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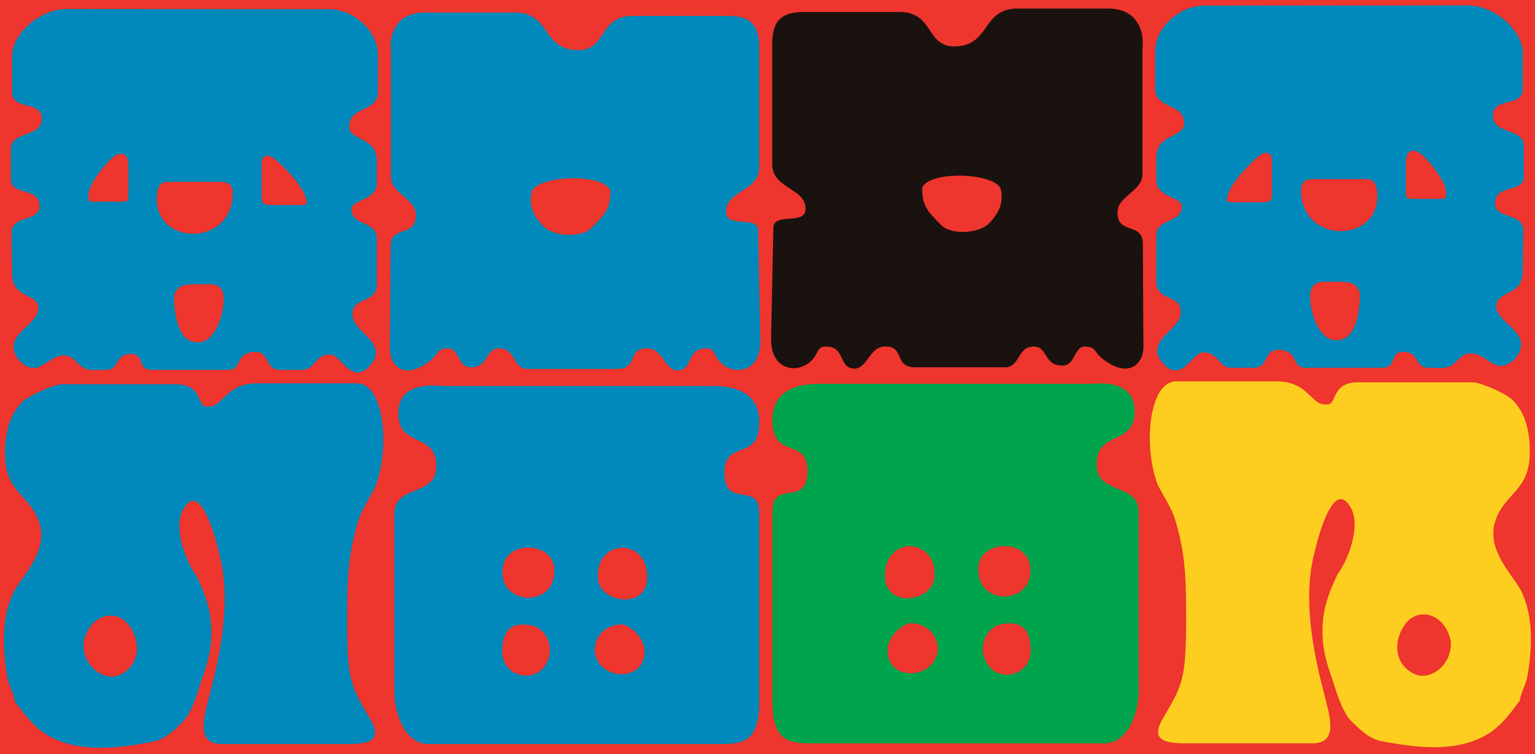
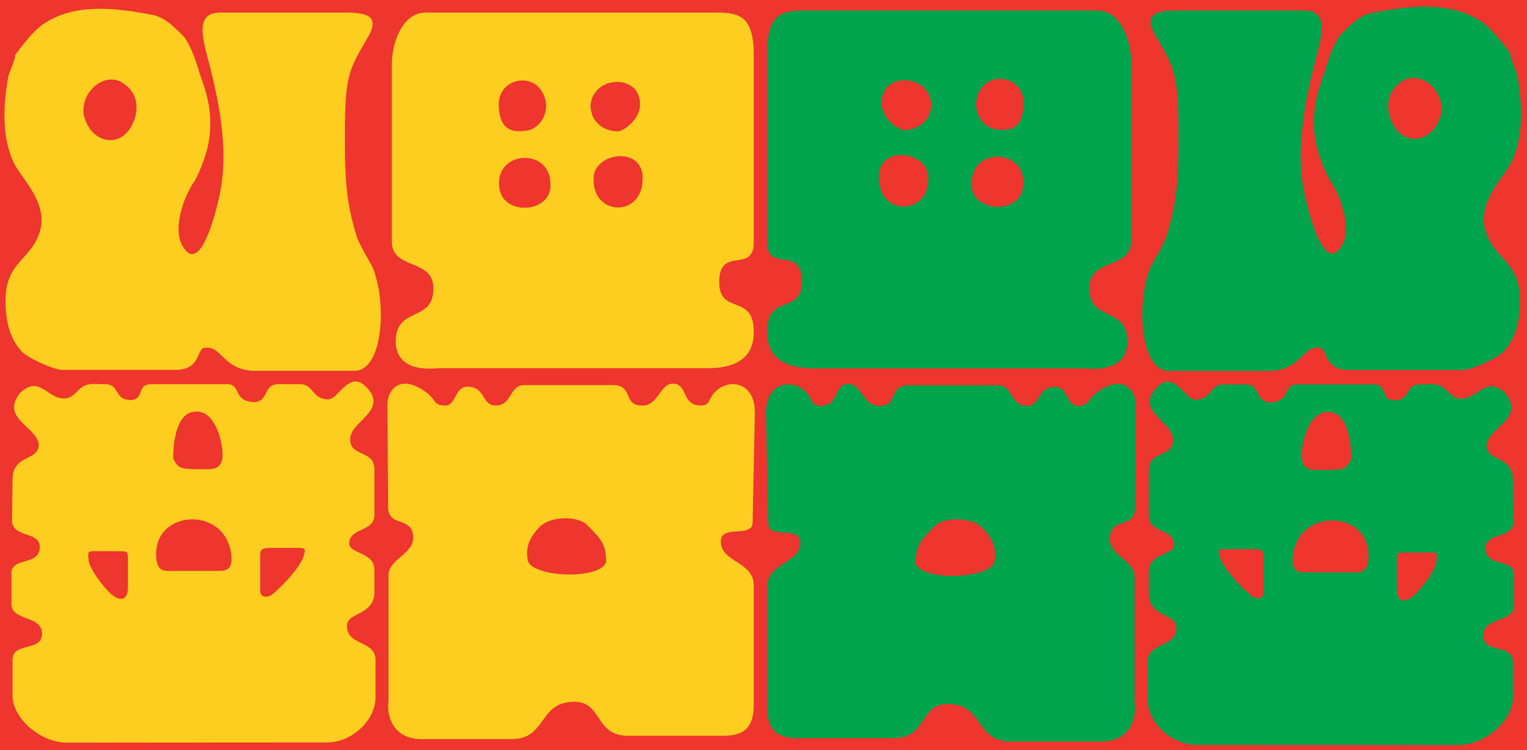


# JOURNAL OF
# FOREST PLANNING



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**Article**

# Effectiveness of the Canopy Closure Curve to Inform Management of Two-Storied Stands

Satoshi Tatsuhara [1,*], Keisuke Toyama [2] and Makoto Suzuki [2, 3]

## ABSTRACT

In this study we examined the validity of the canopy closure curve as a reference in relation to light conditions and demonstrated the applicability of the curve to different thinning types. An even-aged sugi (*Cryptomeria japonica*) plantation of 91 years was thinned heavily and transformed to a two-storied stand by underplanting with sugi and hinoki cypress (*Chamaecyparis obtusa*) seedlings. Three initial sample plots were selected in the stand before thinning. After the conversion, five permanent sample plots were established and both overstory and understory trees were measured up to the age of 118 and 28 years, respectively. The canopy closure curve was estimated from measurements collected in the initial sample plots and crown density (i.e. the ratio of overstory productivity to the maximum stand productivity) was calculated based on the canopy closure curve as a reference. To validate the curve, we derived three time points from the measurements collected in the permanent sample plots: one when the trajectory of stem density and stand volume of the overstory trees intersected the canopy closure curve, one when the relationships between the volume of individual overstory trees and their growth changed, and one point when the growth of understory trees dropped. The first of these time points coincided with the second and third time points. This means that dominant overstory trees suppressed smaller overstory trees and overstory trees constrained the growth of understory trees because of light reduction when the canopy closed. The canopy closure curve was found to be a valid way to assess light controlling the growth of understory trees. Furthermore, we generated virtual thinning data from the measurements taken in the initial sample plots for different thinning types. We obtained the canopy closure curve for these. We plotted the trajectory of stem density and stand volume in relation to the thinning as well as the canopy closure curve to demonstrate the applicability of the canopy closure curve. The thinning simulation showed sufficient effect to demonstrate that there was no need for additional accretion cutting.

*Keywords*: canopy closure curve, crown density, light conditions, thinning, two-storied stand

## INTRODUCTION

In Japan, to deliver environmental benefits, there have been attempts to transform conifer plantations to two-storied stands by artificial or natural regeneration after heavy thinning in 1980s. Recently, the transformation to mixed conifer-broadleaved stands has drawn a lot of attention. In Europe, interest in continuous cover forestry (CCF) was revived in 1980s as a result of environmental problems, and an emphasis is placed on the direct transformation of even-aged plantation forests to mixed uneven-aged forests (Pommerening and Murphy, 2004). Mason et al. (2022) undertook a questionnaire survey and found that a lack of experience of undertaking such transformations is one of the major obstacles that limit wider use of CCF. One of the problems with a multi-storied forest management system is that inappropriate management decreases light intensity, which causes a decrease in the growth of understory trees and possible mortality, leading to the destruction of stand structure (Oka, 1991). Control of light conditions is important to establish and manage multi-storied plantation forests, and indicators of light conditions have been used to predict the growth of understory trees in two-storied stands.

Because light conditions vary inside a stand and light intensity is difficult to measure for all individual trees using light sensors or hemispherical photography (see Fujiyama et al., 2020), stand characteristics have been used as indicators of light con-

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dition. To model the growth of understory trees, relative light intensity is first estimated from a stand characteristic, then their growth is predicted using this figure. Variables related to stem volume, such as yield index and basal area, can be used as indicators of relative light intensity to some extent, as can variables related to crown structure (Fujimori, 1989). For example, Ando (1983) and Kaminaka et al. (1983) used yield index to estimate relative light intensity after thinning in sugi (*Cryptomeria japonica* D.Don) and hinoki cypress (*Chamaecyparis obtusa* (Sieb. et Zucc.) Endl.) plantations, whilst Kiyono (1990) used mean land area per tree and mean crown length to estimate relative light intensity in hinoki cypress plantations and to develop charts for estimating relative light intensity. Yield index has also been used by Ando and Takeuchi (1990) to predict the growth of two-storied stands of sugi and hinoki cypress.

Instead of estimating light conditions directly, stand characteristics can be used to derive an indicator, then the growth of understory trees predicted using this. Yamamoto (1993, 1995) used the relative spacing of overstory trees to predict the growth of understory trees in two-storied stands containing a mixture of Japanese larch (*Larix kaempferi* Carr.) and Sakhalin fir (*Abies sachalinensis* (Fr. Schm.) Masters). Tatsuhara and Suzuki (1995) determined 'stand productivity' from stem density and stand volume and incorporated 'crown density' (i.e. the ratio of overstory productivity to the maximum stand productivity) as an indicator of the shading of the understory by the overstory. They then used the stand productivity to predict the growth of understory trees in two-storied sugi stands.

The 'canopy closure curve' acts as a reference for the measured crown density. The curve theoretically represents the stem density and stand volume when the canopy closes again after thinning and can change depending upon stand conditions just before and after thinning; it is drawn parallel to the full density curve on a stand density control diagram (Tatsuhara, 1993; 2001). The stand density control diagram was developed, assuming typical low thinning; the yield index in the diagram was calculated using the full density curve as a reference. The yield index is calculated simply from the stem density and stand volume of a stand, although it is limited for use as an indicator of the light conditions experienced by understory trees because it depends on individual species only and a typical thinning method is assumed. Conversion thinning from an even-aged stand into a two-storied stand is usually heavier than typical thinning and this type of thinning may be different from low thinning.

In this paper, we examine the validity of the canopy closure curve as a reference in relation to light conditions and demonstrate the applicability of the curve to different thinning approaches. For these, we use long-term measurements from a two-storied stand transformed from an even-aged sugi stand by heavy thinning. To validate the curve, we derived three time points: one when the trajectory of stem density and stand volume of the overstory trees intersected the canopy closure curve, one when the relationships between the volume of individual overstory trees and their growth changed, and one when the growth of understory trees dropped as a result of suppression by the overstory trees. We compare the first of these time points with the second and third time points. To demonstrate the applicability of the canopy closure curve, we generated virtual thinning data, simulated different thinning types, and plotted the trajectory of stem density and stand volume in relation to the thinning as well as the canopy closure curve.

## MATERIALS AND METHODS

### Study Site

The study was conducted in Subcompartment C5, Compartment 2 of The University of Tokyo Chiba Forest (hereafter called Chiba Forest), located in the southern part of Boso Peninsula, in Chiba Prefecture, Japan (35°10′N; 140°6′E). Almost the entire subcompartment was planted with sugi in 1902. A 0.073-ha permanent experimental plot named Anno No.2 was established within the even-aged sugi stand in May, 1916 and has been measured every five years (Takeuchi and Hasegawa, 1975). The even-aged sugi stand was thinned at 91 years of age during the period January to March, 1992. Part of the stand was thinned heavily at that time to transform to a two-storied stand. The thinning ratios of the overstory trees in terms of the number of trees and volume were 50% and 30%, respectively. The relative light intensity just after thinning was 28.2%. The stand was underplanted with sugi and hinoki cypress seedlings in October, 1992. The seedlings were planted in lines, parallel to the direction of the slope and two consecutive lines of sugi seedlings and one line of hinoki cypress seedlings were alternated with lower planting stem density than in an even-aged stand. The stand is situated at an elevation of 190–217 m above sea level on an east-facing slope. Anno No.2 was outside the two-storied stand and have been kept an even-aged stand. Measurements taken in Anno No.2 were also used to compare the growth of underplanted trees on a two-storied stand with that of unshaded trees on an even-aged stand because it has the same site quality as the study site.

### Field Investigation

In December, 1991, prior to the thinning operation, three plots were sampled on lower, intermediate, and upper parts of the slope in the stand to be transformed into a two-storied stand to calculate thinning intensity. The three initial sample plots are referred to as Plots 1, 2, and 3, respectively, in this paper. We measured diameter at breast height (DBH) and height of both trees to be retained and to be thinned. These data were used to obtain a parameter for the canopy closure curve, which requires information on stand structure just before and after thinning in the case of the actual thinning and simulated thinnings.

In December, 1996, after conversion into a two-storied stand, five permanent sample plots were established parallel to the direction of the slope in the stand; these are referred to as Plots A to E (Fig. 1). The DBH and height of all the overstory trees were measured five times: at 95, 98, 102 (the age was regarded as 102 years because the plots were measured at 103 years before the growth period), 111, and 118 years of age. The volume of the

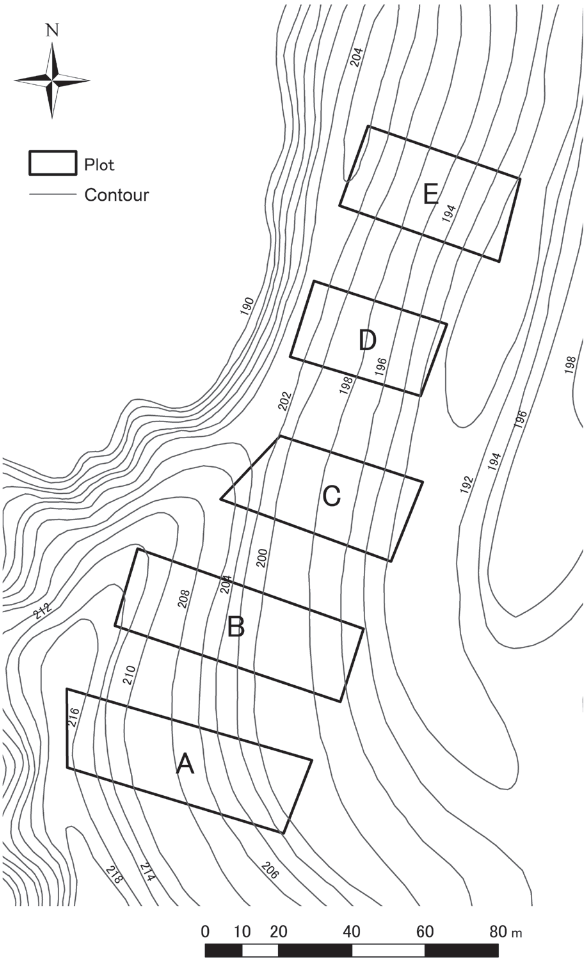

Fig. 1. The layout of the permanent sample plots at the study site. Note: The lowermost part of Plot D was excluded because it contained some different overstory species, including hardwoods.

overstory trees, including trees before the thinning, was calculated using cubic curves to account for stem taper and with parameters calculated from the data obtained by Tange et al. (1987) for Chiba Forest. For all understory trees, DBH and height were measured nine times: at 5, 7, 8, 10, 12, 14, 16, 21, and 28 years of age. These data were used for main analyses of the growth of overstory and understory trees in the two-storied stands.

### Validating the Canopy Closure Curve

#### *Obtaining a parameter for the canopy closure curve*

The stem density and stand volume of each of Plots 1–3 were calculated from the measurements. The stem density and stand volume of Plots A to E were calculated from the measurements and then the total stem density and stand volume for all the plots combined were obtained. Because the five permanent sample plots were established in 1996, the stem density and stand volume in 1991 were unknown. Thus, the stem density in 1991 was assumed to be the same as that in 1996. The stand volume was assumed to have increased by 10 $\mathrm{m}^3\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$ for the five years immediately after thinning in 1991 because the periodic annual increments (PAIs) of stand volume just after thinning were around 10 $\mathrm{m}^3\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$ in Anno No.2. To create a virtual stand with the same stem density and stand volume as the study site in 1991, the area ratio to mix was calculated, using Plots 1–3. The area ratio between the three initial plots was set at 1 for Plot 2 and at $x$ and $y$ for Plots 1 and 3, respectively, and simultaneous equations relating to the stem density and stand volume were solved to obtain the values of $x$ and $y$.

Tatsuhara (1993) suggested that the following equation linking stand volume $V$ ($\mathrm{m}^3\ \mathrm{ha}^{-1}$) and number of trees $N$ (trees $\mathrm{ha}^{-1}$) is true when the canopy closes.

$$\log V + \frac{1-\beta}{\beta}\log N = -\frac{\log\alpha}{\beta} . \tag{1}$$

It is referred to as the 'canopy closure curve'. Parameter β is a constant that is dependent on species. Parameter α is a constant that is dependent on species before the first canopy closure, and depends on thinnings thereafter; it is obtained from the stand structures before and after thinning by Eq. (2):

$$\alpha = \frac{v_{max}{}^{0.15} \sum v_A^{0.85}}{V_A^{\beta} N_A^{1-\beta} V_B} , \tag{2}$$

where $V_B$ is the stand volume ($\mathrm{m}^3\ \mathrm{ha}^{-1}$) before thinning, $v_{max}$ is the volume ($\mathrm{m}^3$) of the largest tree in a stand, and $V_A$, $N_A$, and $v_A$ are the stand volume ($\mathrm{m}^3\ \mathrm{ha}^{-1}$), stem density (trees $\mathrm{ha}^{-1}$), and the volume ($\mathrm{m}^3$) of each tree after thinning, respectively. We calculate parameter α with Eq. (2) from the virtual stand created from the three initial sample plots. We determined the canopy closure curve expressed by Eq. (1), setting parameter β at 0.521, which was obtained for sugi by Tatsuhara (1993). We calculated the stem density and stand volume for overstory trees every time they were measured and plotted them on a log-log scale with the canopy closure curve. 'Crown density' $C$ is expressed as the ratio of overstory productivity $P_o$ ($\mathrm{m}^3\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$) to the maximum stand productivity $A$ ($\mathrm{m}^3\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$) (Tatsuhara and Suzuki, 1995) as follows:

$$C=P_o/A=\alpha V^{\beta} N^{1-\beta}. \tag{3}$$

The equation above is transformed as follows:

$$\log V + \frac{1-\beta}{\beta}\log N = \frac{\log C - \log\alpha}{\beta} . \tag{4}$$

The curves with $C$ of 0.9, 0.8, 0.7, 0.6, 0.5, and 0.4 were also drawn on the graph. They are 'equivalent crown density curves', and are plotted parallel to the canopy closure curve on a log-log scale.

#### *Obtaining a growth model parameter for overstory trees*

Tatsuhara (1992a) derived the following volume growth equation:

$$dv/dt = kv^{n} - bv^{2/3}, \tag{5}$$

where $k$ is a variable which is constant for trees in the same stand at the same time and $b$ is a constant that varies according to species and region. Parameter $n$ is around 1 for closed stands and varies between 0.7 and 1 for open stands (Tatsuhara, 1992b; 1993). This means that the relationships between the volume of individual trees and their growth change when the canopy closes and that the value of parameter $n$ indicates whether the canopy is open or closed. The first term on the right-hand side of Eq. (5) is referred to as 'productivity' (Tatsuhara, 1992b). We calculated the productivity $p$ (m$^3$ year$^{-1}$) from two consecutive measurements of each of the overstory trees in the permanent sample plots, setting parameter $b$ at 0.0305, which was obtained for sugi by Tatsuhara (1992), as follows:

$$p = \frac{v_2 - v_1}{\Delta t} + b\frac{v_2^{2/3} - v_1^{2/3}}{2}, \tag{6}$$

where $\Delta t$ is the interval (year) between two consecutive measurement, $v_1$ and $v_2$ are volumes (m$^3$) of each overstory tree at the beginning and at the end of the measurement period, respectively. Then we obtained parameter $n$ for each pair of consecutive measurements. The measurements in December, 1996 were excluded from this analysis because tree numbers were not the same as in the next investigation.

#### *Growth of understory trees*

We counted the number of understory trees in the permanent sample plots and calculated their mean DBH and height and their PAIs. A lot of understory trees were damaged by snow and deer browsing during the experiment. The trees fatally damaged by stem breakage, uprooting, or deer browsing were excluded from this analysis. That is, these trees were not counted as live trees, even though they were still alive during part of the investigation. Trees whose tops had been damaged but continued to grow were included in this analysis. That is, these trees were counted as live trees, and their DBHs and heights were included in the average calculation once they exceeded the size before the damage.

We compared the DBH and height mean values and PAIs of sugi in the experimental plots to those in Anno No. 2 to compare the growth of the understory trees to that of trees grown without shading. The measurements in Anno No. 2 before the age of 40 years, that is, 14, 19, 23, 28, 33, and 39 years were used. Anno No. 2 was thinned at the age of 19 years (Takeuchi and Hasegawa, 1975).

### Applying the Canopy Closure Curve to Different Thinning Types

We simulated different thinning types and derived the canopy closure curves for them. At the study site, low thinning was implemented to transform an even-aged stand to a two-storied stand. Thus, different thinning types, that is, mechanical thinning and crown thinning were simulated in the virtual stand. In the simulation of the mechanical thinning, random numbers were generated for each tree between 0 and 1 with MS Excel and the half of the trees with the lowest allocated numbers were selected for thinning. In the simulation of the crown thinning, trees that were actually thinned were retained and the remaining trees were thinned. After the selection of trees to be thinned, the values of parameter $\alpha$ from Eq. (2) were calculated and the canopy closure curves were obtained using Eq. (1). The crown densities were calculated from stem density and stand volume after thinning using Eq. (3). We compared the canopy closure curve and the crown density after thinning for low thinning, mechanical thinning, and crown thinning.

## RESULTS

### Validating the Canopy Closure Curve

#### *Overstory trees*

The stem density and stand volume of the three initial sample plots and the overstory trees in the five permanent sample plots are shown in Tables 1 and 2. Simultaneous equations relating to the stem density and stand volume were as follows:

$$(238x+392+634y) / (x+1+y) = 376, \tag{7}$$

$$(755x+565+488y) / (x+1+y) = 594. \tag{8}$$

Solving Eqs. (7) and (8), the values of the two variables obtained were $x$=0.219 and $y$=0.055. The stem density and stand volume of the study site just before thinning were estimated using an area ratio between the three initial plots of 0.219:1:0.055. The parameter $\alpha$ was 0.001745. Eq. (1) was expressed as follows:

$$\log V + 0.919\log N = 5.311. \tag{9}$$

Thus the trajectory of stem density and stand volume was drawn continuously from the virtual stand to the total value for the five permanent sample plots (Fig. 2). The stand transitioned from low stem density/stand volume with a crown density of 0.82 immediately after thinning, increasing until values approached the canopy closure curve. The crown density at 106 years, when the understory trees were 16 years old, was estimated to be 0.95 from the values at 102 years and 111 years. The value for crown density became 1.0 at 111 years when the understory trees were 21 years old, meaning that the trajectory of stem density and stand volume reached the curve at 111 years and crossed over

Table 1. Condition of the three initial sample plots before and after thinning

| Plot | Area (ha) | Site location on the slope | Stem density (trees ha$^{-1}$) | | Stand volume (m$^3$ ha$^{-1}$) | |
|---|---|---|---|---|---|---|
| | | | Before thinning | After thinning | Before thinning | After thinning |
| 1 | 0.122 | Low | 508 | 238 | 1,041 | 755 |
| 2 | 0.120 | Intermediate | 742 | 392 | 832 | 565 |
| 3 | 0.101 | Upper | 1,307 | 634 | 723 | 488 |

Table 2. Initial condition of the five experimental plots

| | | Overstory trees at establishment of the plots | | Understory trees at planting | | |
|---|---|---|---|---|---|---|
| Plot | Area (ha) | Stem density | Stand volume | Stem density | Species composition (%) | |
| | | (trees ha$^{-1}$) | (m$^3$ ha$^{-1}$) | (trees ha$^{-1}$) | Sugi | Hinoki cypress |
| A | 0.1379 | 486 | 589 | 2,212 | 68 | 32 |
| B | 0.1398 | 365 | 650 | 2,082 | 71 | 29 |
| C | 0.1020 | 343 | 656 | 2,255 | 65 | 35 |
| D* | 0.0803 | 324 | 708 | 2,017 | 62 | 38 |
| E | 0.1044 | 316 | 645 | 2,146 | 65 | 35 |
| Total | 0.5644 | 376 | 644 | 2,147 | 67 | 33 |

* The lowermost part of Plot D was excluded because it contained some different overstory species, including hardwoods.

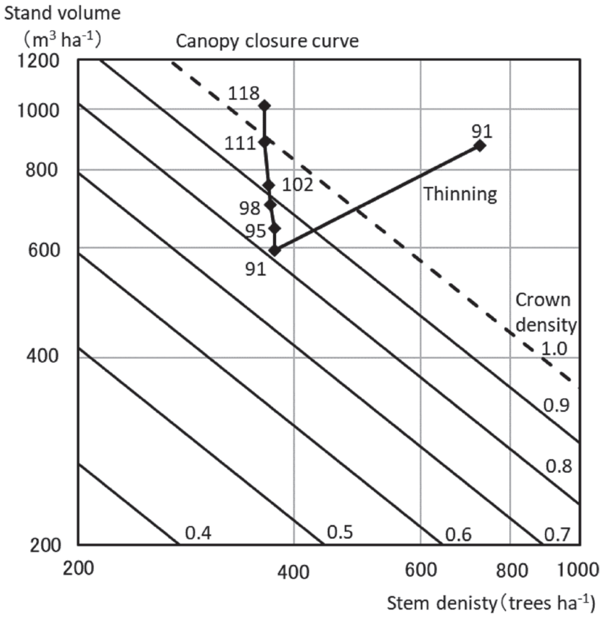

Fig. 2. The actual trajectory of stem density and stand volume with respect to the overstory trees.
The trajectory between thinnings was estimated from the measurements collected in the three initial plots and the trajectory after thinning was determined using measurements from all the permanent sample plots. The numbers besides the dots indicate the stand ages.

the curve at 118 years.

Parameter *n* in Eq. (5) for the overstory trees was around 0.85 for the first two measurement periods, 98–102 years and 102–111 years, and increased to over 0.9 in the last measurement period, 111–118 years (Table 3). The time when the overstory trees intersected the canopy closure curve coincided with the time when parameter *n* approached 1.

*Understory trees*

The stem density of the understory trees had reached about two-thirds of their planting stem density at 28 years (Fig. 3). Hinoki cypress always exhibited larger mean values than sugi both for DBH and for height, and hinoki cypress had larger PAI than sugi in many cases both for DBH and for height (Fig. 4). PAI peaked at an age younger than 10 years both for DBH and height for both sugi and hinoki cypress and after that it tended to decrease (Fig. 4). PAI of DBH dropped sharply in the penultimate measurement period, 16–21 years, and continued to decrease in the last measurement period, 21–28 years (Fig. 4a). For height, PAI dropped in the last measurement period, 21–28 years, after leveling off in the two to three previous measurement periods (Fig. 4b).

Comparing the increments of sugi to those of the same species in Anno No.2, the stem density of the latter was high and was estimated to be about 4,000 trees ha$^{-1}$ (Fig. 5). At 14 years, when Anno No.2 was established, the mean DBH of the sugi understory trees at the study site was 39% of that in Anno No.2. Thereafter, the PAI of DBH in Anno No.2 was around 0.2 cm and that of the sugi understory trees at the study site during the last two measurement periods dropped to 0.15 cm and 0.08 cm (Fig. 6a). At 14 years, the mean height of the sugi understory trees at the study site was 52% of those in Anno No.2. Thereafter, the PAI of height in Anno No.2 was around 0.2 m and that of the sugi understory trees at the study site during the last measurement period dropped to 0.13 m (Fig. 6b).

### Applying the Canopy Closure Curve to Different Thinning Types

In the thinning simulation, the crown densities immediately after mechanical thinning and crown thinning were 0.63 and 0.42, respectively. The crown density after mechanical thinning was lower than that in the actual thinning, as was the value for crown thinning in relation to mechanical thinning (Fig. 7). The parameter α obtained was 0.001545 for mechanical thinning and 0.001481 for crown thinning. The canopy closure curve after mechanical thinning was in the upper right on the graph of stem density and stand volume compared to that for the actual thinning, and the canopy closure curve after crown thinning was in the upper right on the graph of stem density and stand volume compared to that for the mechanical thinning (Fig. 7).

## DISCUSSION

We analyzed the measurements of overstory and understory trees in a two-storied stand. We found that the time point during the period 111–118 years of age at which the trajectory of

Table 3. Stand conditions and the values of parameters for the overstory trees

| Age (year) | 98 | | 102 | | 111 | | 118 |
|---|---|---|---|---|---|---|---|
| Stem density (trees ha$^{-1}$) | 370 | | 369 | | 363 | | 363 |
| Stand volume (m$^3$ ha$^{-1}$) | 702 | | 755 | | 885 | | 1,013 |
| Mean volume (m$^3$ tree$^{-1}$) | 1.90 | | 2.05 | | 2.44 | | 2.79 |
| Crown density | 0.88 | | 0.92 | | 0.99 | | 1.00 |
| Parameter $k$ | | 0.0456 | | 0.0472 | | 0.0449 | |
| Parameter $n$ | | 0.8442 | | 0.8372 | | 0.9174 | |

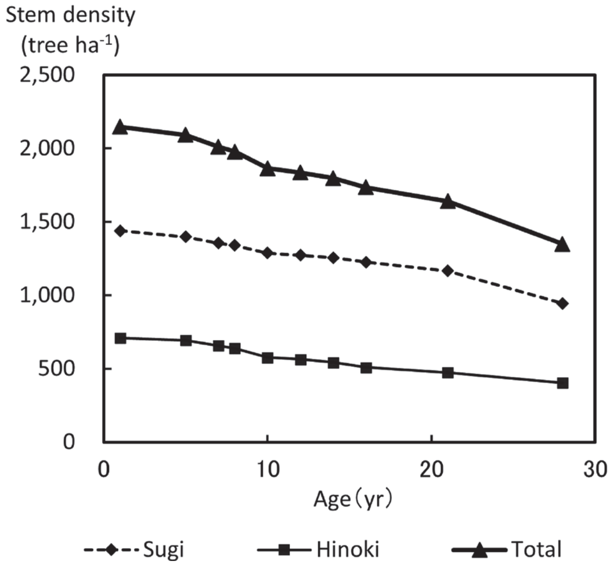

Fig. 3. The change in the stem density of understory trees in all the permanent sample plots over time.

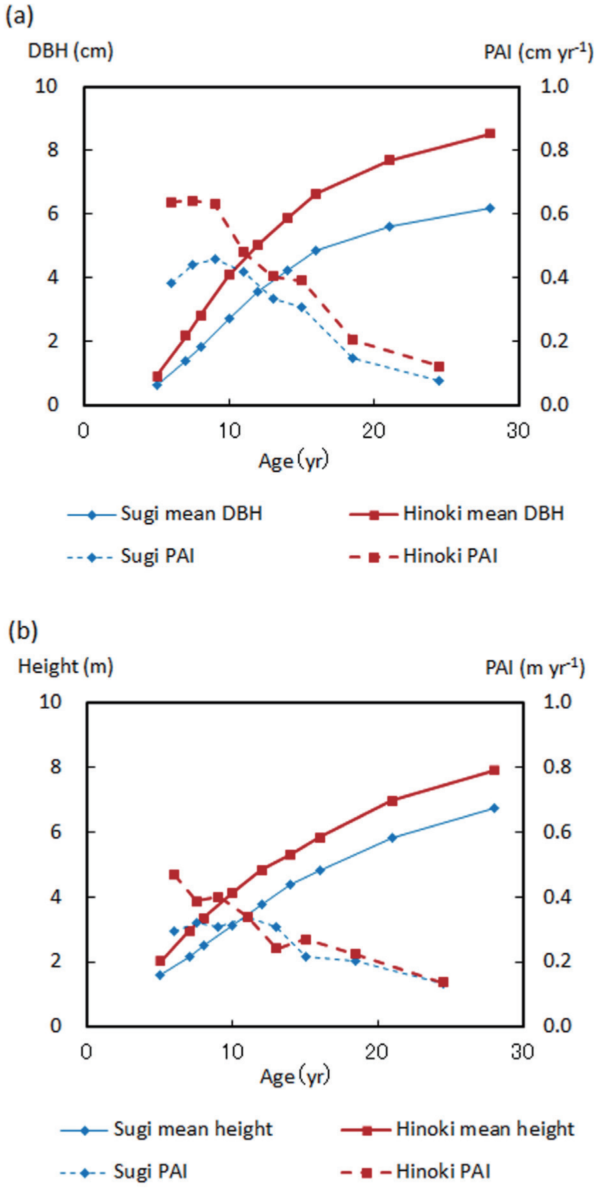

Fig. 4. Means and PAIs of (a) DBH and (b) height of understory trees in all the permanent sample plots.

stem density and stand volume of the overstory trees intersected the canopy closure curve (Fig. 2) coincided with the time when parameter *n* for the overstory trees approached 1 (Table 3) and the time when the PAI of the mean height of understory trees dropped sharply, when they were aged 21–28 years (Fig. 4). It follows from this that the relevant point on the canopy closure curve corresponded to the time when the canopy had just closed and constrained the growth of understory trees. Thus, the canopy closure curve can be used as a reference in relation to light control of underplanted trees. It can also be used as a criterion to judge when to undertake thinning. When the trajectory of the stem density and stand volume crosses through the curve, the stand should soon be thinned. However, this point would be too late for thinning if there are understory trees, and thinning should be implemented before the curve is intersected.

Kawahara (1983) suggested that sugi is more sensitive to shading than hinoki cypress and DBH is more responsive to this than height. In addition, the light compensation point of photosynthesis for hinoki cypress is about half that for sugi, and hinoki cypress proved to be more tolerant of shading than sugi (Osono et al., 2021). At our study site, hinoki cypress understory trees have grown more than sugi understory trees (Fig. 4). Note that sugi understory trees were not suppressed by hinoki cypress understory trees in the study site. Comparisons of DBH and height of sugi understory trees at 14 years of age at the study site against unshaded trees in Anno No.2 revealed that the relative value of DBH of understory trees compared to unshaded trees was smaller than that of height (Fig. 6). PAIs of DBH dropped sharply in the penultimate measurement period, 16–21 years, although

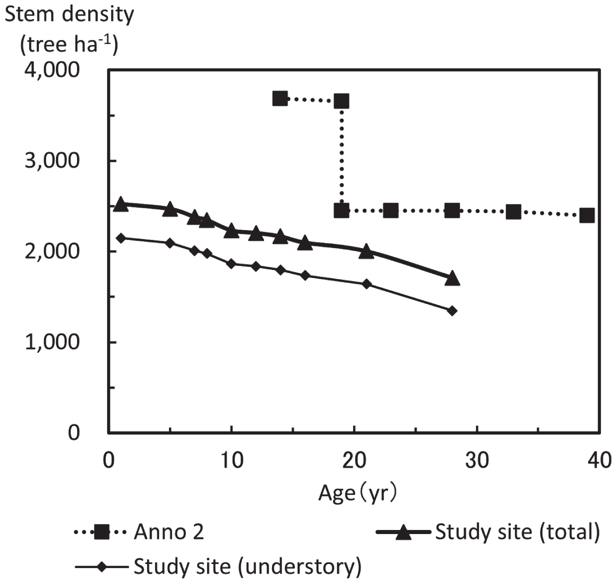

Fig. 5. Comparison between the stem density in all the permanent sample plots and that in Anno No.2.

PAIs of height clearly reduced in the last measurement period, 21–28 years (Fig. 6). These results correspond to those reported by Kawahara (1983). It is difficult to compare the understory trees at the study site with Anno No.2 because in Anno No.2, the first canopy closure occurred earlier and DBH growth was lower as a result of the high planting stem density (Fig. 5). We compared the measurements of the two stands at 14 years of age because of the limited effect of stem density on the measurements in the earlier growth stage. Relative values of DBH and height were 39% and 52%, respectively, and these correspond to the relative light intensities of 17% and 16%, respectively according to Kawahara's (1983) equations describing relative values of diameter at the ground and height and relative light intensities. This result would be reasonable if we consider the relative light intensity of 28.2% just after thinning.

Twenty years after thinning, the stand volume of overstory trees recovered to the value just prior to thinning, and the canopy of the overstory trees was considered to have closed at that time (Fig. 2). PAIs of DBH for the understory trees, especially of sugi, approached zero in the last measurement period, 21–28 years, after having dropped sharply in the penultimate measurement period, 16–21 years (Fig. 4a). PAIs of height also dropped in the last measurement period, 21–28 years (Fig. 4b). Thus future DBH growth of understory trees will be very restricted and the future height growth is expected to be small. Therefore, the overstory trees should have been thinned around 106 years (16 years for understory trees), or 111 years (21 years for understory trees) at the latest, to allow the understory trees to grow. It suggests that a crown density of 0.95 can be used to indicate the time when accretion cutting operation should be undertaken.

To avoid the need for additional thinning, more intensive thinning should have been implemented to the overstory trees before conversion into a two-storied stand. Thinning more trees has been employed to increase canopy openness in experiments to develop two-storied stands by Suzuki et al. (1996). However, even with the same thinning ratio in terms of the number of trees, mechanical thinning and crown thinning led to greater canopy openness, and the stem density and stand volume attained lower values early on than the values recorded for the actual thinning (Fig. 7). Moreover, the value of parameter α decreased and the value of the right side of Eq. (1) increased, moving closer to the canopy closure curve later on, with higher values of stem density and stand volume on the log-log scale. Furthermore, the productivity of residual trees decreased, resulting in slow increases in stand density. More time is needed before the next canopy closure.

The same effect can be achieved by raising the thinning ratio

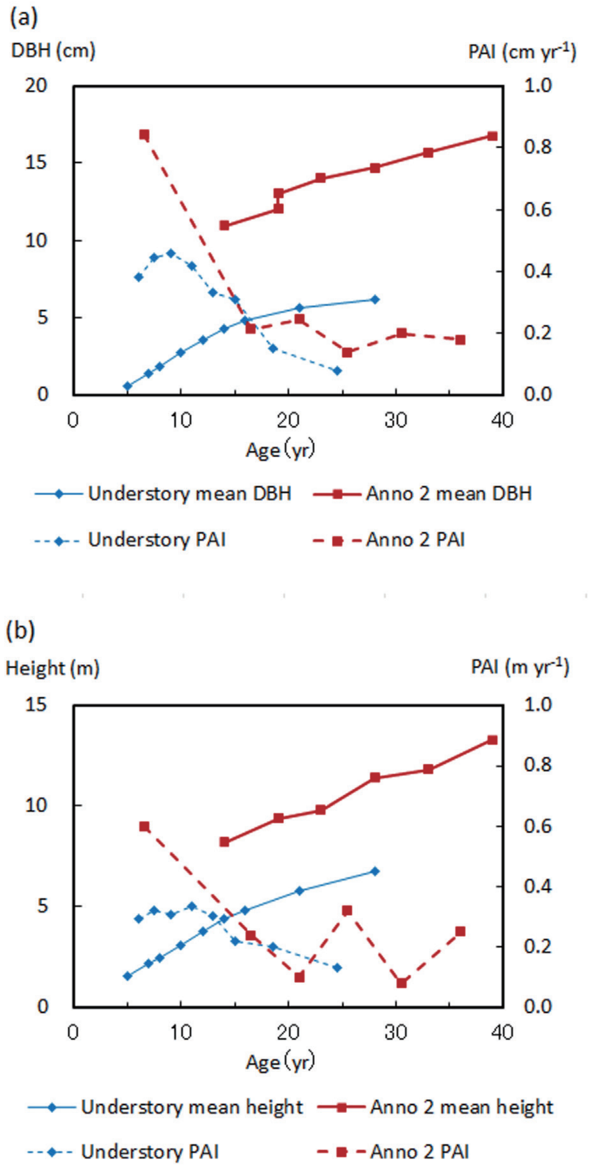

Fig. 6. Comparison of means and PAI of (a) DBH and (b) height between understory sugi trees in all the permanent sample plots and the unshaded trees in Anno No.2.

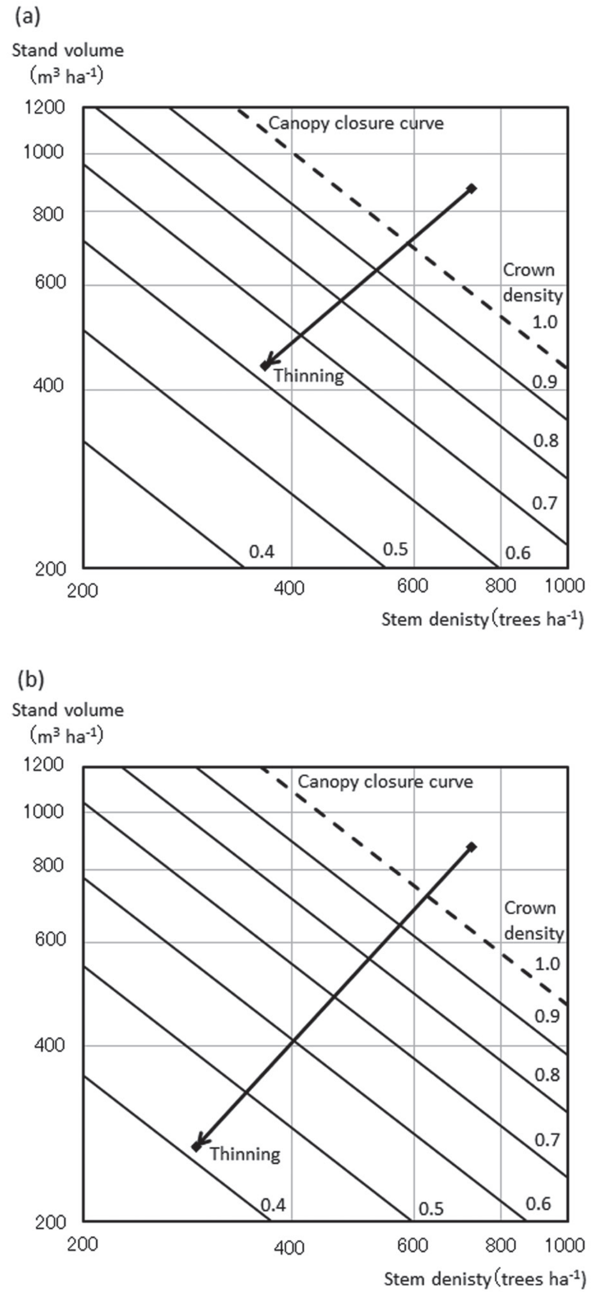

Fig. 7. The simulated trajectory of stem density and stand volume with respect to the overstory trees in the case of (a) mechanical thinning and (b) crown thinning.

in terms of the number of trees managed by low thinning. However, the thinning simulation showed sufficient effect to prevent the need for additional accretion cutting. The method is applicable to different thinning types other than low thinning.

## CONCLUSIONS

In this paper we have shown that the canopy closure curve of overstory trees is relevant to light control of the growth of understory trees according to the relationships between the growth of overstory trees and the change in growth of understory trees. The canopy closure curve is a useful reference for light control because it can be derived easily from the thinning condition of the stand upon which it depends. Crown density based on the canopy closure curve as a reference can also be a useful indicator of light condition. The results reveal the need for additional thinning at the study sites, and suggest that a crown density of 0.95 indicates the need for an accretion cutting to keep the PAI of DBH. Because limited thinning was implemented at the study site, mechanical thinning and crown thinning were simulated as the conversion thinning. This showed the possibility of avoiding the need for a second thinning. The canopy closure curve could also act as a reference in relation to stand density control, although further investigations are necessary to determine the specific value indicating the need for thinning.

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**Short Communication**

# Movements of Semi-captive Elephants during Skidding Season in Myanmar

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## ABSTRACT

Semi-captive Asian elephants (*Elephas maximus*) engaged in forestry activities in Myanmar account for 20% of all captive and semi-captive Asian elephants in the world, and are important for both forestry and the conservation of Asian elephant populations. Understanding moving behavior of the semi-captive elephants is required to sustain them. Our specific goals are 1) to determine the moving range during free time, and 2) to determine the hourly moving distance during skidding and when off duty. Three elephants were fitted with handheld global navigation satellite systems with the signals of global positioning system to collect data on their movements. The elephants were generally located between 0.534 and 0.875 km from the camp with temporary housing of the elephant handler when not skidding (i.e., free time) and between 1.365 and 1.372 km when skidding (i.e., work time). The hourly moving distance during free time (0.622–0.655 km) and work time (1.522 and 1.629 km) did not differ greatly from the hourly moving distance of wild Asian elephants (0.010–1.500 km). The elephants remained within 0.875 km of the camp of the elephant handler, and some variation in movements among individuals was observed during free time. Thus, the conservation of forest in areas near the camp is important for the well-being of these elephants.

*keywords*: *Elephas maximus*, moving distance, moving range, Myanmar Selection System, semi-captive elephant

## INTRODUCTION

Selective logging is a common logging practice, especially in tropical natural forests (Bicknell et al., 2014). Well-planned and carefully controlled selective logging has a small negative impact on biodiversity (Gibson et al., 2011; Burivalova et al., 2015), while selective logging without careful planning can result in forest degradation or intensive ground disturbance (Pereira et al., 2002). Myanmar Selection System (MSS) is the system of selective logging conducted in Myanmar. Selective logging under the MSS results in considerably lower ground disturbance compared with selective logging in other countries (Khai et al., 2020), because MSS use Asian elephants (*Elephas maximus*) instead of machines for skidding (Khai et al., 2020).

The elephants used for skidding for the MSS are semi-captive, which means that they are partially free-ranging when off duty. Because the semi-captive elephants for MSS rest and get forage by themselves in forests when off duty, conservation of forest areas where the semi-captive Asian elephants spend their time is critically important for the MSS. In order to determine the forests that should be conserved for the semi-captive elephants for MSS, it is first necessary to understand the moving range of the elephants when off duty.

Recently, an increasing number of studies have focused on the semi-captive elephants. However, the behavior of elephants when off duty has not yet been examined. Most studies of semi-captive elephants have focused on topics related to elephant populations, such as mortality rate (Mar et al., 2012), reproduction (Robinson et al., 2012), and population dynamics (Jackson et al., 2019). Other studies have focused on the personality of elephants (Seltmann et al., 2018, 2019) and their diet (Campos-Arceiz et al., 2008). Crawley et al. (2019) investigated the attitude and experience of elephant handlers and their relationships to recent political and economic changes in Myanmar. No studies to date have investigated the behavior of the semi-captive elephants used in the MSS.

An understanding of the behavior of semi-captive elephants used in the MSS is also important for the conservation of Asian elephants. The Asian elephant is listed as an endangered species in the International Union for Conservation of Nature (IUCN) Red List (Choudhury et al., 2008). The estimated total popula-

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tion of the Asian elephant is approximately 63,000–67,000 in the world (Menon and Tiwari, 2019) and captive and semi-captive Asian elephants account for approximately 15,000 (23%) of the total estimated population of Asian elephants. While captive elephants in zoos around the world only number approximately 1,000 and rarely breed (Sukumar, 2006), the number of semi-captive elephants used in the MSS is nearly 3,000 (Ministry of Natural Resources and Environmental Conservation, 2018). The value is equivalent to 20% of the captive and semi-captive Asian elephants in the world, despite the ban on routine capturing elephants used in the MSS over 25 years ago (Mar et al., 2012). Therefore, appropriate management of semi-captive elephants used in the MSS is important for the conservation of Asian elephants. Moving distance per unit of time is one of the criteria used in describing animal behavior patterns (e.g. Mills et al., 2018; Crawley et al., 2019). By showing the moving distance per unit of time when semi-captive elephants used in the MSS are used for skidding and when off-duty, information can be provided about the workload that the semi-captive elephants are exposed to.

Here, we studied the behavior of semi-captive elephants used in the MSS when they were being used for skidding and when off-duty. Our specific goals are 1) to determine the moving range during free time, and 2) to determine the hourly moving distance during skidding and when off duty. We tracked the movements of three semi-captive elephants using a handleld global navigation satellite system (GNSS) with the signals of global positioning system and determined the moving speed and moving distance of the elephants. We expect that this quantitative information on their movements will facilitate the management and conservation of semi-captive elephants.

CONTEXT: Ordinary daily schedule of semi-captive elephants in the skidding season

During the skidding season, which is generally between June and February, elephant handlers stay at a camp with temporary housing near the skidding site and a stream. The camp and the area surrounding the camp are also where the semi-captive elephants spend much of their time when off duty.

Before skidding, the elephant handler locates the semi-captive elephants that were released the previous night and escorts them to the camp. The elephants are then washed in a stream and fed a light meal, which composed of 0.16 kg of tamarind and 0.08 kg of salt. This helps the elephants' health as an appetizer and as a digestive catalyst. The health status of the elephants is also examined by the handler when they are being washed. The leader of the camp also checks the health status of elephants. Health conditions are checked from a variety of perspectives, including injury and degree of tiredness. After that, semi-captive elephants and the handlers leave the camp for skidding. After skidding, the semi-captive elephants and handlers return to the camp, the health status of the elephants is assessed, and elephants are fed a light meal. Semi-captive elephants are generally released to forests to rest and forage. Sometimes, the elephants are not free to roam but instead tied to a place where food is ample near the camp depending on their health. This is a procedure that is occasionally employed when necessary. When elephants are at the camp, they are provided with food, bathed, and subjected to health assessments.

## STUDY AREA

The study site was located in compartment 18 of Pyinde Reserved Forest in Katha and Kawlin, Myanmar (23°57′–58′N, 95°55′–57′E). The site is mountainous with an altitudinal range from 196 to 350 m above sea level. The forests are dominated by hardwood species such as teak (*Tectona grandis*), tauk-kyant (*Terminalia tomentosa*), and bamboo (*Thyrsostachys oliveri*). Monthly average temperature is ranging from 21°C to 31°C and monthly average rainfall is ranging from 4.8mm to 489.8mm. The camp is situated near a stream where the shade, water food is ample.

## MATERIALS AND METHODS

### GNSS Tracking and Time Records

Three semi-captive elephants were fitted with handheld GNSSs (GPSmap 62SJ, Garmin Ltd., Schaffhausen, Switzerland) by hitching a collar around their necks and were tracked from 11:15 a.m. on December 23th to 4:30 p.m. on December 27th in 2019 (Fig. 1). The three elephants were 19–35 years old (Table 1). Two elephants were male, and the other was female.

Because our study focused on the behavior of semi-captive elephants during their free time and work time, we defined both free time and work time at first. Work time was defined as the period between the time when the elephants left the camp for skidding and the time when the elephants returned to the camp. Free time was defined as the period between the time when the elephants were released from the camp and the time when the elephants returned to the camp. The elephants were equipped with the handheld GNSS just before their work time and free time, and it was removed when they returned to the camp. The start

Fig. 1. An example of semi-captive elephants with a GNSS.

Table 1 Summary of the features of elephants fitted with GNSSs

| Elephant | Sex | Age (years) | MTE (Myanmar Timber Enterprise) classification |
|---|---|---|---|
| 1 | Male | 19 | Full growth |
| 2 | Male | 29 | Full growth |
| 3 | Female | 35 | Full growth |

and end time of the work time and free time for each elephant was also recorded. The GNSS data were acquired approximately every 30 s during the tracking period.

The GNSS fell off an elephant during free time one time. We found this GNSS in the field and could estimate the time when the GNSS fell off the elephant because the GNSS tracking data showed the time when the GNSS arrived at the point where it fell off. We thus removed data acquired after the GNSS fell off the elephant in our analysis.

### Data Analysis

Before analyzing the data, we categorized the GNSS data into two classes: free time and work time. We then removed outlier points based on the moving speed and turning angle following previous studies of animal movement using GNSS data (Bjørneraas et al., 2010). Points exceeding the pre-defined moving speed were defined as outliers. Points were also classified as outliers when the turning angle was smaller than the pre-defined threshold. Because the appropriate thresholds for the semi-captive Asian elephant was not determined, we used a data-driven threshold (Gupte et al., 2022). We assumed that outliers corresponded to the 1 percentile of all data points and defined the pre-defined moving speed threshold and the turning angle threshold as 5.18 km/hour and 1.72 degrees, respectively. If a given point (outlier) was removed, the moving speed and turning angle were updated using the new data set without the outlier. Because the updated moving speed and turning angle may still exceed the pre-defined threshold, we recursively removed the outliers until the updated moving speed and turning angle satisfied the criteria.

After filtering the GNSS data, we calculated the distance from the camp and the moving distance. The distance from the camp was defined as the horizontal distance between the center of the camp and each GNSS data point. The center location of the camp was recorded using a handheld GNSS (GPS map 62SJ). The distances were summarized for every elephant by discriminating free time and work time (i.e., the time for skidding).

The moving distance was also calculated horizontally. Based on the GNSS data classified into work time and free time, we calculated the total moving distance and hourly moving distance of each elephant by dividing the total moving distance by the free time and work time.

The analysis was conducted in R ver. 4.0.3 (R Core Team, 2021).

## RESULTS AND DISCUSSION

All three elephants spent approximately the same amount of time for skidding (13% of the study period) regardless of both their age and sex. However, the amount of free time varied (ranging from 63% to 80%) (Fig. 2). The free times of each elephant were between 3739 and 4925 minutes. The reason for the variation in the amount of free time is that elephant handlers judged two elephants, one male and one female, were tired. The two elephants were tied down for long periods as described in context section.

Figure 3 showed movement trajectories of elephants. The trajectories varied among elephants during free time but were concentrated around the camp (Fig. 3). The mean distances from the camp for each elephant were between 0.172 and 0.364 km for free time (Fig. 4) and significantly varied among elephants ($P < 0.05$, Games-Howell test). The maximum distance that elephants moved from the camp was 0.875 km. The results suggested that the elephants were located near the camp where elephant handlers could find them.

The trajectories of the three elephants during work time were similar (Fig. 3). The mean distances from the camp for each were between 1.365 and 1.396 km (Fig. 4) and did not significantly differ among elephants ($P > 0.05$, Games-Howell test). This is because all three elephants went to the same logging sites and worked as a group during the study period.

The total moving distances of elephants during free time were more than twice as long as the total moving distances during work time (Fig. 5). This was because free time was much longer than work time (Fig. 2). The hourly moving distance was between 0.622 and 0.655 km and between 1.522 and 1.629 km for free time and work time, respectively (Fig. 5). The hourly distance traveled by wild Asian elephants ranged from 0.010 to 1.500 km (Leighty et al., 2009). Thus, the hourly distance of semi-captive Asian elephants in both free time and work time was similar to that of wild Asian elephants, but the time in work

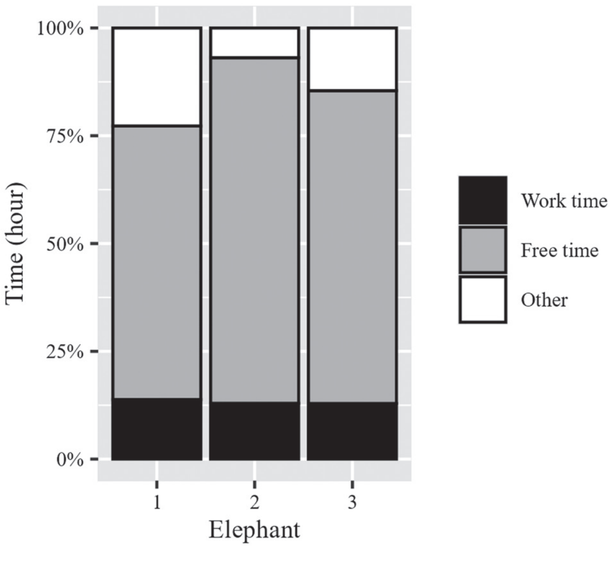


Fig. 2. Free and work time ratio of each elephant.

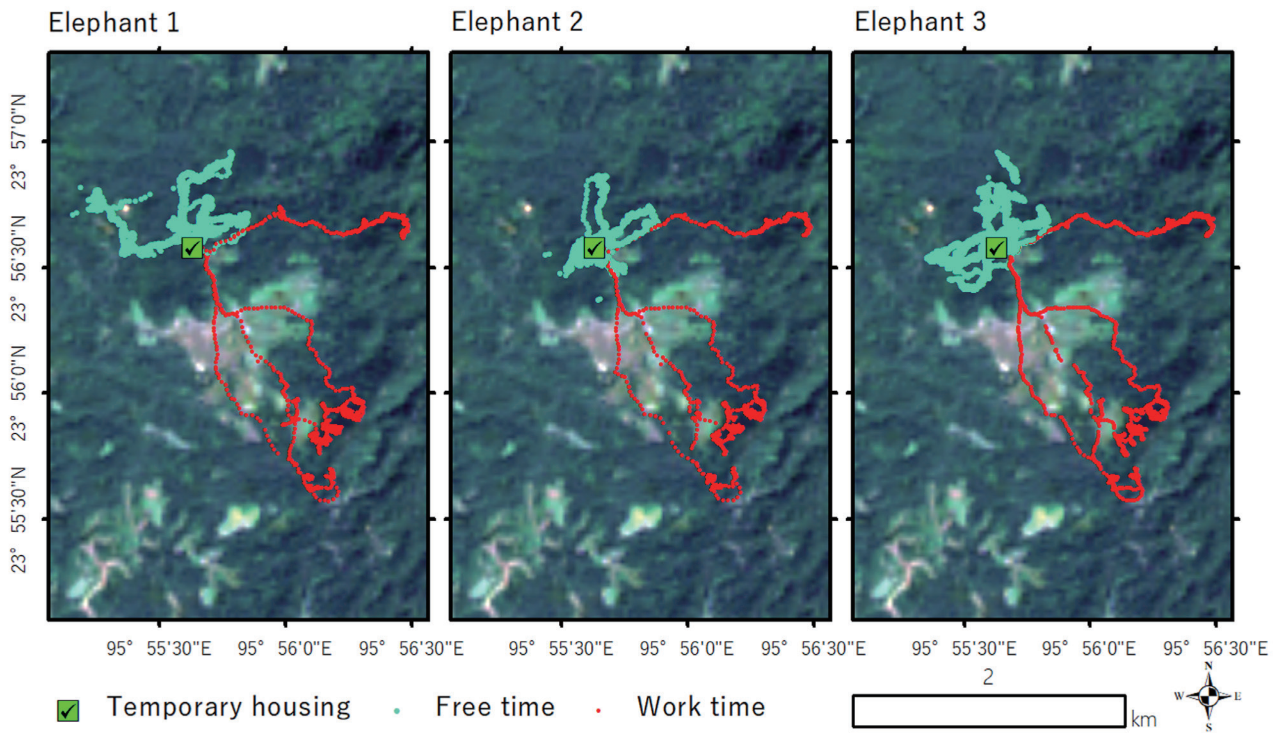


Fig. 3. Movement trajectories of elephants and the location of the camp of elephant handlers. The background image is the true-color image derived from Landsat 8 (acquired 18 November 2019).

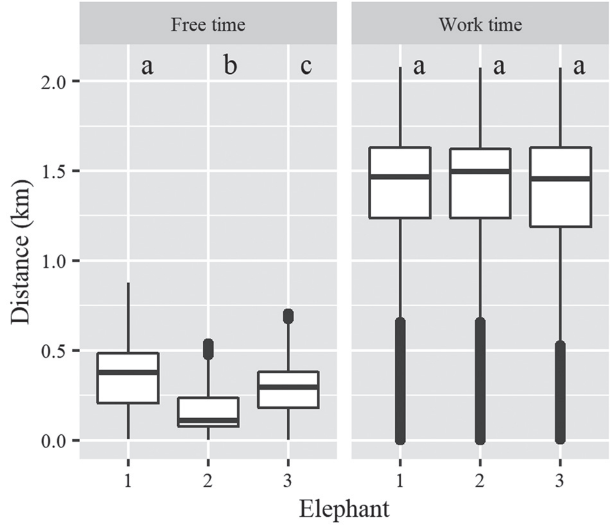
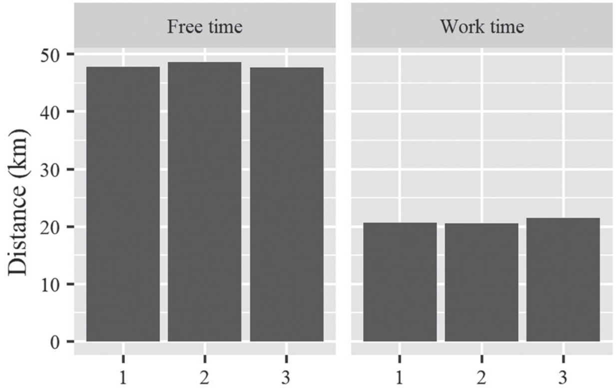


Fig. 4. Distance from the camp of elephant handlers. Different letters in each plot indicate significant differences (Games-Howell test, p <0.05).

time was close to the upper limit of wild Asian elephants.

Semi-captive elephants spent their free time within 0.875 km of the camp. Because the semi-captive elephants forage (especially bamboo) and rest during free time, sufficient supplies of food near the camp are needed. Therefore, the conservation of forest in areas used for camp is important for the MSS as well as the conservation of Asian elephants.


(a) Total distance

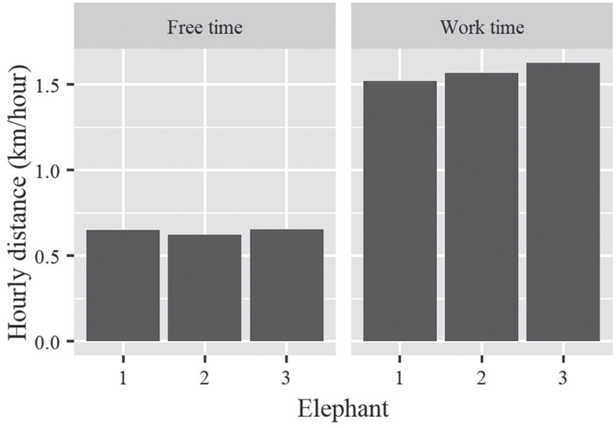

(b) Hourly moving distance

Fig. 5. Total moving distance and hourly moving distance of elephant.

## CONCLUSION

The semi-captive elephants mainly spent their time within 0.875 km of the camp of the elephant handler, but there was some variation among individuals when semi-captive elephants were off duty. During work time, the elephants needed to go more than 1 km away from the camp. No significant differences in the movements between elephants were observed during work time because the elephants worked as a group. The hourly moving distance of the semi-captive elephants during free time and work time in this study was similar to that of wild elephants. Additional studies are needed to explore the movement behavior of semi-captive elephants under other seasonal schedules, in resting camps, in tourism camps, and in other skidding sites.

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