

Article

Estimation of the Optimal Seed Production Management Cycle of a Miniature Seed Orchard, Based on the Crown Recovery Process and Spatiotemporal Light Variation After Pruning

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Abstract: Seed orchards play important roles in supplying good seeds. Miniature orchards have the advantages of reducing management areas, but rapid crown development will decrease light intensity and seed production. Block-rotation cycles within an orchard need to be evaluated to optimize total seed production per unit time and area. The development of tree height and primary branches, as well as spatial light variation over the years after pruning and defoliation manipulation were evaluated in a miniature orchard of *Chamaecyparis obtusa* (Sieb. et Zucc.) Endl. set on the Pacific side of Japan. Just two years after manipulation, the branches of the upper-crown parts had grown so long that they were touching each other, and the light environments of the lower-crown parts had become drastically darker. Next, based on the crown development and light variation and the relationship between cone production and light intensity, we performed a simulation of total cone production over the years in a hypothetical orchard composed of multiple blocks. Then, the simulated total cone production was compared between the block-rotation cycles, where crown management was performed every three or four years. Compared to the three-year block rotation, the distribution of within-tree cone production for the four-year block rotation was more biased towards only the upper crown, since the lower crown became suddenly darker. It was estimated that cone production for the entire tree and the entire seed orchard would be lower than in the three-year block rotation. The approach and findings of this study will be useful for improving seed orchard management.



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1. Introduction

Improvements in seed quality and quantity are important for afforestation challenges, and also contribute to improving carbon fixation capacity by improving forestry success [1,2]. Seed orchards composed of superior genotypes with better growth and wood quality play an important role in ensuring a stable supply of good seeds, and the importance of stable seed supply is expected to increase further [3,4]. The area of seed orchards is usually divided into several blocks, and management—such as promoting flower bud initiation and pruning and topping—is carried out by rotating these blocks, but often relies on empirical experience.

To maximize the fruit yield per unit area, agricultural studies have been carried out that strictly examine planting space, placement, and management cycles [5], and as a result, fruit yield per unit area has effectively increased [6]. Spatiotemporal variations in microenvironment factors, such as light intensity and moisture conditions, have recently

been evaluated using sensors (i.e., sensing technology [7]), drones, and rovers [8]. Other studies have also evaluated tree status, such as photosynthetic activity, growth rates, and fruit production, for each tree within a given orchard [9,10]. The relationships surrounding fruit production per tree were then modeled against environmental conditions such as light intensity to quantitatively simulate the optimal production system [10].

Plant responses in terms of growth and reproduction to increases in light intensity have been reported [11]. Trees located on well-lit sites produce more flowers, and seed quality and quantity are positively correlated with flowering magnitude [12]. When increasing orchard tree height and branch density, available light resources decrease, and seed cone production will inevitably be affected [13,14]. Exploring combinations of planting density and thinning and pruning cycles in orchard design and management may enable increased seed production per unit time and area [15]. By incorporating information on responses to environmental conditions, such as shoot elongation and seed production in relation to spatiotemporal light variation, it would be possible to improve orchard management guidelines.

Chamaecyparis (Cupressaceae) is distributed around the Pacific and Atlantic Oceans, is native to eastern Asia and the western and eastern margins of America [16], and is often dominant in forests, acting as large carbon stocks, e.g., *C. lawsoniana* (A.Murray bis) Parl. in America [17] and *C. obtusa* (Sieb. et Zucc.) Endl. in Japan [18]. In Japan, *C. obtusa* is the second-largest forestry species, comprising 25% and 8% of plantation and national land areas, respectively [19]. The national tree breeding program was started in the 1950s, and the selection of superior genotypes as second-generation plus trees is ongoing [20]. Superior genotypes with desirable traits (higher growth, greater biomass production, better wood quality) are favored [21,22], and demand for next-generation seedlings is increasing [23]. It has also become more important to evaluate responses to climate change [20].

Regarding *Chamaecyparis obtusa* and *Cryptomeria japonica* D. Don, the variation in their flowering depending on genotype in naturally planted conditions has been studied [24]. Even when their trees are young, floral buds can be easily induced artificially by the application of gibberellin [24,25]. Miniature seed orchards, which are based on the premise of promoting floral buds by gibberellin, are now mainstream in Japan [26], as they allow for a compact area with high density (1.0–2.5 m spacing and 1.0–1.5 m topping height) and a shorter cultivation period within a few years of planting. Compared to traditional seed orchards, which are studied mainly in terms of planting density [15] and thinning [13,14], and often renewed by top-grafting on largely grown trees [27], miniature orchards have the advantage of shortening the time until the seed production of next-generation genotypes can start [28]. However, in miniature seed orchards, where trees are planted closely together, the rapid growth of seed trees and the overlapping of their crowns result in shading, which reduces seed production capacity. The management cycle series (i.e., floral bud initiation, flowering, cone maturation and seed collection, pruning, and crown recovery) is thus more rigorous than in conventional seed orchards. Planning the management cycle of miniature seed orchards needs to be optimized, so as to improve the seed cone production capacity in relation to crown development and spatiotemporal light variation.

To effectively reap the benefits of miniature seed orchards, crown management and block-rotation cycles need to be evaluated to optimize seed production per unit time and area. Improving management processes allows seed orchards to be established effectively within a shorter period, contributing to the increased productivity of high-quality seedlings. So, the objective of this study was to improve the cone production capacity of *C. obtusa* seed orchards by focusing on crown development after pruning and the associated changes in light environments. The results from this study will fill the information gap related to pruning and rotation cycles within orchard management, which has traditionally relied on

experience and intuition, and also provide quantitative guidelines useful for orchard management. Specifically, we first investigated spatial light variation, as well as tree height and branch length, in a miniature orchard over several years after crown management. Then, using the observed data regarding crown development and light variation, as well as the relationship between cone production and light intensity provided by a previous study [29], we performed a simulation of total cone production over the years in a hypothetical seed orchard and compared block rotations with different years of crown management cycles.

2. Materials and Methods

2.1. Study Site and Plant Materials

This study was conducted at the Forest Tree Breeding Center, Forestry and Forest Products Research Institute, Hitachi city, Ibaraki, Japan (36°41′34″ N, 140°41′28″ E, 55 m above sea level). The annual precipitation and average temperature in this area are 1455.7 mm and 14.3 °C, respectively, and the monthly mean temperatures for the warmest and coldest months are 25.0 °C and 4.6 °C for August and January, respectively. The study site is located on the Pacific Ocean side of Japan, and has a maritime climate like many other monsoonal Asian regions, with sufficient rainfall in summer and warm and sunny winters with little snow. The site is on a hill that has been levelled to be almost completely flat, with well-drained and fertile brown forest soil or andosols, and the climatic and moisture conditions were well kept during the study period by natural precipitation without harsh weather. The experimental miniature seed orchard of the first-generation plus trees of *C. obtusa* was set up in March 2014, and was divided into four replicated blocks. In total, 150 grafts belonging to 15 plus-tree clones were initially planted into the four blocks. The initial planting density was set at 6800 trees/ha (1.2 m × 1.2 m intervals), and thinning was then carried out in a staggered manner to adjust planting density to about 1700 trees/ha (2.4 m × 2.4 m intervals). For the first 3–4 years after planting, the planted grafts were grown to increase their height. Then, at a height of ca. 1.5 m, the trunks were cut with a saw and top pruning was performed, and tree shapes suitable for a miniaturized seed orchard were implemented through management methods such as pruning and placing support poles.

Out of the four blocks, three blocks (Blocks #1, #2, and #3) were targeted. Pruning and defoliation manipulation were carried out for the trees in Blocks #1 ($n_{\text{trees}} = 18$), #2 ($n_{\text{trees}} = 16$), and #3 ($n_{\text{trees}} = 18$) in January 2023, 2022, and 2021, respectively. In other words, Blocks #1, #2, and #3 correspond to just after the manipulation (i.e., 0 years), 1 year, and 2 years after the manipulation at the time of the field survey in 2023, respectively. This pruning and defoliation manipulation was carried out using methods commonly used in miniature orchard management. To explain briefly, this method consists of leaving lignified primary branches extending out from the main trunk at a length of ca. 25–40 cm and leaving several secondary branches with leaves extending out from each primary branch.

2.2. Field Measurement

To obtain basic information for a simulation of block-rotation cycles, a field survey was conducted on the real blocks. In March 2023, the tree stems (trunks) within each real block were mapped, and their height and diameter at breast height (DBH) were measured using height poles and calipers. The number of primary branches for each individual tree was also counted for each height class every 0.5 m from the ground. To assess the variation in leader shoot length along the vertical and horizontal axes, measurements were conducted in March 2023 using a convex measure. For each individual tree, one representative branch extending southward or northward from the center of the trunk was randomly selected at

every 0.5 m height interval. For these branches, the branch length from the trunk center to the tip of the leader shoot was measured using a convex measure.

Photosynthetic photon flux density (PPFD) was used as an indicator of light intensity in this study. Measurements were conducted on cloudy days in March 2023 using LI-250 light meters (LI-COR, Lincoln, Dearborn, MI, USA). The PPFD value was measured on selected branches for a shoot elongation survey (a representative branch extending southward or northward from the center of the tree trunk selected at every height interval of 0.5 m). We evaluated variations in the relative PPFD (rPPFD) along the vertical direction (from the top of the tree to the ground) and horizontal direction (southward or northward from the center of the tree trunk). We also simultaneously measured the PPFD values at a nearby open site. The rPPFD was then calculated for each measurement position as follows: $\text{rPPFD} = \text{PPFD at each position} / \text{PPFD at the open site}$.

2.3. Statistical Analysis of the Tree and Branch Traits and Light Environments

For data curation and analyses, we used R 3.2.5 [30]. We analyzed the response variables below with a mixed-effects model using the “lme4” package. In the explanatory variable, we set “clone” as a random-effect factor to account for the variation among the clones (genotypes). For tree height and primary branch number, “year”—representing the time after manipulation—was set as a fixed-effect factor. For branch length at each height class, “year” was also set as a fixed-effect factor. Post hoc tests were performed with Tukey’s method.

2.4. Simulation of Cone Production

In the present simulation (Appendix A), we assumed two different block-rotation cycles: Cycle I (3-year rotation) and Cycle II (4-year rotation). We assumed that virtual blocks (virtual Blocks A, B, and C for 3-year rotation in Cycle I; virtual Blocks A, B, C, and D for 4-year rotation in Cycle II) within a virtual orchard were rotated at different years after pruning. Under the conditions of continuous sunny weather with higher sunlight duration levels until early summer of the previous year (year_t), abundant flowers bloom in the following spring (year_{t+1}). Therefore, according to the branch and light conditions in the year of GA treatment (year_t), the cone amount in the fall of the following year (year_{t+1}) is affected. So, the results of the branch and light conditions measured in the real Blocks #2 (1 year after pruning) and #3 (2 years after pruning) were used for the cone production simulation of Cycle I (autumn of 2nd year) and II (autumn of 3rd year), respectively.

The usual pruning method involves removing obstructive primary branches from less than 50 cm in height and top pruning to a height of 155 cm. Thus, within the range of h : 50–155 cm, it is assumed that the 17 primary branches are evenly arranged in a cylindrical manner with the trunk as the center. The number of primary branches per trunk was set according to the results measured in the real Blocks #2 and #3 (see Section 3.1). The vertical distribution of the rPPFD over each branch-tip position along the height class was also set by interpolation according to the present results (see Section 3.2).

In the normal management process of *C. obtusa* seed orchards, gibberellic acid (GA) treatment for floral bud initiation is conducted during July–August on fully lignified and well-developed primary branches of more than *ca.* 1 cm diameter and 60 cm length. The bark is peeled off at the basal side, and *ca.* 0.1 mL of GA paste is embedded between the peeled bark and the cambium. The length of the primary branches just after pruning is too short to conduct GA treatment. So, in our simulation (Appendix A), the GA treatment was assumed to be conducted on the primary branches at one year (hereafter, block-rotation Cycle I) or two years (block-rotation Cycle II) after pruning manipulation.

Using the data on branch number and length and rPPFD variation obtained from the real Blocks #2 and #3 in this study, as well as the relationship between cone production and rPPFD provided by a previous study [29], a simulation of seed cone production was performed. Then, a relationship between GA-induced cone production per branch (n_{cones}) and rPPFD was modeled [29] as an exponential equation:

$$n_{\text{cones}} = \exp(-2.774 + 0.11 \times \text{rPPFD}) \quad (1)$$

For each primary branch within a virtual tree within a virtual block, the cone production per branch (n_{cones}) at each rPPFD condition was fitted using the exponential equation (Equation (1)). Then, for each virtual tree within a virtual block, cone production per tree (N_{cones}) was estimated by adding up the amount of estimated cone production per branch (n_{cones}). The mean value of the total amount of estimated cone production per virtual tree was compared between block-rotation Cycles I and II. The coefficient of variation (CV) in the cone production per branch (n_{cones}) within an individual tree was then calculated as the variance in n_{cones} among the branches divided by the mean of n_{cones} .

Total cone production per virtual orchard over 12 years was simulated and compared between Cycles I and II. In this simulation, we assumed a hypothetical miniature seed orchard containing 120 virtual trees. In Cycle I, the 120 virtual trees were divided into three virtual blocks—A, B, and C—with 40 virtual trees in each block, and the three virtual blocks were managed in a three-year cycle. In Cycle II, the 120 virtual trees were divided into four virtual blocks—A, B, C and D—with 30 virtual trees in each block, and the four virtual blocks were managed in a four-year cycle. For Cycle I and Cycle II, the estimated cone production per tree (N_{cones}) was multiplied by the number of virtual trees in each virtual block to obtain the cone production in the virtual block, as well as the total cone production of the seed orchard in a certain year. We then estimated the total cone production of a hypothetical miniature seed orchard over a 12-year period by repeating these three- or four-year work cycles for four or three rotations for Cycle I and Cycle II, respectively.

3. Results

3.1. Tree Size and Branch Length

In the orchard, the overall values for mean ($\pm$ SD) height, DBH, and primary branch number were 2.3 ± 0.5 m, 4.1 ± 0.6 cm, and 17.4 ± 2.7 , respectively. In Block #1, the mean height was 1.69 ± 0.08 m just after pruning and defoliation manipulation (Figure 1). In Block #2, one year after defoliation, the mean height was 2.08 ± 0.24 m (Figure 1). In Block #3, two years after defoliation, the trees grew well and the tree heights reached 2.77 ± 0.24 m, with some of the trees reaching over 3.0 m in height (Figure 1). There were significant differences in tree height considering years after pruning and defoliation manipulation ($F_{2,30.9} = 93.4$; $p < 0.01$; Figure 1).

On the other hand, there was no difference in primary branch numbers (17.5, 17.8, and 17.1 for Blocks #1, #2, and #3, respectively; $F_{2,30.9} = 0.22$; $p = 0.804$). Figure 2 shows the size variation in primary branches by height class. Just after pruning and defoliation manipulation (Year 0), the length of the primary branches was on average 0.43–0.60 m. In each height class, there was a significant difference in branch length between the years after manipulation, and branch lengths from the trunk center to the tip of the leader shoot were longer after more years post-manipulation, as shown by the post hoc significance in Figure 2.

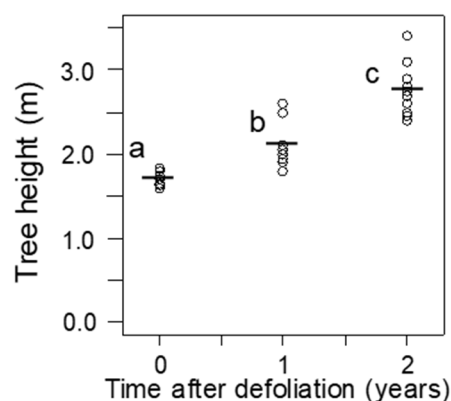


Figure 1. Differences in tree height between the blocks with different years after crown management of pruning and defoliation treatment. Horizontal bars indicate the mean values. Different lower-case letters indicate the significance based on post hoc comparisons.

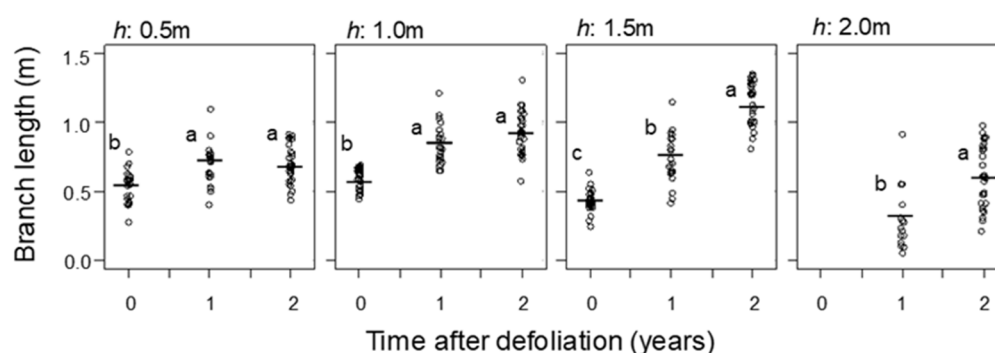


Figure 2. Differences in primary branch length between Blocks #1, #2, and #3 with different lengths of time after crown management of pruning and defoliation treatment. Each panel shows the result for the different ground height classes at 0.5 m, 1.0 m, 1.5 m, and 2.0 m, respectively. Horizontal bars show the means. Different lower-case letters show the significance based on post hoc comparisons.

3.2. Crown Enlargement and Light Environment

Based on the results of branch length measured in Blocks #1, #2, and #3 at each height class, Figure 3A–C schematically show the crown development of the trees. Just after pruning and defoliation manipulation (Figure 3A), the primary branches were pruned almost uniformly within a range of about 50 cm length from the trunk, and the crown was distributed in cylindrical form. One year after pruning and defoliation (Figure 3B), compared to the bottom and top of the crown at h : 0.5 m and h : 2.0 m, the elongation of the primary branches at the height classes h : 1.0–1.5 m was more vigorous, so the crown developed in a spherical shape. Two years after manipulation (Figure 3C), in the height class h : 1.5 m, the elongation of primary branches in the lateral direction continued to be vigorous, and the leader shoot elongation at h : 2.0 m was remarkable, so there was a tendency for the upper part of the tree canopy to develop, while the lower part was shaded by the upper leaves and suppressed.

Figure 3D–F show the trends in the vertical and horizontal distribution patterns of rPPFD measured in Blocks #1, #2, and #3, and Figure 4 summarizes the time-series trends in rPPFD over time after pruning and defoliation manipulation. Just after manipulation (Figure 3D), the primary branches were pruned uniformly within a range of *ca.* 50 cm length from the trunk, and the rPPFD at the branch tips was over 60%, while rPPFD was lower near the center of the trunk. One year after manipulation (Figure 3E), at the height classes h : 1.0–1.5 m, branch length reached nearly 0.8–1.0 m from the trunk center, and the rPPFD near the tip of the branch was maintained at 60–80%, while rPPFD decreased gradually from the tip of the branch to the center of the trunk (Figure 4). In Figure 3F, two years after

manipulation, when the tree height reached 2.5 m and the branch length at h : 1.5 m reached more than 1.0 m from the trunk center, the tips of the branches at h : 1.5–2.0 m kept the rPPFD at >60%, but the rPPFD inside the crown decreased markedly (Figure 4). For the lower branches at h : 1.0 m, the branch length was almost 0.8–1.0 m, and the corresponding rPPFD value was *ca.* 20%. For the lowest branches at h : 0.5 m, the rPPFD values were very low, ranging only between 3 and 10% when within a 0.6 m distance from the trunk center (Figures 3F and 4). This tendency was apparent in the lower branches (h : 0.5–1.0 m) and inside the canopy (d : 0.0–0.6 m) after two years (lower and left-side panels in Figure 4).

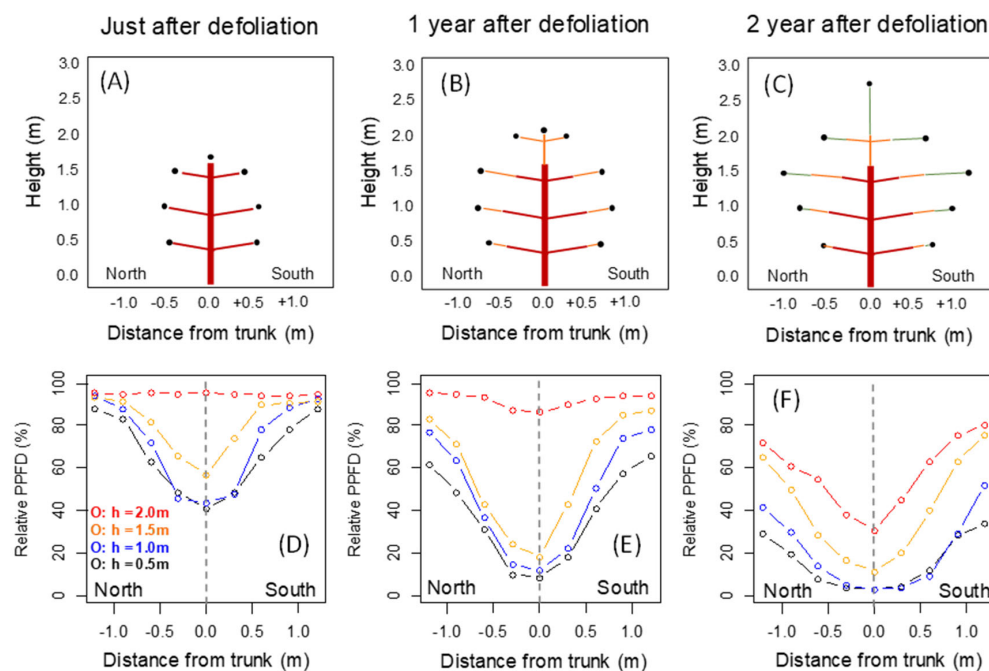


Figure 3. (A–C) schematically show the development of crown enlargement over the years after crown management of pruning and defoliation. (D–F) show the corresponding trends in the vertical and horizontal distribution patterns of relative photosynthetic photon flux density (rPPFD). Just after pruning and defoliation manipulation (A,D). One year after pruning and defoliation (B,E). Two years after pruning and defoliation (C,F).

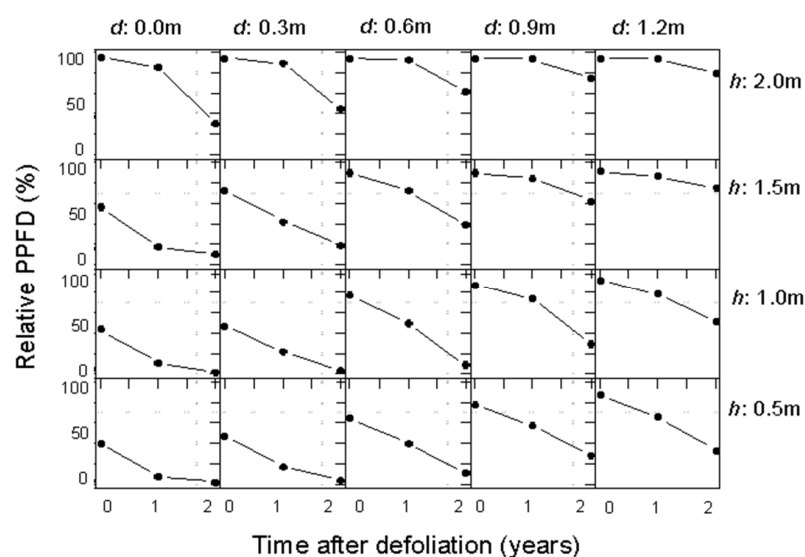


Figure 4. Summary of the time-series trends of relative photosynthetic photon flux density (rPPFD) over the years after pruning and defoliation manipulation. Each panel shows combinations of horizontal distances from the trunk (d : 0.0 m, 0.3 m, 0.6 m, 0.9 m, and 1.2 m) and ground height classes (h : 0.5 m, 1.0 m, 1.5 m, and 2.0 m).

3.3. Simulation of Block-Rotation Cycles in Relation to Cone Production Amount

A simulation of cone production per tree was performed, assuming that the number of years after pruning was varied. The CV in cone production among branches within a virtual tree for block-rotation Cycle II (CV = 3.3) was 1.57 times higher than that for Cycle I (CV = 2.1). Since cone production per branch was modeled as exponentially increasing with increasing rPPFD, in Cycle II, only the upper branches were estimated to produce cones, while the branches at the middle-to-lower crown parts bore no or very few cones (black circles in Figure 5). On the other hand, in Cycle I, the upper-to-lower branches were estimated to produce relatively moderate numbers of cones (white circles in Figure 5).

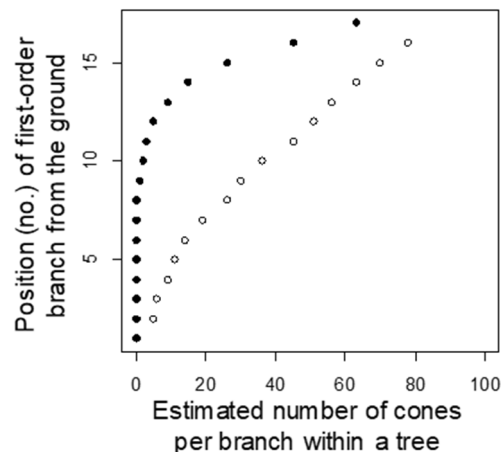


Figure 5. Vertical distribution patterns of the estimated amount of seed cone production per primary branch within a virtual tree. White and black circles correspond to simulated block-rotation Cycle I and Cycle II, respectively. In the simulation, Cycle I is assumed to be operated on a three-year management cycle, while Cycle II is assumed to be operated on a four-year management cycle.

The results of the estimations of cone production per individual tree and per virtual block are shown in Table 1. As seen in the results (Table 1), the estimates of cone production per tree varied by 3.1 times between block-rotation cycles: the estimated cone production per tree was greater for rotation Cycle I ($N_{\text{cones}} = 525$) than II ($N_{\text{cones}} = 169$). The simulation was conducted on a hypothetical miniature seed orchard consisting of 120 virtual trees, where the operation area was rotated over a 12-year period (Table 1). The total cone production over the 12-year period was estimated to be 252,000 cones in Cycle I and 60,840 cones in Cycle II, with Cycle I displaying 4.1 times the production of Cycle II (Table 1).

Table 1. The simulation results estimating total cone production of a hypothetical miniature seed orchard over a 12-year period when blocks in the orchard were rotated with different management cycles. In this simulation, the hypothetical miniature orchard was assumed to contain 120 virtual trees. In Cycle I, the 120 virtual trees were divided into three virtual blocks (A, B, C), with 40 virtual trees in each virtual block, and the three blocks were operated on a three-year cycle. In Cycle II, the 120 virtual trees were divided into four virtual blocks (A, B, C, D), with 30 virtual trees in each virtual block, and the four blocks were operated on a four-year cycle.

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Total
Cone production per tree in A	525			525			525			525			
Cone production per tree in B		525			525			525			525		
Cone production per tree in C			525			525			525			525	
Cone production by 40 trees in A	21,000			21,000			21,000			21,000			
Cone production by 40 trees in B		21,000			21,000			21,000			21,000		
Cone production by 40 trees in C			21,000			21,000			21,000			21,000	
Total cone production per annual	21,000	21,000	21,000	21,000	21,000	21,000	21,000	21,000	21,000	21,000	21,000	21,000	
Total cone production over 12 years										\			252,000

Table 1. Cont.

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Total
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Total
Cone production per tree in A	169				169				169				
Cone production per tree in B		169				169				169			
Cone production per tree in C			169				169				169		
Cone production per tree in D				169				169				169	
Cone production by 30 trees in A	5070				5070				5070				
Cone production by 30 trees in B		5070				5070				5070			
Cone production by 30 trees in C			5070				5070				5070		
Cone production by 30 trees in D				5070				5070				5070	
Total cone production per annual	5070	5070	5070	5070	5070	5070	5070	5070	5070	5070	5070	5070	
Total cone production over 12 years													60,840

4. Discussion

Well-lit environments have substantial positive effects on the growth and fecundity of many plant species [11]. Light resources have crucial impacts on the survival and growth of forest trees [31–33], and low light intensity reduces shoot elongation [34] as a result of limited carbon availability [35] and lower meristem activity [36]. The present study also confirmed that the branches at the upper-crown parts in well-lit conditions expand vigorously, and the upright branches sprout dense shoots and fill adjacent spaces quickly. In addition to the present results, large vertical variations have been found in relative light intensity within *C. obtusa* stands [37]; Itoh [37] shows 42% and 2% relative light intensity for the upper- and lower-crown parts, respectively, and the branches of the former grow ten times longer. Similarly, in our study, the observed rPPFD at the lower-crown parts drastically decreased only two years after pruning manipulation in the studied orchard (Figure 3F). It has been suggested that there is only a relatively short-term pronounced effect of improved light intensity achieved by pruning and thinning on growth and fecundity in old larch seed orchards [14]. The light environment within a dense canopy is unfavorable, and will decrease bud activity potential [36]. Compared to Japanese cedar, it has been shown that *C. obtusa* is more difficult to re-sprout from latent buds. It also has management problems in that the vigor of its crown is easily compromised by the crowding of branches, which can easily cause the crown to wither [38]. Based on our results, crown management, especially the cycle of pruning and topping, is thought to be important to keep the crown vigor of miniature orchards.

According to the within-canopy interception and spatiotemporal variation in light, which depends on orchard management, a non-uniform shoot growth pattern along vertical light gradients is responsible for the development of plant architecture. Plant architecture itself has effects on subsequent shoot growth, from its early stages just after crown management to the later stages, when branches are fully elongated and overlap with each other [9,39]. A more even branching and leaf distribution leads to better light interception and deeper light penetration into the canopy vertically [9]. In such a situation, diffuse light generates a more homogeneous light distribution, resulting in the avoidance of light saturation constraints resulting from higher light intensity [40]. This allows plants to use diffuse light more efficiently within multiple crown layers than strong direct light, which is intercepted mostly at the upper layers [41]. It has been proposed that more even branching and leaf distribution patterns lead to lower-part shoots receiving greater total light resources, and this improved light utilization has a positive effect on total fruit production in orchard trees [6,9].

Trees that received higher levels of insolation tended to produce abundant cones, and the branches within a crown that received sufficient sunlight achieved higher cone production [12]. In previous studies on the traditional spacing of larch orchards with ages > 60, light intensity over 50% rPPFD was suggested as being better for cone production [13]. In *C. obtusa*, it has been reported that more than 80% of trees tend to produce seed cones when the light conditions reach rPPFD > 50% [29]. In the present miniature seed orchard, there

was a large spatial variation in rPPFD along both the vertical and horizontal axes when the *C. obtusa* trees developed. Crown management, such as pruning and thinning to remove crowded branches and maintain well-lit environments, appears to be an efficient means of improving reproductive status and total seed production capacity.

Our results suggest that it is important to manage orchard trees with cycles of pruning and defoliation before the canopy becomes overcrowded. The present study investigated the spatial variation in relative light intensity during the years after crown management, as well as the distribution of the number and elongation length of primary branches in a miniature seed orchard spaced at 2.4 m intervals with trunks top-pruned at ca. 1.5 m tall. Our simulation of hypothesized seed orchards provides an estimation of cone production depending on crown management cycles. In the studied situations, it was suggested that after more than 3–4 years, the dark environments decreased the vigor of the primary branches at the lower-to-middle crown parts, so a three-block rotation cycle (Cycle I) seemed to be better (i.e., orchards containing just-pruned blocks, blocks left for 1 year after pruning, and blocks left for 2 years after pruning). In previous studies, it has been reported that variations in initial planting density, pruning height, and pruning cycles affect the total crop per annum per land area and enhance economic efficiency over multiple years [15].

This is a case study of a miniature seed orchard of *C. obtusa*, and we recognize that there are still issues to be addressed, such as the initial setup of planting density, pruning height and width, the training system, and the consideration of variations between years and between site locations. By accumulating knowledge from a large number of seed orchards with more diverse management systems and developing a big data study using statistical approaches including meta-analysis, future studies are expected to provide further insights into optimizing the management of conifer seed orchards. There have been few studies on conifer seed orchard management that quantitatively consider the crown development process after pruning and the associated spatiotemporal changes in the light environment, and therefore the approach and findings of the present study will be useful in developing this line of research on orchard management.

5. Conclusions

This study investigated the development of tree crowns and light variation over the years after pruning manipulation in a miniature orchard of *C. obtusa*. Just two years after manipulation, the upper branches had grown longer, and the light environments at the lower crowns had become darker. Based on the observed crown development and light variation, as well as the relationship between cone production and light intensity, we then performed a simulation of total cone production over multiple years. The estimates of cone production for the entire tree and the entire seed orchard decreased if the years of the block-rotation cycles were greater. In many traditional conifer seed orchards, as well as miniature *C. obtusa* orchards, assessments of planting intervals, tree shape management through pruning, and rotation cycle duration have been carried out empirically. The present findings, focusing on canopy development and environmental light changes after pruning, will be useful for improving the management of seed orchards.

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Data Availability Statement: The datasets and materials generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

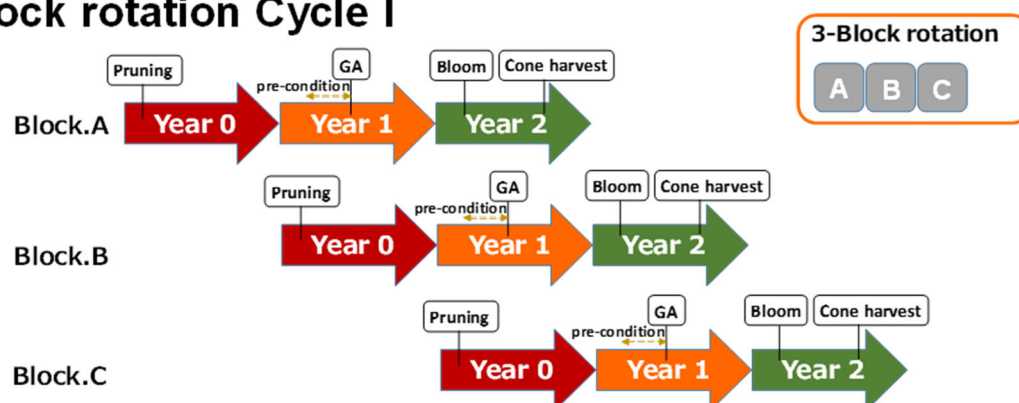
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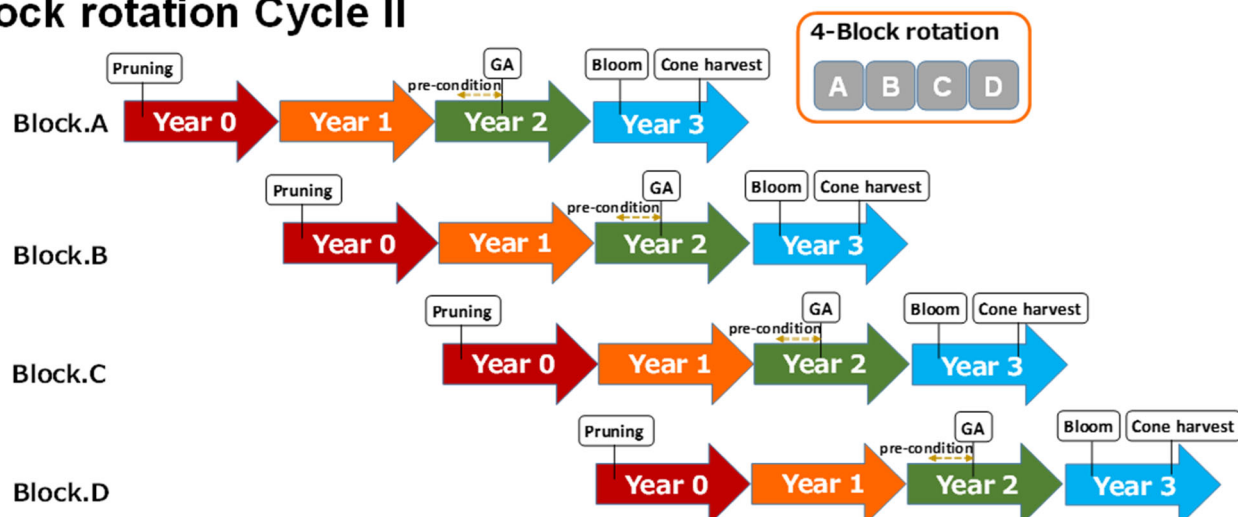
Appendix A

Schematic diagram showing the rotation of three or four virtual blocks (Blocks A, B, C, or D) in a hypothetical seed orchard. Block-rotation Cycle I and Cycle II are assumed to be managed every three and four years, respectively. In this diagram, if less than 12 months have passed since pruning, it is represented as “Year 0”, and if a full year (12 months or more) has passed, it is represented as “Year 1”. GA indicates gibberellic acid manipulation for stimulating floral bud initiation. After GA treatment in summer, the floral buds start to develop; they mature after the winter and then bloom in the spring of the following year. Then, in the autumn of the year following GA treatment, cones mature and are harvested. Under conditions of continuous sunny weather with higher sunlight duration levels until early summer of the previous year (year t), abundant flowers bloom in the following spring (year $t + 1$). Therefore, according to the pre-conditions of branch and light environments in the year of GA treatment (year t), the cone amount in the fall of the following year (year $t + 1$) is affected.

Block rotation Cycle I



Block rotation Cycle II



References

1. Ameray, A.; Bergeron, Y.; Valeria, O.; Montoro Girona, M.; Cavard, X. Forest carbon management: A review of silvicultural practices and management strategies across boreal, temperate and tropical forests. *Curr. Rep.* **2021**, *7*, 245–266. [\[CrossRef\]](#)
2. Ray, D.; Berlin, M.; Alia, R.; Sanchez, L.; Hynynen, J.; González-Martínez, S.; Bastien, C. Transformative changes in tree breeding for resilient forest restoration. *Front. Glob. Change* **2022**, *5*, 1005761. [\[CrossRef\]](#)
3. Lindgren, D. The Role of tree breeding in reforestation. *Reforesta* **2016**, *1*, 221–237. [\[CrossRef\]](#)
4. Thomas, B.R.; Stoehr, M.; Schreiber, S.G.; Benowicz, A.; Schroeder, W.R.; Soolanayakanahally, R.; Steffner, C.; Elliott, K.A.; Philis, N.; Rubal, N.; et al. Tree Improvement in Canada—past, present and future, 2023 and beyond. *For. Chron.* **2024**, *100*, 59–87. [\[CrossRef\]](#)
5. Robinson, T.L. Effects of tree density and tree shape on apple orchard performance. *Acta Hort.* **2007**, *732*, 405–414. [\[CrossRef\]](#)
6. Robinson, T.; Gonzalez, L.; Cheng, L.; Ziang, Y.; Peck, G.; Arnoldussen, B.; Gomez, M.; Guerra, M.; Sazo, M.M.; Kahlke, C.; et al. Studies in precision crop load management of apple. *Acta Hort.* **2023**, *1366*, 219–226. [\[CrossRef\]](#)
7. Usha, K.; Singh, B. Potential applications of remote sensing in horticulture—A review. *Sci. Hort.* **2013**, *153*, 71–83. [\[CrossRef\]](#)
8. Rejeb, A.; Abdollahi, A.; Rejeb, K.; Treiblmaier, H. Drones in agriculture: A review and bibliometric analysis. *Comput. Electron. Agric.* **2022**, *198*, 107017. [\[CrossRef\]](#)
9. Tang, L.; Yin, D.; Chen, C.; Yu, D.; Han, W. Optimal design of plant canopy based on light interception: A case study with Loquat. *Front. Plant Sci.* **2019**, *10*, 364. [\[CrossRef\]](#)
10. Magro, R.B.; Alves, S.A.M.; Gebler, L. Computational models in precision fruit growing: Reviewing the impact of temporal variability on perennial crop yield assessment. *SN Comput. Sci.* **2023**, *4*, 554. [\[CrossRef\]](#)
11. Poorter, H.; Niinemets, Ü.; Ntagkas, N.; Siebenkäs, A.; Mäenpää, M.; Matsubara, S.; Pons, T. A meta-analysis of plant responses to light intensity for 70 traits ranging from molecules to whole plant performance. *New Phytol.* **2019**, *223*, 1073–1105. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Despland, E.; Houle, G. Aspect influences cone abundance within the crown of *Pinus banksiana* Lamb. trees at the limit of the species distribution in northern Quebec (Canada). *Écoscience* **1997**, *4*, 521–525. [\[CrossRef\]](#)
13. Matsushita, M.; Nishikawa, H.; Tamura, A.; Takahashi, M. Effects of light intensity and girdling treatments on the production of female cones in Japanese larch (*Larix kaempferi* (Lamb.) Carr.): Implications for the management of seed orchards. *Forests* **2020**, *11*, 1110. [\[CrossRef\]](#)
14. Matsushita, M.; Nishikawa, H.; Tamura, A. Effects of girdling intensity, pruning season and thinning on tree growth, crown vigor and wound recovery in Japanese larch. *Forests* **2022**, *13*, 449. [\[CrossRef\]](#)
15. Almqvist, C. High stand density improves seed production in seed orchards of the masting species *Picea abies*. *Silva Fenn.* **2024**, *58*, 23073. [\[CrossRef\]](#)
16. Farjon, A. *A Monograph of Cupressaceae and Sciadopitys*; Royal Botanic Gardens, Kew: London, UK, 2005.
17. Farjon, A. *Chamaecyparis lawsoniana*. *IUCN Red List. Threat. Species* **2013**, e.T34004A2840024. Available online: <https://www.iucnredlist.org/species/34004/2840024> (accessed on 10 February 2025).
18. Egusa, T.; Kumagai, T.; Shiraishi, N. Carbon stock in Japanese forests has been greatly underestimated. *Sci. Rep.* **2020**, *10*, 7895. [\[CrossRef\]](#)
19. Forestry Agency. *Annual Report on Forest and Forestry in Japan for FY 2020*; Forestry Agency, Ministry of Agriculture, Forestry and Fisheries of Japan: Tokyo, Japan, 2020.
20. Takahashi, M.; Miura, M.; Fukatsu, E.; Hiraoka, Y.; Kurita, M. Research and project activities for breeding of *Cryptomeria japonica* D. Don. *Jpn. J. Res.* **2023**, *28*, 83–97. [\[CrossRef\]](#)
21. Kijidani, Y.; Sakai, N.; Kimura, K.; Fujisawa, Y.; Hiraoka, Y.; Matsumura, J.; Koga, S. Termite resistance and color of heartwood of hinoki (*Chamaecyparis obtusa*) trees in 5 half-sib families in a progeny test stand in Kyusyu, Japan. *J. Wood Sci.* **2012**, *58*, 471–478. [\[CrossRef\]](#)
22. Takahashi, Y.; Matsushita, M.; Tamura, A.; Ohira, M.; Takahashi, M. Age trends in genetic parameters and genetic gains of growth traits in multiple progeny test sites of hinoki cypress (*Chamaecyparis obtusa*). *J. Res.* **2023**, *29*, 103–111. [\[CrossRef\]](#)
23. Masaki, T.; Oguro, M.; Yamashita, N.; Otani, T.; Utsugi, H. Reforestation following harvesting of conifer plantations in Japan: Current issues from silvicultural and ecological perspectives. *Reforesta* **2017**, *3*, 125–142. [\[CrossRef\]](#)
24. Tsubomura, M.; Nakada, R.; Fukatsu, E. Inheritance of male flower setting in control-pollinated families of hinoki (*Chamaecyparis obtusa*). *Kanto Res.* **2009**, *60*, 97–100. (In Japanese)
25. Tsubomura, M.; Fukatsu, E.; Nakada, R.; Fukuda, Y. Inheritance of male flower production in *Cryptomeria japonica* (sugi) estimated from analysis of a diallel mating test. *Ann. Sci.* **2012**, *69*, 867–875. [\[CrossRef\]](#)
26. Moriguchi, Y.; Yamazaki, Y.; Taira, H.; Tsumura, Y. Mating patterns in an indoor miniature *Cryptomeria japonica* seed orchard as revealed by microsatellite markers. *New For.* **2010**, *39*, 261–273. [\[CrossRef\]](#)
27. Heuchel, A.; Hall, D.; Almqvist, C.; Wennström, U.; Persson, T. Topgrafting as a tool in operational Scots pine breeding. *J. Res.* **2024**, *35*, 111. [\[CrossRef\]](#)

28. Kolpak, S.E.; Smith, J.; Albrecht, M.J.; DeBell, J.; Lipow, S.; Cherry, M.L.; Howe, G.T. High-density miniaturized seed orchards of Douglas-fir. *New For.* **2015**, *46*, 121–140. [\[CrossRef\]](#)
29. Matsushita, M.; Tsubomura, M.; Kimura, M.; Takahashi, Y.; Ogawa, K.; Ohira, M.; Tamura, A. The effects of light intensity on the shoot growth, survival, and reproductive traits of *Chamaecyparis obtusa* clones. *New For.* **2025**.
30. R Core Team. *A Language and Environment for Statistical Computing*; R 3.2.5; R Found Stat Comput Vienna: Vienna, Austria, 2016.
31. Brown, C.E.; Mickelbart, M.V.; Jacobs, D.F. Leaf physiology and biomass allocation of backcross hybrid American chestnut (*Castanea dentata*) seedlings in response to light and water availability. *Tree Physiol.* **2014**, *34*, 1362–1375. [\[CrossRef\]](#)
32. Chen, L.; Sumida, A. Patterns of branch growth and death in crowns of Sakhalin spruce, *Picea glehnii* (F. Schmidt) Mast. *Forests* **2017**, *8*, 26. [\[CrossRef\]](#)
33. Sevillano, I.; Short, I.; Grant, J.; O'Reilly, C. Effects of light availability on morphology, growth and biomass allocation of *Fagus sylvatica* and *Quercus robur* seedlings. *For. Ecol. Manag.* **2016**, *374*, 11–19. [\[CrossRef\]](#)
34. Chen, L.; Sumida, A. Effects of light on branch growth and death vary at different organization levels of branching units in Sakhalin spruce. *Trees* **2018**, *32*, 1123–1134. [\[CrossRef\]](#)
35. Yang, Y.; Wang, A.; Cherubini, P.; Kräuchi, N.; Ni, Y.; Wu, Z.; He, S.H.; Li, M.-H.; Schaub, M. Physiological and growth responses to defoliation of older needles in *Abies alba* trees grown under two light regimes. *Ecol. Manag.* **2021**, *484*, 118947. [\[CrossRef\]](#)
36. Yoshida, S.; Mandel, T.; Kuhlemeier, C. Stem cell activation by light guides plant organogenesis. *Genes Dev.* **2011**, *25*, 1439–1450. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Itoh, A.; Yoshihara, M.; Tamai, S. Shoot elongation characteristics of *Cryptomeria japonica* and *Chamaecyparis obtusa*. *Bull. Kyoto Univ. For.* **1989**, *61*, 85–94. (In Japanese)
38. Nakamura, K.; Nara, M. Study of pruning method for *Chamaecyparis obtusa* with few pollen cultivars in tree seed miniature orchard. *Kanto For. Res.* **2016**, *67*, 163–164. (In Japanese)
39. Burgess, A.J.; Retkute, R.; Herman, T.; Murchie, E.H. Exploring relationships between canopy architecture, light distribution, and photosynthesis in contrasting rice genotypes using 3D canopy reconstruction. *Front. Plant Sci.* **2017**, *8*, 734. [\[CrossRef\]](#)
40. Gu, L.; Baldocchi, D.; Verma, S.B.; Black, T.A.; Vesala, T.; Falge, E.M.; Dowty, P.R. Advantages of diffuse radiation for terrestrial ecosystem productivity. *J. Geophys. Res.* **2002**, *107*, 4050. [\[CrossRef\]](#)
41. Urban, O.; Klem, K.; Ač, A.; Havráňková, K.; Holířová, P.; Navrátil, M.; Zitová, M.; Kozlová, K.; Pokorný, R.; Šprtová, M.; et al. Impact of clear and cloudy sky conditions on the vertical distribution of photosynthetic CO₂ uptake within a spruce canopy. *Funct. Ecol.* **2012**, *16*, 46–55. [\[CrossRef\]](#)

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