	12.81	20.4	520.77	106.76	20.5
11	0.25	1074	270	25.1	52.92	12.44	23.5	439.60	102.43	23.3
2	0.50	944	507	53.7	60.63	31.40	51.8	512.10	264.24	51.6
5	0.50	895	490	54.8	47.88	26.24	54.8	400.10	219.25	54.8
8	0.50	1019	494	48.5	55.24	26.51	48.0	461.92	221.26	47.9
9	0.50	1184	596	50.3	58.32	28.86	49.5	484.17	239.18	49.4

function showed that the point pattern of the tree spatial distribution varied depending on the spatial scale used (Fig. 5).

The SCI is an index which can be used to describe the structural complexity of DBH or tree height in a 3D format. Regarding the 2 scales used in computing the SCI, theoretically, the more homogeneously distributed the spatial point is, the closer these 2 scales of the SCI should be. This study showed a tendency that because of the heterogeneity of the point spatial pattern in the plot (Fig. 2), the SCI obtained at the small scale (10×10 m) was greater than that obtained at the larger scale (80×80 m) for each plot before thinning in terms of both the DBH and tree height structural complexity (Fig. 6). However, the difference between the 2 scales was reduced after thinning (Fig. 7). Moreover, for a larger scale, thinning will reduce the structural complexity for both attributes, but with different impacts between them (Fig. 8). The change of the SCI in the short-term reveals that the SCI was decreasing over time even in the control plots (Fig. 9).

DISCUSSION

Stand density and structure

In general, the percentage of area, num-

ber of stems, and basal area or tree volume are often used to express thinning intensities (Knoebel et al. 1986, Pukkala et al. 1998, Mäkinen and Isomäki 2004.). Nevertheless, the same figure expressed by a different criterion often conveys a different meaning. For example, thinning from below extracts the suppressed, intermediate and smaller codominant trees. Those trees contribute a smaller proportion to the stand basal area and volume; hence, a given thinning intensity expressed as a percentage of the number of trees will leave a very different residual stand compared to one in which the same percentage is applied to removing the basal area or tree volume (Weiskittel et al. 2011). In this study, however, because of the systematic allocation of the cutting area (Fig. 1), although heterogeneity in stand attributes exists among plots (Table 1), all overstory trees in the cutting area were removed. Because of their relatively even distribution over the study area, the same percentage for the thinning intensity in patch thinning can be roughly applied to the area, number of trees, basal area, and tree volume (Table 2).

Patch thinning used in this study ignores tree species, tree size, and crown class by selecting trees for removal based solely upon whether the tree is located in the patch that is allocated for cutting. Therefore, patch

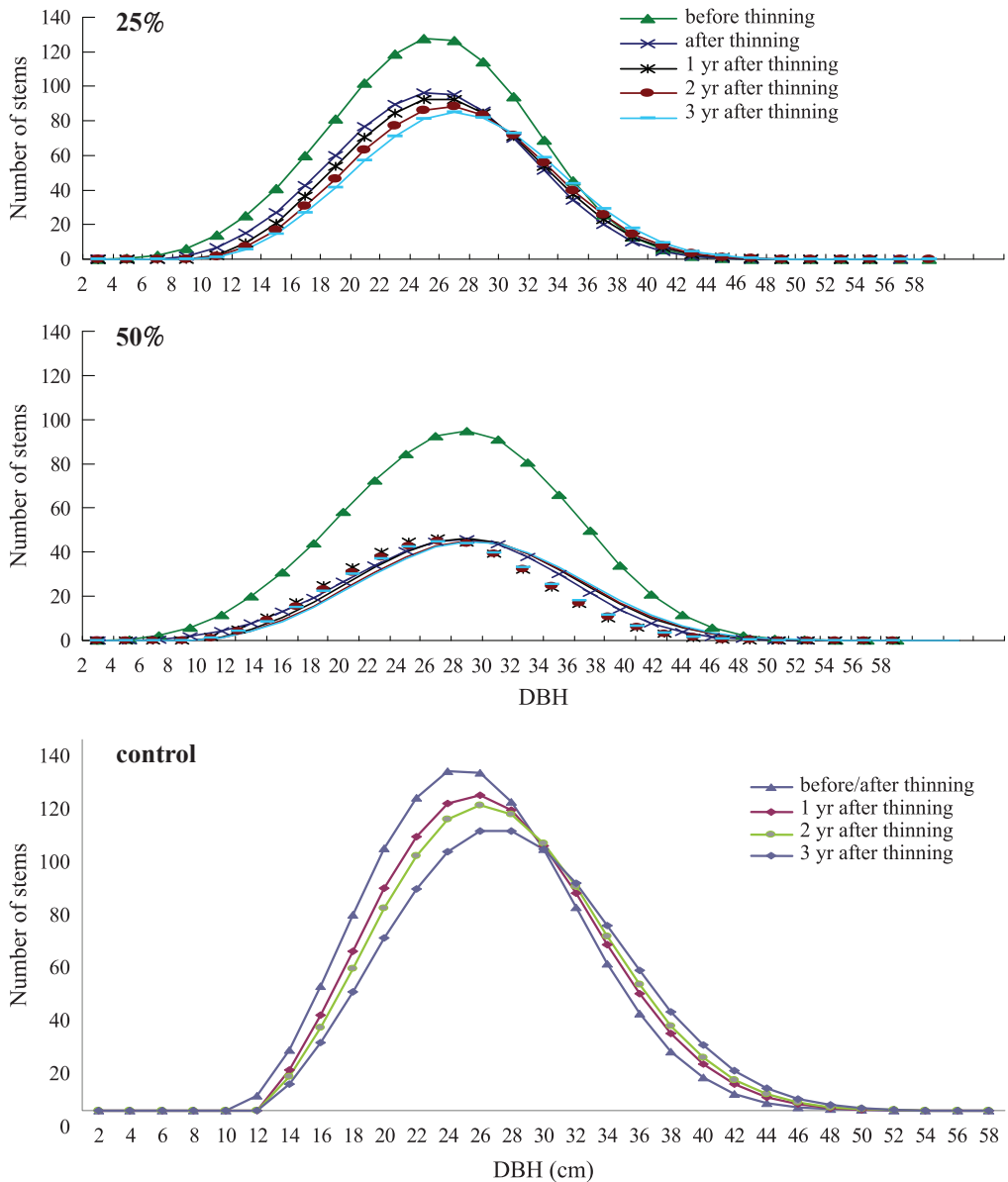


Fig. 3. Diameter at breast height (DBH) distribution for plot 11 with a 25% thinning intensity, plot 5 with a 50% thinning intensity, and plot 3 with no treatment (control).

thinning can be regarded as a type of strip or row thinning (Weiskittel et al. 2011).

An earlier study on the same site showed that in addition to the dominant overstory species of sugi and China fir, several broad-leaf species occur as the understory woody vegetation. While the basal area shared by

understory woody plants was quite small in the plantation (i.e., < 5%), an enhancement of biodiversity was obvious. The biological diversity (Shannon diversity index) of all woody plants increased after thinning, but there was little change in overstory trees (Wang et al. 2011).

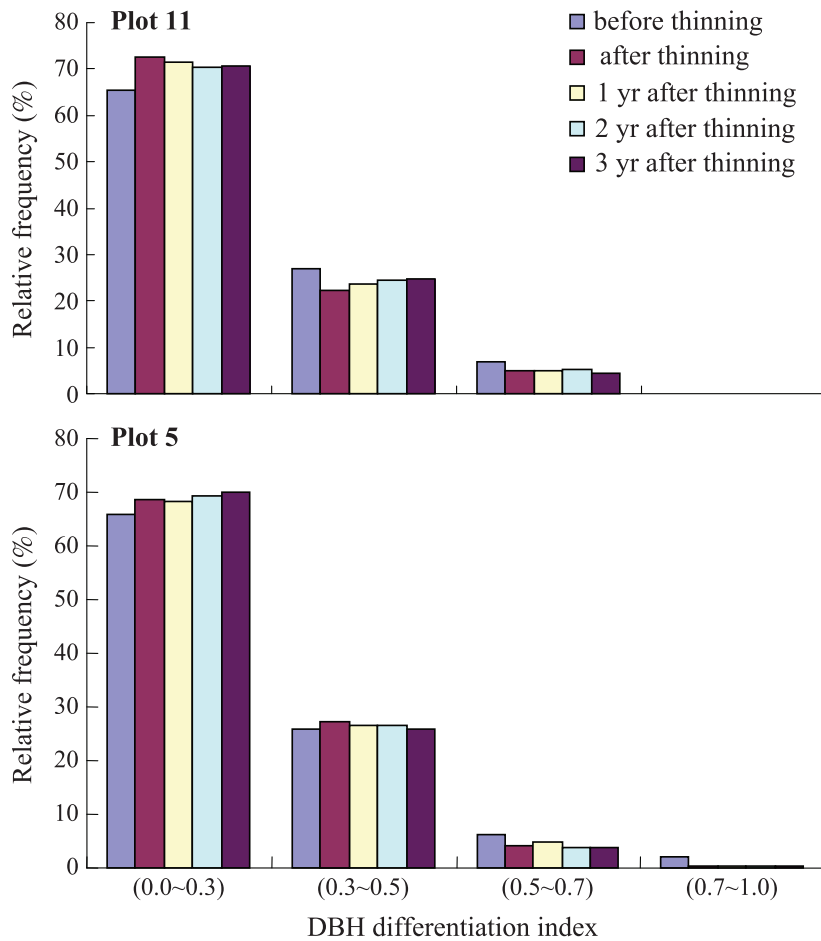


Fig. 4. Distribution of the diameter at breast height (DBH) differentiation index based on the first nearest neighboring distance with 25% (plot 11) and 50% of the thinning intensity (plot 5).

Effects of thinning on the vertical and horizontal structure

Vertical structure plays an important role in forest ecosystems (North et al. 1999, Barbeito et al. 2009). Analyzing spatial patterns within different tree height classes can provide many important clues about the underlying processes that have generated those patterns (Zenner and Hibbs 2000). Using the same categories of canopy layers as used in this study, Wang et al. (2011) demonstrated that, while little difference was found among plots, the evenness index value was > 0.5

for all plots before thinning, and the vertical evenness of the canopy was slightly reduced immediately after patch thinning for all thinning intensities adopted with the same as these used in our study. Moreover, this study showed that no significant difference in vertical evenness existed even when the understory trees (i.e., broadleaf trees) were included (1-sample *t*-test $n = 12$, $p = 0.152$). This is because all understory trees were < 13 m in height, and their inclusion did not make a notable change in vertical evenness index values. As the residual trees and understory

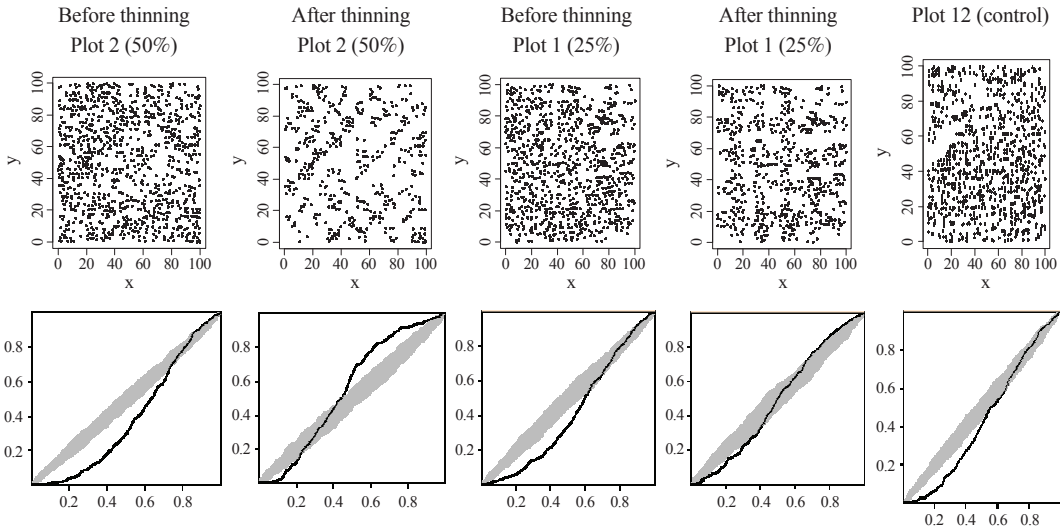


Fig. 5. G function for plots before and after the thinning practice for thinning intensities of 25 and 50%.

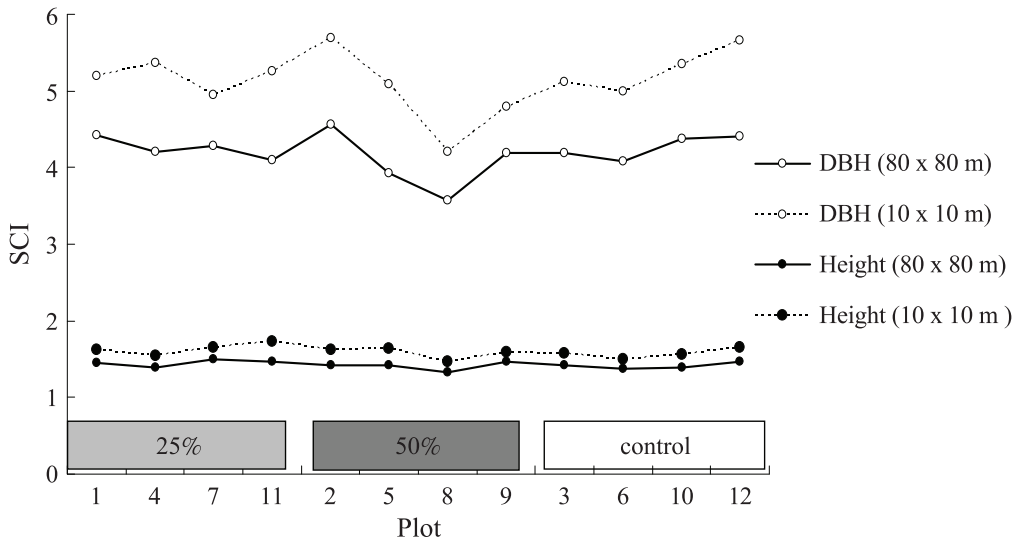


Fig. 6. Comparisons of the Structural Complexity Index (SCI) for diameter at breast height (DBH) and height on 2 scales (80×80 vs. 10×10 m) for 12 plots before thinning. Plots 1, 4, 7, and 11 had a thinning intensity of 25%; plots 2, 5, 8, and 9 had a thinning intensity of 50%, and plots 3, 6, 10, and 12 were controls.

woody plants will grow over time, it is expected that the resulting vertical evenness structure will gradually recover.

The stand horizontal structure in DBH distribution will be affected by thinning op-

erations. As discussed, the change in the DBH distribution depends on the thinning type used, such as thinning from below where the diameter distribution is notably left-truncated after thinning because trees of a small size

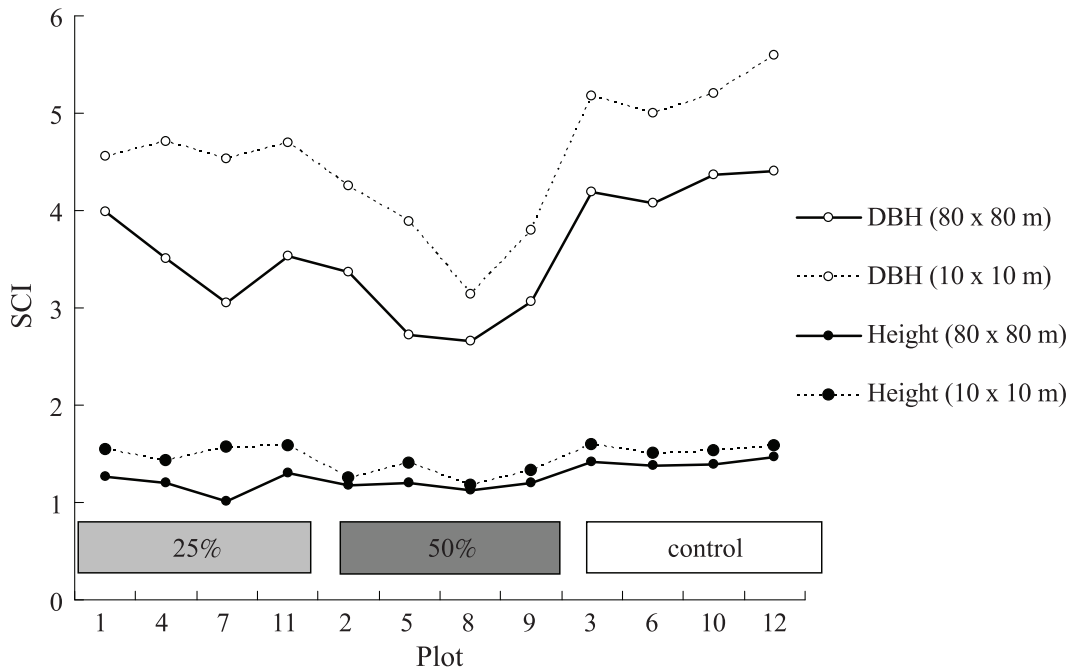


Fig. 7. Comparisons of the Structural Complexity Index (SCI) for diameter at breast height (DBH) and height on 2 scales (80 × 80 vs. 10 × 10 m) for 12 plots after thinning. Plots 1, 4, 7, and 11 had a thinning intensity of 25%; plots 2, 5, 8, and 9 had a thinning intensity of 50%, and plots 3, 6, 10, and 12 were controls.

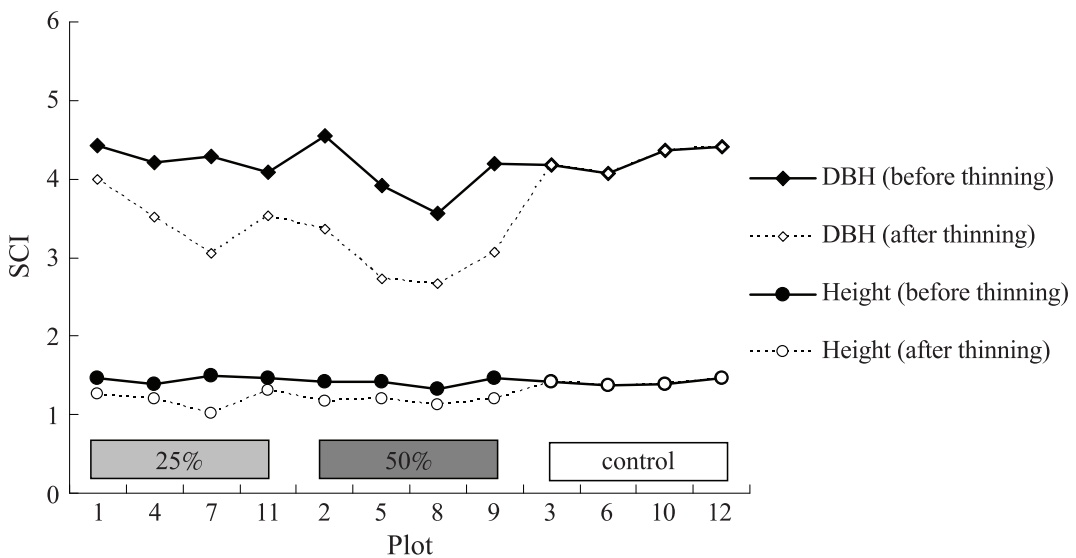


Fig. 8. Changes in the Structural Complexity Index (SCI) for diameter at breast height (DBH) and height on the 80 × 80-m scale before and after thinning. Plots 1, 4, 7, and 11 had a thinning intensity of 25%; plots 2, 5, 8, and 9 had a thinning intensity of 50%; and plots 3, 6, 10, and 12 were controls.

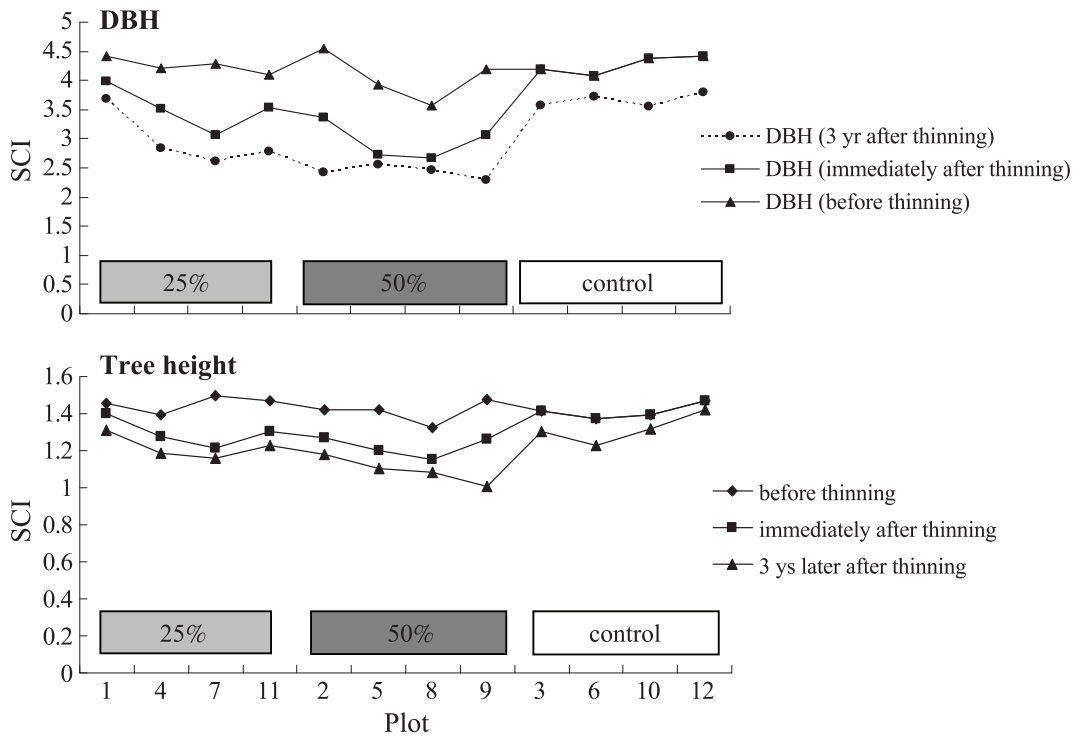


Fig. 9. Changes in the Structural Complexity Index (SCI) for diameter at breast height (DBH) and tree height over 3 yr after thinning on the 80×80 -m scale. Plots 1, 4, 7, and 11 had a thinning intensity of 25%; plots 2, 5, 8, and 9 had a thinning intensity of 50%, and plots 3, 6, 10, and 12 were controls.

or suppressed trees are removed (Wang et al. 2003, 2006, Li and Yen 2010). However, under systematic patch thinning, the DBH distribution type depends on the spatial distribution of small trees and their location relative to the cutting area. If fairly uniform, only a slight truncation of the tree diameter distribution after thinning would exist, as observed in this study (Fig. 3). Among the treated plots in this study, almost each plot showed a non- or slightly truncated DBH distribution after thinning. This finding was valid regardless of the thinning intensity adopted (Fig. 3). As mentioned earlier, patch thinning is a type of row thinning, and this finding for the DBH structure confirms that in row thinning, the average DBH, crown size, and species com-

position of the residual trees should remain the same as those of the stand as a whole before thinning (Weiskittel et al. 2011).

Thinning effects on function and spatial indices of the stand structure

Just like Gadov's differentiation index used by Barbeito et al. (2009) for the tree height distribution, Pommerening's DBH differentiation index (Pommerening 2002) can be used to measure small-scale spatial variabilities in the DBH size distribution. Thinning impacts on the DBH differentiation index pattern depend on the method used for thinning. In traditional thinning from below, as the removed trees are concentrated on small trees and suppressed trees, thus narrow-

ing the range of residual trees, the proportion of the DBH differentiation that falls at the 'small level' substantially increases (Wang et al. 2006). However, in this study, as all overstory trees were removed regardless of size, the range of DBH for residual trees did not shrink as rapidly, and therefore, the DBH differentiation pattern at various levels did not notably change by and thinning practice. This pattern was not influenced by the thinning intensity (Fig. 4). Moreover, over 3 yr, the pattern of the DBH differentiation index among different levels did not remarkably change for either intensity.

Interpretation of the point pattern expressed by the G function for a given plot varies depending on the spatial distance scale used in a plantation. At a small distance scale (e.g., 0.2 or 0.4), the point pattern is regarded as a regular pattern; however, at a larger distance scale (i.e., > 0.8), the point pattern shifts toward a randomized pattern (Fig. 5). Specifically, the type of point pattern for a given subject relies on the spatial scale used.

The trend of the point pattern going from a small distance level to a large distance level expressed by the G function is affected by thinning, and the direction of change is influenced by the intensity of thinning used (Fig. 5). At the lower thinning intensity, for example, the distance scale at which the point pattern remained regular was reduced from 0.8 to 0.4 after thinning. This reduction in the distance scale became larger in the case of the higher thinning intensity (e.g., from 0.8 to 0.3 for the 50% intensity). Moreover, the point pattern change at a larger distance scale was also influenced by the intensity of thinning employed. At the lower intensity, the trend of the point pattern over the distance scale moved from regular to randomized. But, at the higher thinning intensity, the sequence of this change was from regular to random and

then to clustered (Fig. 5). Based on a distance scale of 0.5, all plots were viewed as regularly spatially distributed before thinning; however after thinning, plots with the 25% intensity were viewed as being randomly distributed, and plots with the 50% intensity had a cluster distribution (Fig. 5).

The SCI depends on the spatial scale used (Zenner and Hibbs 2000), and this study showed the difference in the SCI between 2 scales. The SCI obtained from the small scale was greater than that obtained with the larger scale for each plot before thinning, because there was quite a variety in the SCI among subunits (Figs. 2, 6). However, these differences in the SCI between the 2 scales were reduced after thinning (Fig. 7). This is because all overstory trees in the cutting area (10×10 m) were removed, and the SCI for these areas was reduced to 1, thus reducing the average value of the SCI. The narrowing of the difference was more apparent for the case of thinning at 50%. In other words, the impacts on the SCI caused by the spatial scale gradually vanished after thinning (Fig. 7).

As the SCI is calculated based on the gradient surface among trees, the range and standard deviation of the DBH or height (z) will influence the SCI value. Since the stand deviation of the DBH in our study was much greater than that of tree height (Table 1), the SCI for DBH was, therefore, bigger than the tree height SCI (Fig. 6). In other words, low SCI values for tree height indicated that these plots were extremely homogeneous in terms of the tree spatial vertical complexity structure. On the contrary, a higher SCI values for DBH meant that a much higher heterogeneity existed in the tree horizontal spatial complexity structure.

In an earlier study, the SCI was used to evaluate the DBH structural complexity of Douglas fir-dominated mixed conifer stands

in the west-central Cascades of Oregon, USA (Zenner 2004). Compared to this study, SCI values in Zenner's study were much higher than those we obtained. For example, the highest SCI in Zenner's study was 13.34 compared to the highest SCI of 5.8 for diameter structural complexity seen here (Fig. 6). This is because the stands studied in Oregon ranged from natural mature (80~150 yr old) to old growth (> 150 yr old) in contrast to the quite young (< 40 yr old) and higher-density plantation examined in this study (Table 1). In old-growth forests, a higher SCI exists because diameter distributions reflect the multiple pathways of development resulting from complex regional disturbance regimes (Spies and Franklin 1991, Spies 1998).

The lack of a correlation of the diameter SCI with tree density ($p = 0.655$) and mean DBH ($p = 0.194$) shown in our study closely mirrors results in evaluating the relationship of the index of old-growth structure with tree density and average DBH as reported by Acker et al. (1998). A stronger positive association between the SCI and the standard deviation of the DBH ($p = 0.003$) in this study confirms that a large variation in tree sizes is an important requirement for higher structural complexity (Zenner 2004).

The SCI for the DBH of all plots did not significantly differ among treatments before thinning ($F = 0.71$, $p = 0.518$, Fig. 8); however, a significant difference occurred among treatments after thinning ($F = 36.5$, $p = 0.000$, Fig. 8). Among them, the average SCI for the DBH of the control was highest (4.2514), followed by the DBH SCI for the 25% thinning intensity (3.8014), and then by that for the 50% thinning intensity (3.0335).

While a high variability in tree sizes is a necessary condition for higher structural complexity, the processes influencing spatial patterns of differently sized trees (e.g.,

thinning) ultimately determine the extent of structure complexity (Zenner and Hibbs 2000, Zenner 2004). Our study shows that the stand structural complexity was reduced by thinning, just like the case of thinning from below (Barbeito et al. 2009). The reason for the lower SCI caused by thinning is that after thinning, the complexity of the structure in the cut area was lost due to the removal of all overstory trees, and this consequently reduced the structure complexity of the entire plot. With a greater area cut, more structure complexity will be lost (Fig. 8).

Impacts on the SCI caused by thinning varied among stand attributes (Fig. 8). Compared to the SCI for the DBH, the change in the SCI caused by thinning on tree height was quite small. This is because the coefficient of variation (CV) of tree height in each plot was quite small before thinning (Table 1), and no notable change occurred after thinning (Table 3). Nevertheless, the CV for the DBH in each plot was higher than that for tree height both before and after thinning; thus, the reduction of the SCI for the DBH was more substantial than that for tree height. This finding is consistent with the result reported by Zenner (2004) that a higher SCI for the DBH structural complexity was associated with a greater CV ranging from 48 to 98% for the DBH.

The trend of the SCI over time is also of interest. In a comparison of the SCI immediately after thinning and at 3 yr after thinning, even that of the control plot was reduced after 3 yr (Fig. 9). A paired t -test showed that for all plots, a significant difference in the SCI existed 3 yr after thinning for DBH ($t = 4.36$, $p = 0.001$) and tree height ($t = 5.35$, $p < 0.0001$). The probable reason for this reduction may have been the decrease in the CV for both attributes over 3 yr for all plots (Table 3). However, longer observation periods will be required to see the trend of the SCI over time.

Table 3. Characteristics of the diameter at breast height (DBH) and tree height for overstory residual trees immediately after and 3 yr after thinning

Plot	DBH (cm) ^{a)}	Height (m) ^{a)}
1	25.8±6.8 ^{b)}	17.0±1.4 ^{b)}
	29.6±7.5 ^{c)}	18.0±1.4 ^{c)}
2	27.0±7.3	17.5±1.5
	30.7±7.7	18.2±1.2
4	27.2±6.7	17.5±1.4
	29.2±7.0	18.0±1.3
5	25.0±6.8	17.1±1.8
	26.6±6.5	17.5±1.4
7	24.5±6.2	17.0±1.6
	25.5±6.2	17.3±1.5
8	25.5±5.7	17.4±1.4
	27.5±6.0	17.8±1.1
9	24.0±6.2	17.0±1.5
	27.1±7.0	17.6±1.3
11	23.3±6.2	16.6±1.5
	26.4±6.2	17.5±1.3

^{a)} Mean ± standard deviation.

^{b)} Immediately after the thinning operation.

^{c)} Three years after the thinning operation.

In the absence of tree height data, just like the height-DBH curve, the SCI for tree height can be estimated by the SCI for the DBH. In our case, the SCI for tree height = $0.689 + 0.1556$ SCI for the DBH, with $n = 12$, $R^2 = 0.60$ at the 80×80 -m scale. This confirms that greater SCI values for the tree height also means greater SCI values for the DBH as reported by Zenner (2000).

CONCLUSIONS

This study showed the immediate and 3-yr effects of patch thinning on the stand structure of overstory trees in a sugi plantation. Several stand structure indices were used to measure the stand structural complexity and evaluate the short-term impacts on the stand structure caused by patch thin-

ning. Based on the ecosystem management approach to sugi plantations in Taiwan, this study provides an understanding of short-term changes to overstory stand structures following patch thinning. However, longer-term monitoring of the dynamics of the structure indices examined in this study is still needed to evaluate the dynamics of patch thinning on the stand structural complexity as the stands develop. While it is beyond the scope of this study, the impact on the biodiversity and structural diversity of the understory trees due to patch thinning will be studied in the future.

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