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Articles

Article

Regeneration Process after Clear-cutting of a Secondary *Abies* and *Tsuga* Forest in Kirishima, Southwest Japan

Tomohiro Nishizono*[1], Akio Inoue*[2], Shigejiro Yoshida*[3] and Morio Imada*[3]

ABSTRACT

The objective of this study was to clarify the regeneration process of a secondary *Abies firma* and *Tsuga sieboldii* forest after clear-cutting in Kirishima. The stand structure and individual tree height growth pattern were analyzed. Then, the regeneration process of such a forest was discussed based on the above results. The dominance of coniferous species such as *Pinus densiflora*, *A. firma*, and *T. sieboldii* was observed. The study stand was considered to be stratified into two strata from tree height distributions, but the degree of separation between the strata was low. However, analysis of the individual height growth pattern showed that this study stand was in a transition period to discontinuous tree height distribution in the *Abies* and *Tsuga* population. Therefore, we consider that the structure of this *Abies* and *Tsuga* stand will shift in the future to one observed in a nearby old-growth stand. Based on the age of *P. densiflora*, the approximate year of clear-cutting on this site was determined. *P. densiflora* trees colonized after clear-cutting, whereas some *A. firma* and *T. sieboldii* seedlings were established before clear-cutting. It is suggested that the advance growth of *A. firma* and *T. sieboldii* played an important role in the regeneration process of the secondary *Abies* and *Tsuga* forest after clear-cutting. Therefore, advance growth must be left on clear-cut areas in order to grow the forest as fast as possible after clear-cutting.

Keywords: *Abies* and *Tsuga* forest, regeneration process, clear-cutting system, stem analysis, advance growth

INTRODUCTION

Abies firma and *Tsuga sieboldii* natural forests are distributed in the transition zone between warm and cool temperate zones in southwest Japan (Nakao, 1985). In the Kirishima mountain system located over Kagoshima and Miyazaki prefectures, southwest Japan, are the natural forests dominated by *Pinus densiflora* with *A. firma* and *T. sieboldii*. However, the conversion to commercially more valuable tree species has recently reduced and fragmented the natural forests (Nishizono *et al.*, 2000).

Since *A. firma* and *T. sieboldii* natural forests are very precious from the ecological viewpoint (Nakao, 1985) and have to be preserved, we have studied an application of various silvicultural systems to the natural forests in Kirishima (Nishizono *et al.*, 2001; Uema *et al.*, 2000; Yoshida, 1990; Yoshida *et al.*, 1991; 1992). Yoshida *et al.* (1992) studied the regeneration and stand structure of a secondary *A. firma* and *T. sieboldii* forest after clear-cutting, and suggested that the clear-cutting system was one of the most effective silvicultural systems for preserving the natural forests.

There have been many studies on the regeneration process of *A. firma* and *T. sieboldii* natural forests in southwest Japan (Aragami, 1987; Nakao, 1985; Suzuki, 1979; 1980; 1981a; 1981b; Sanquetta *et al* 1994). However, only a few studies on the regeneration process of *A. firma* and *T. sieboldii* forests after clear-cutting have been undertaken, and little is known about it (Yoshida *et al.*, 1992).

The objective of this paper is to clarify the regeneration process of a secondary *A. firma* and *T. sieboldii* forest after clear-cutting in Kirishima. First, it deals with the species composition and size distribution of the forest. Second, it explains the establishment time and height growth pattern of major component coniferous species which were estimated by stem analysis. Third, the regeneration process of the secondary forest is discussed on the basis of the above results.

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MATERIALS AND METHODS

Study Site

This study was conducted in a secondary *A. firma* and *T. sieboldii* forest located near Lake Ohnami in Kagoshima Prefecture, southwest Japan. The altitudinal range is from 975 to 1,060m a.s.l. The average annual temperature is 10℃ and annual precipitation is about 3,000 mm. The soils are mainly colluvial, and the slope is almost flat. According to the register of the forest, it regenerated naturally after clear-cutting and no silvicultural operation had been conducted (Yoshida *et al.*, 1992).

Field Survey

In 1997, three circular plots of 0.01ha were established in the forest. All trees of 4cm or more in DBH were identified, and their height and DBH were measured. Sample trees of *P. densiflora*, *A. firma*, *T. sieboldii*, and broad-leaved species were selected randomly, and felled for collecting stem disks. The numbers of sample trees were 13 in plot 1, and 12 in each of plots 2 and 3. Stem disks were cut for each sample tree at 1.0m intervals from the stump (0.2m above ground) to the tree tip. Where possible, the stem disc at 0.1m above ground was also cut. A general description of sample trees is shown in Table 1.

Table 1 General description of the sample trees

Plot	Tree name	Species	DBH (cm)	Height (m)	Age (year)
1	P1	*Pinus densiflora*	15.3	11.4	50
	P2	*Pinus densiflora*	17.7	11.7	54
	P3	*Pinus densiflora*	9.4	10.2	46
	P4	*Pinus densiflora*	14.9	10.4	53
	A1	*Abies firma*	7.1	6.8	58
	A2	*Abies firma*	15.1	10.7	61
	A3	*Abies firma*	12.4	9.1	63
	T1	*Tsuga sieboldii*	4.8	6.0	54
	T2	*Tsuga sieboldii*	9.8	8.5	56
	T3	*Tsuga sieboldii*	7.5	7.5	53
	M1	*Magbolia obovata*	7.6	8.1	53
	Ace1	*Acer spp.*	10.6	8.2	52
	I1	*Illiciumrelisiousum*	5.3	6.4	43
2	P5	*Pinus densiflora*	23.2	14.2	52
	P6	*Pinus densiflora*	13.9	13.3	46
	P7	*Pinus densiflora*	15.8	12.5	51
	P8	*Pinus densiflora*	17.3	12.3	48
	A4	*Abies firma*	4.2	5.7	55
	A5	*Abies firma*	6.0	7.0	62
	T4	*Tsuga sieboldii*	15.8	9.3	59
	T5	*Tsuga sieboldii*	7.8	6.7	60
	T6	*Tsuga sieboldii*	5.9	6.5	58
	T7	*Tsuga sieboldii*	8.5	8.2	66
	D1	*Daphniohyllum maacropodum*	13.2	9.3	52
	Aca1	*Acanthopanax sciadophylloides*	17.2	12.5	62
3	P9	*Pinus densiflora*	24.8	12.2	52
	P10	*Pinus densiflora*	13.2	11.4	51
	P11	*Pinus densiflora*	21.2	12.6	52
	A6	*Abies firma*	9.4	7.7	58
	A7	*Abies firma*	15.5	11.4	60
	A8	*Abies firma*	4.9	6.2	53
	A9	*Abies firma*	13.4	8.8	62
	A10	*Abies firma*	7.2	5.7	61
	A11	*Abies firma*	6.4	6.5	57
	T8	*Tsuga sieboldii*	3.5	5.9	57
	T9	*Tsuga sieboldii*	5.3	5.6	57
	Ace2	*Acer spp.*	7.2	7.8	44

Analysis Methods

First, the species composition and size distribution for the forest were analyzed. The summed dominance ratio (SDR: the arithmetic mean of relative density and relative basal area) for each species was calculated as a measure of species composition. Second, the age and height growth pattern of each sample tree were estimated by the stem analysis. In this study, the age of sample trees was taken to be the number of rings of the stem disc at 0.1m or 0.2m above ground.

RESULTS

Species Composition and Size Structure

Table 2 shows species composition for each plot. A total of 21 species (4 coniferous and 17 broad-leaved species) was found in the three plots. The major coniferous species found were *P. densiflora*, *A. firma* and *T. sieboldii*. For all plots, P. densiflora had the highest SDR (over 30%) and the mean dimensions (tree height and DBH) of *P. densiflora* were higher than for other species. Among the 17 broad-leaved species, *Illicium relisiousum* tended to have the highest SDR, followed by *Acer* spp., *Daphniphyllum macropodum*, and *Camellia japonica*. However, the mean dimensions of these broad-leaved species seemed to be smaller than coniferous species. These results suggest that the secondary forest is dominated by the coniferous species such as *P. densiflora*, *A. firma,* and *T. sieboldii.*

Fig. 1 and 2 show the frequency distributions of DBH and tree height, respectively. The distributions of DBH showed an L-shape, with many smaller trees and few larger ones. The distributions of tree height showed a unimodal-shape, with a peak at the 7m tree height class. *P. densiflora* was found in the larger size classes. The other major coniferous species, *A. firma* and *T. sieboldii* were primarily in the smaller and middle classes. The distributions of tree height suggested that each plot was stratified into two classes, but the separation between the two strata was not clear.

Age Distribution

The ages of sample trees ranged from 43 to 66 years (Table 1). The age structure clearly differed between the major coniferous species. The oldest age of *P. densiflora* was 54 yrs, whereas the youngest age of both *A. firma* and *T. sieboldii* was 53 yrs. All broad-leaved trees, except for a 62 year-old *Acanthopanax sciadophylloides*, were younger than 53 yrs.

Height Growth Pattern

The height growth for sample trees was divided into two growth patterns - fast and slow (Fig. 3). The height growth

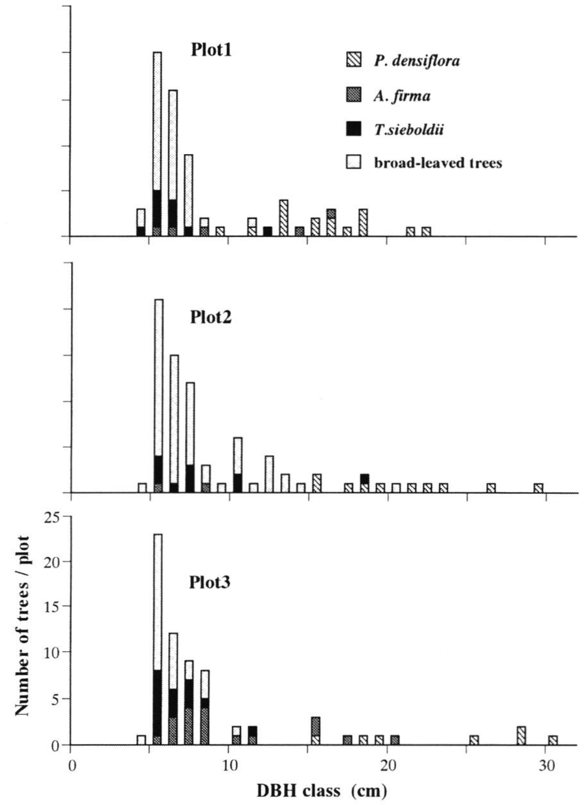

Fig 1 DBH distributions of each plot

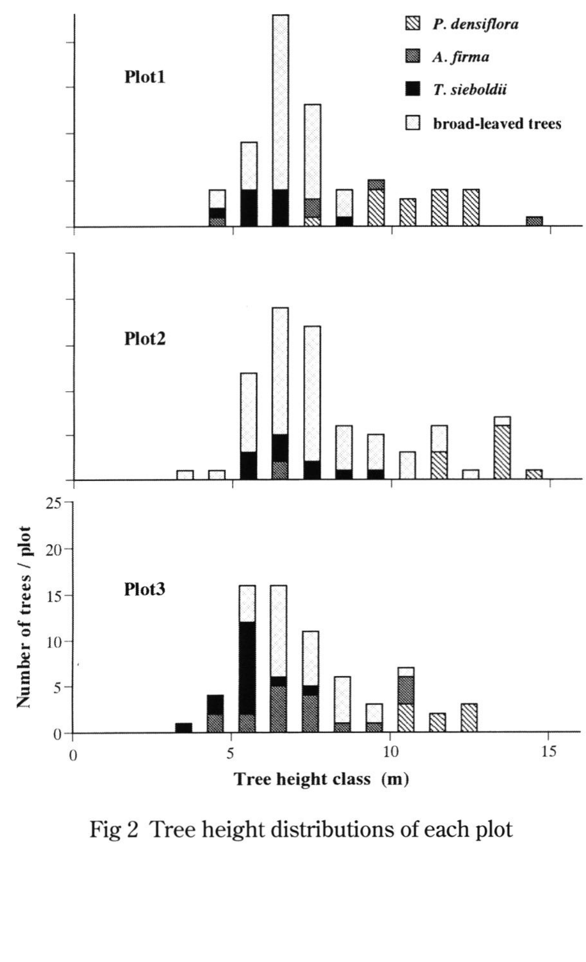

Fig 2 Tree height distributions of each plot

Table. 2 Species composition for each plot

Species	Plot 1				Plot 2				Plot 3			
	Density (trees/ha)	Mean DBH (cm)	Mean Height (m)	SDR (%)	Density (trees/ha)	Mean DBH (cm)	Mean Height (m)	SDR (%)	Density (trees/ha)	Mean DBH (cm)	Mean Height (m)	SDR (%)
Coniferous species												
Pinus densiflora	1600	15.1	10.3	43.8	1000	20.4	12.5	32.2	800	23.9	10.2	37.1
Abies firma	500	9.4	8.2	8.2	200	6.1	6.0	1.7	1800	9.0	6.8	24.1
Tsuga Sieboldii	1000	5.6	5.6	10.1	1000	7.6	6.4	10.5	1500	5.7	4.9	14.2
Torreya nucifera	-	-	-	-	100	5.1	6.0	0.8	-	-	-	-
Broad-leaved species												
Illicium relisiosum	1300	5.2	5.8	12.4	1400	5.3	5.8	11.3	600	5.0	5.5	5.3
Acer spp.	1200	5.3	6.5	11.8	1000	6.2	7.4	8.7	900	5.1	7.1	8.0
Daphniphyllum macropodum	-	-	-	-	800	11.1	10.1	11.2	-	-	-	-
Camellia japonica	-	-	-	-	700	6.3	6.6	6.2	-	-	-	-
Quercus acuta	200	5.8	6.0	2.0	200	7.3	7.0	2.4	200	4.7	6.0	1.7
Eurya japonica	100	5.6	5.0	1.0	200	5.6	5.5	1.7	200	4.7	6.0	1.7
Stewartia monadelapha	-	-	-	-	200	5.6	7.5	1.6	200	4.4	6.0	1.7
Cleyera japonica	200	5.6	7.0	2.0	100	4.5	5.0	0.8	-	-	-	-
Ilex pedunculosa	-	-	-	-	200	6.7	6.5	1.8	-	-	-	-
Others	900	7.9	7.0	17.4	900	8.7	7.4	9.7	700	5.8	7.1	6.6
Total	7000	7.9	7.2	100.0	7900	8.7	7.7	100.0	6900	8.6	6.9	100.0

patterns clearly differed between the major coniferous species. All *P. densiflora*, a typical pioneer species, showed the fast growth pattern. And they formed canopy layers faster than other species. The other major coniferous species, *A. firma* and *T. sieboldii*, and broad leaved trees attaining the canopy layer showed the fast growth pattern, but individuals under the canopy grew slower.

DISCUSSION

Stand Structure

The dominance of coniferous species such as *P. densiflora*, *A. firma*, and *T. sieboldii* was observed. Many trees of *P. densiflora* were large in both DBH and height, while many trees of *A. firma* and *T. sieboldii* were distributed in the middle or small class in both DBH and height, and competed with broad leaved trees. It was estimated from tree height distributions that the stand as of 1997 was divided into two strata, but the degree of separation between each stratum was low.

Abies and *Tsuga* forest is not stratified clearly in immature, 40-50 year-old forest (YOSHIDA *et al*, 1990; NAKAO, 1985), but as the stand develops is divided into about four strata (NAKAO, 1985). Then, the populations of *A. firma* and *T. sieboldii* show discontinuous tree height distribution (NAKAO, 1985). With further stand development, such coniferous trees as *A. firma* and *T. sieboldii* compose the upper stratum, and have a few trees in the shrub stratum, but few regeneration trees of *A. firma* and *T. sieboldii* can be found in the middle stratum (SUZUKI, 1979; NAKAO, 1985).

This was also observed in an old-growth stand of *Abies* and *Tsuga* near this study stand in Kirishima (YOSHIDA, 1990). *Abies* and *Tsuga* forests often have *P. densiflora*, and seem to shift to *Abies* and *Tsuga* forests without *P. densiflora* (SUZUKI, 1979; KUNISAKI, 1998). The degree of stratification in this study stand is not high. However, the analysis of individual height growth pattern showed that our study stand was in a stage of transition to discontinuous tree height distribution in the *Abies* and *Tsuga* population. Therefore, we consider that this *Abies* and *Tsuga* stand will shift to a stand structure like the nearby old-growth stand in future.

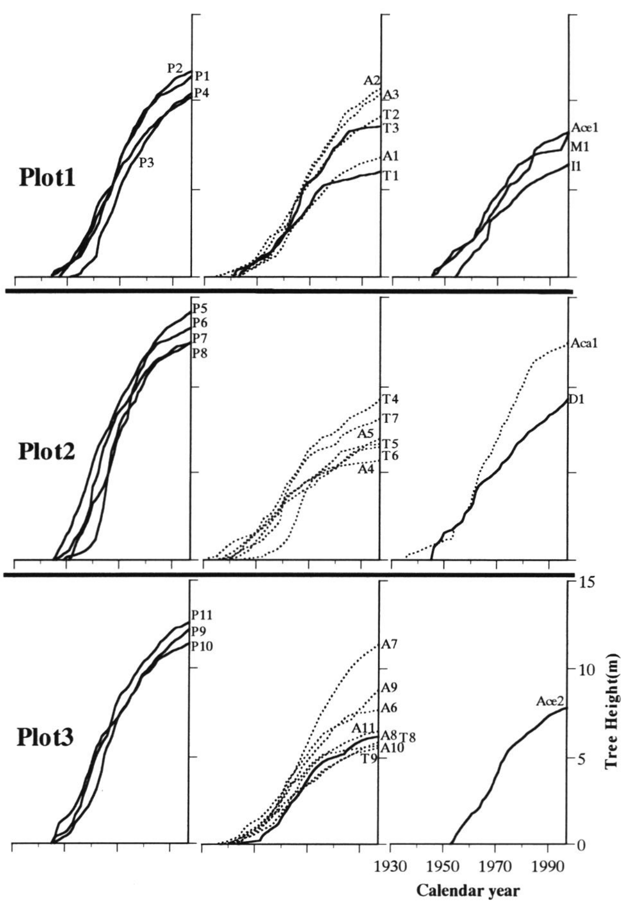

Fig. 3 Height growth curves of sample trees
Note: The left, center, and right columns show *P. densiflora, A. firma* and *T. sieboldii*, and broad-leaved trees, respectively. The solid line and the dashed line show after growth and advance growth, respectively. Advance growth was defined as trees which established before 1943.

Regeneration Process after Clear-Cutting

The age of sample trees ranged from 43 to 66 years. The *P. densiflora* tended to be younger than the other species. The year of establishment was estimated from the age of *P. densiflora* in plot 1, 2, and 3, and ranged from 1943 to 1951, 1945 to 1951, and 1945 to 1946, respectively. Thus, *P. densiflora* in this stand colonized after 1943 regardless of their size. Since *P. densiflora* is typical a shade-intolerant pioneer tree, it requires higher light conditions to grow. Accordingly, the clear-cutting was considered to be conducted in 1943-1945 approximately.

It was assumed that, as a matter of course, *P. densiflora* trees colonized after clear-cutting. *A. firma* and *T. sieboldii* trees became established mostly before clear-cutting, except that some sample trees colonized simultaneously with clear-cutting, but were mostly suppressed by 1997. Thus, there was advance growth of *A. firma* and *T. sieboldii* on the clear-cut area which had survived the clear-cutting. Broad-leaved trees with large height in 1997 colonized before or simultaneously with clear-cutting. The trees colonizing about 10 years after clear-cutting were almost all suppressed.

From the above results, we deduced the regeneration process after clear-cutting of the forest (Fig. 4). First, clear-cutting was conducted in 1943-1945 approximately. Some saplings of *A. firma*, *T. sieboldii* and broad-leaved trees which had established under the canopy before clear-cutting were left on the clear-cut area. Next, the coniferous trees of *P.*

densiflora, *A. firma*, and *T. sieboldii* and broad-leaved trees colonized by natural seeding or sprout. Then, the fast growing trees of *P. densiflora* and broad-leaved species overtook most of the advance growth of *A. firma* and *T. sieboldii*, and formed the crown layer. Some advance growth of *A. firma* and *T. sieboldii* grew as fast as *P. densiflora*, joining the crown layer. But the growth of most of them was affected by various ecological conditions such as low light irradiation under the canopy, resulting in suppressed trees. Therefore, the difference in size between each group of trees became wider. *A. firma* and *T. sieboldii* which were not advance growth, but after growth did not become canopy trees, became suppressed trees. The later-established broad-leaved trees almost all became suppressed.

In this paper, the present stand structure and individual tree height growth patterns in a secondary *Abies* and *Tsuga* forest in Kirishima were analyzed, and the regeneration process of the forest after clear-cutting was examined. As a result, we consider that this *Abies* and *Tsuga* stand will shift in the future to a stand structure like that seen in a nearby old-growth stand, and that advance growth of *A. firma* and *T. sieboldii* plays an important role in the regeneration process of a secondary *Abies* and *Tsuga* forest after clear-cutting. Our later results agrees with those obtained on Shikoku island (Suzuki, 1981b ; Sanquetta *et al.* 1994). From these results, advance growth must be left on clear-cut areas in order to grow the forest as fast as possible after clear-cutting. Nishizono *et al.*

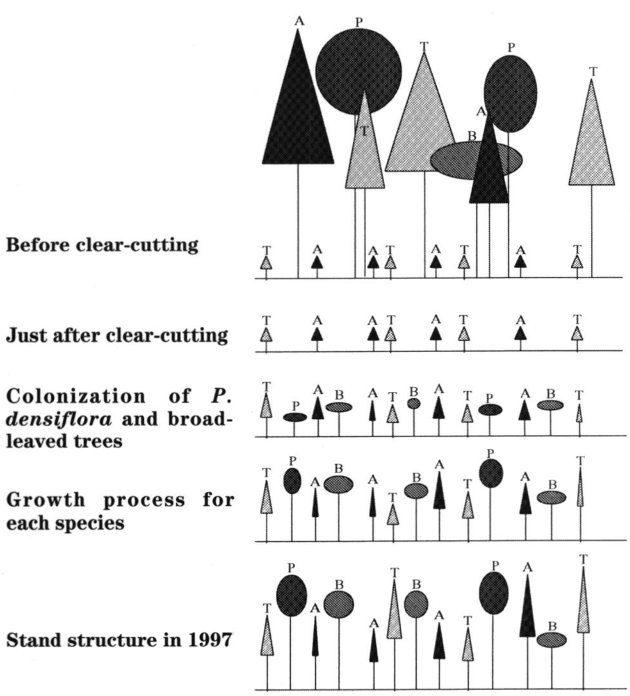

Fig. 4 Schematic diagram of regeneration process after clear-cutting
Note: P, A, T and B show *P. densiflora*, *A. firma*, *T. sieboldii*, and Broadleaved-trees, respectively.

(2001) pointed out that selective-cutting had the possibility to promote growth of regeneration trees on the forest floor in an *Abies* and *Tsuga* forest. It is therefore better to conduct selective-cutting before clear-cutting to enrich advanced growth. Maeda (1978) reported that large-scale clear-cutting resulted in high mortality of advanced growth of *Abies Mariesii* Mast., *Abies Veitchii* Lindl., and *Tsuga diversifolia* Masters in subalpine coniferous forests in Central Japan. Therefore, improved clear-cutting systems to maintain advanced growth should be developed in the future.

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Article

Relationship between Mean Free Path and Leaf Area in Boreal Forest Canopies

Emmanuel R. G. Abraham*[1], Hayato Tsuzuki*[2] and Tatsuo Sweda*[2]

ABSTRACT

The free (unobstructed) sight through the foliage layer of forest canopy is expected to depend on the density of the foliage, i.e. dense foliage shortens the free sight while sparse one extends it. Conversely, it is possible to estimate foliage density from the free sight. Furthermore, it is possible to estimate from the free sight the amount of leaves in terms of leaf area or leaf area index (LAI) as a product of estimated foliage density and the thickness of the foliage layer. This paper presents a simple theory of estimating LAI from the free sight along with its verification using a set of field data from boreal forest of Canada. Free sight through the canopy was measured using airborne laser altimetry (ALA). Laser beams emitted vertically from an aircraft are reflected from different layers of the canopy, ranging from the uppermost canopy surface to the ground. The distance that a laser beam travels unimpeded into the canopy was assumed to be the free sight or more aptly, the free path, and the mean of a number of penetrations within the canopy as a good measure of the amount of leaf area. We assembled a set of field leaf area and mean free path data for 13 boreal forest sites in central Alberta, Canada. We related leaf area density with mean free path and found an inverse relationship between them. Furthermore, we verified that LAI can be estimated as a product of mean free path-based leaf area density and an estimate of canopy depth (D) obtained based on the relationships we found between D and mean tree height (H) and between H and mean laser vegetation height.

Keywords: Airborne laser altimetry, boreal forest, mean free path, leaf area density, leaf area index

INTRODUCTION

Leaves serve as the primary interface between forest ecosystems and the atmosphere, serving both as solar energy collectors and as exchanger for gases. Models that are used for calculating radiant energy interception by canopies require information on amount of leaf area per unit of ground (leaf area index, LAI) and angle distribution; while models for the turbulent exchanges of heat and mass, and calculations of size of penumbra also require a knowledge of the vertical distribution of leaf area within the canopy (Campbell and Norman, 1989). Leaf area index is therefore an important variable for climate and ecosystem studies and is one of the vital boundary conditions fed to general circulation models for projecting global warming (Trenberth, 1992; Mabuchi, 2000).

Direct measurement of leaf area and its distribution within forest canopies is very difficult and time consuming. Although methods have been developed to directly and indirectly measure LAI on the ground (Chason *et al.*, 1991; Cutini *et al.*, 1998; Fassnacht *et al.*, 1994; Gower *et al.*, 1999), expanding such estimates over extensive areas (e.g. to a regional scale) is still a major challenge and relies heavily on the use of remote sensing products.

Conventional methods of large-scale LAI measurement generally involve the comparison of vegetation indices developed from reflectance data obtained using optical sensors to *in-situ* measurements of LAI, but not a single vegetation index seem to be equally effective in relating with it (Campbell, 1996). Airborne laser altimetry (ALA) remote sensing, however, is emerging as a potentially powerful tool in forest

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inventory and mapping (Lefsky *et al.*, 2001) and in estimating LAI over extensive areas (Kusakabe *et al.*, 2000; Sasaki *et al.*, 2001).

ALA systems have three basic components: an infrared laser altimeter (ILA), a global positioning system (GPS), and an inertial navigation system (INS) mounted on an aircraft. The ILA emits infrared laser beams at a high frequency (100 – 20,000 Hz) and records the time difference between laser pulse emission and reception of the reflected signal. The GPS continuously monitor the three-dimensional position of the aircraft whose orientation is controlled and determined by the INS. The round trip travel time of the laser beam multiplied by the speed of light equals twice the distance from aircraft to the target. The distance data is processed together with GPS and INS data to obtain the three-dimensional position of the objects that reflected the laser beams, that in the case of forests, could be the uppermost canopy surface or the ground in two extremes, or canopy elements in between (Fig. 1).

ALA systems currently employed in forest applications could be grouped into two. First are those that employ low-altitude, small (<1 m) footprint (size of ground illuminated by the laser beam), range-only pulsed laser systems, with high repetition rates (2,000 – 20,000 Hz) that can be configured to measure the first-return pulse or the last-return pulse on a vertical or scanning mode (Aldred and Bonnor, 1985; Magnussen and Boudewyn, 1998; Ritchie *et al.*, 1993). The second group employs medium altitude, medium to large footprint (5-25 m) pulsed laser systems with lower repetition rates (<100 Hz) but are capable of digitizing the power of the entire return signal within a single footprint, resulting in a waveform that records the vertical distribution of laser reflections (Blair and Hofton, 1999; Blair *et al.*, 1999; Means *et al.*, 1999; Lefsky *et al.*, 1997, 1999).

While studies on the application of the latter type of sensors to predict LAI has been undertaken (e.g. Lefsky *et al.*, 1997), we are not aware of any that uses first-return altimetry data to directly estimate LAI in forest canopies. Kusakabe *et al.* (2000) for example, obtained LAI estimates from ALA data but did it indirectly using LAI's correlation with stand stocking and the latter's correlation with the area under the laser vegetation canopy height profile as established by Tsuzuki *et al.* (1998).

First-return ALA, however, is a potentially powerful tool to measure leaf area and its distribution within forest canopies. The area density of leaves (leaf area density, A) and the thickness of the foliage layer (i.e. canopy depth, D) basically determines the total amount of leaf area. The density is expected to influence the length of free (unobstructed) sight in such a way that dense foliage shortens the free sight while sparse one extends it. Conversely, it is possible to estimate foliage density from the free sight. Furthermore, it is possible to estimate from the free sight the amount of leaves in terms of leaf area or LAI as a product of estimated A and D. Here, the advantage of first-return laser altimetry comes into play. With only one recorded reflection, a vertically emitted beam that penetrates the canopy from above and travels for a certain distance before it hits foliage and is reflected back is tantamount to the free sight and could be termed as the free path. Obtaining the mean free path within a laser profiling segment using a number of within-canopy penetrations should then provide a good measure of the amount of leaf area.

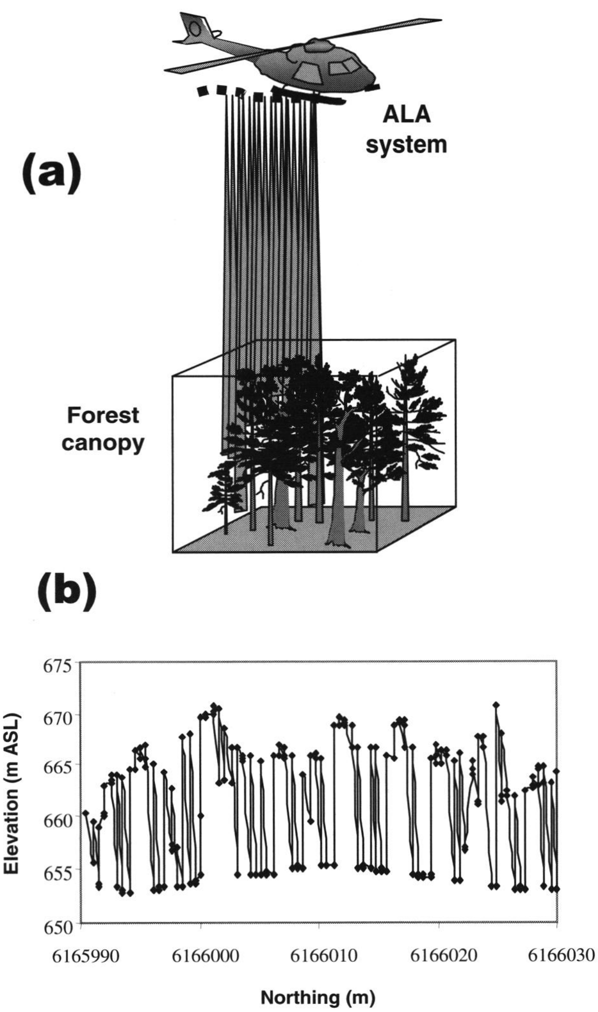

Fig. 1. Airborne laser altimetry remote sensing of vegetation height profiles. (a) The system uses a small footprint, ranging laser to continuously measure the vertical distance between the aircraft and reflecting objects while a GPS component measure the three-dimensional position of the aircraft. Post flight processing generates the three-dimensional position of reflecting objects along a flight course. (b) Shows a typical profile showing that beams are reflected from various levels of the canopy.

This paper presents a simple theory of estimating LAI from the free sight—obtainable using ALA—along with its verification using a set of field data. We assembled a set of field leaf area and mean free path data for 13 boreal forest sites in northern Alberta, Canada. We related leaf area density with mean free path and found an inverse relationship between them. We further verified that LAI can be estimated as a product of mean free path-based leaf area density estimate and an estimate of D obtained based on the relationship we established between D and mean tree height (H) and between H and mean canopy height also obtained via laser altimetry.

MATERIALS AND METHODS

Theoretical Basis

Suppose a forest canopy layer in which leaves of exactly the same leaf area a are distributed randomly with mean inclination angle θ as measured as dip from a horizontal plane. Suppose also that N leaves are packed in a unit space of the canopy, i.e. at leaf density of N so that the vertical mean free sight through the foliage layer would be l. Then, the probability of the vertical free sight being obstructed by going a minute distance dx can be expressed in two different ways.

Since the unobstructed sight on an average is l according to the assumption, the first expression of the probability is given by

$$dx/l. \qquad (1)$$

On the other hand, the expected number of leaves appearing in going a distance dx in unit area perpendicular to the direction of sight is

$$Ndx,$$

posing an obstruction area of

$$Na\cos\theta dx, \qquad (2)$$

where $a\cos\theta$ represents an effective obstruction area each leaf contributes. Being the proportion of sight obstructing area, (2) is another expression of the probability of the sight being obstructed in dx. Thus, equating (1) and (2), we get

$$l = \frac{1}{Na\cos\theta}.$$

By substituting $1/\cos\theta$ by another constant c,

$$l = \frac{c}{Na}$$

results, which signifies that the mean free sight is inversely proportional to leaf area density Na, i.e. leaf area in unit space. Our interest is to estimate leaf area density from the mean free sight, and thus by transposing the above equation we get

$$Na = \frac{c}{l}.$$

Substituting Na with a single variable A for leaf area density, we finally get

$$A = Na = \frac{c}{l} \qquad (3)$$

By introducing yet another variable D to represent canopy thickness or depth, Eq. (3) can be converted to one relating the mean free sight to the most common indicator of leaf amount, leaf area index I, i.e. the total leaf area per unit of ground as follows:

$$I = AD = \frac{c}{l} D \qquad (4)$$

In application of the above theory to the reality of leaf area remote sensing using airborne laser altimetry, the term 'free sight' would be more aptly expressed as 'free path', i.e. the depth a laser beam penetrates into canopy without being obstructed by leaves. The more practical side of the difference between the free sight and free path is that while the sight is an imaginary line without thickness, the laser beam has a footprint of a certain size. This difference, however, only enlarges the collision area $a\cos\theta$ and accordingly makes c smaller by a certain factor proportional to footprint size.

Deduction of Mean Free Path from Laser Altimetry Data

Laser penetration depth into forest canopy was acquired for 13 boreal forest sites in central Alberta, Canada (Fig. 2) over which a laser profiling mission was flown in September 1997 using a helicopter-borne vertical first-return ALA system. The original ALA data consisted of a series of clearance measurements between the aircraft and whatever the objects on the ground reflecting the laser beam. Incorporating the flight altitude data continuously monitored by the airborne GPS simultaneously with laser profiling, the original data were calibrated into a surface profile consisting of reflections from the ground objects. For each study site, individual components of the surface profile were classified into three categories. They are the reflections from (1) the ground itself, (2) the uppermost canopy surface, and (3) within the canopy layer. Then from the respective set of ground hits and of canopy hits above, a continuous topographic profile and a canopy profile were generated using cubic spline interpolation.

Subsequently using these two different profiles representing topography and vegetation profile, two measures characterizing each study site was compiled. One is the ALA-based canopy height calculated as the difference between the individual canopy hits and the corresponding topographic surface. They were then averaged as an estimated mean canopy height (H_{est}) for each study site for comparison with the observed counterpart (H_{obs}). As shown in Fig. 3 they were well correlated, confirming the capability of airborne laser altimetry to measure vegetation height effectively and accurately.

The other stand measure compiled was the free path or the depth of laser penetration into the canopy. It was calculated as a difference between the canopy profile and individual reflections from within the canopy. They were then averaged for each study site to obtain the mean free path (l), the principal subject of the present paper, for estimating the leaf area density and leaf are index in the subsequent analyses.

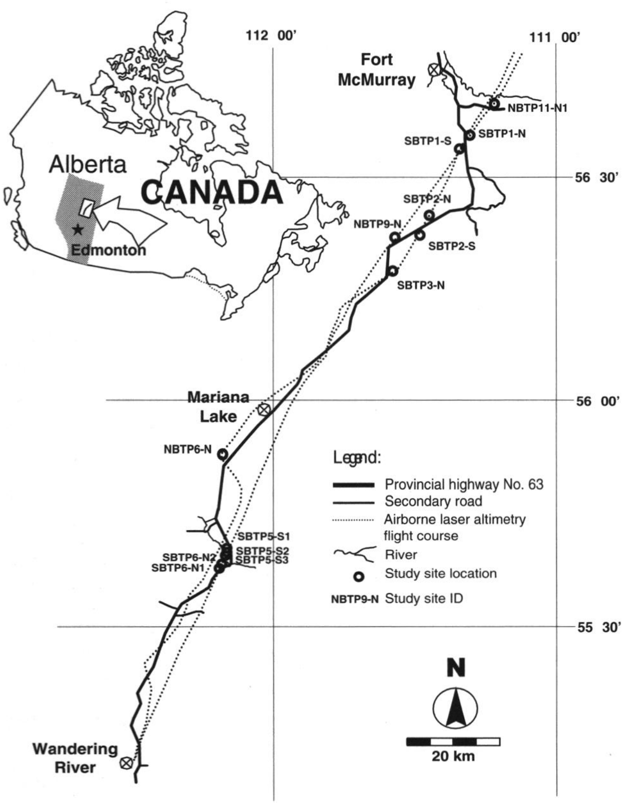

Fig. 2. Location of study sites

Ground Measurement of Leaf Area Density and Leaf Area Index

To obtain actual leaf area density (A_{obs}) and leaf area index (I_{obs}), ground truthing surveys were conducted in August and September 1999 for the 13 plots co-located with the ALA profiling segments. Plot size varied in accordance with the average size of constituent trees, i.e. plot length and plot width as twice the average tree height and crown diameter, respectively. In each plot, the species and, diameter at breast height (*dbh*) of all the trees exceeding breast height (1.3m) were inventoried. Then a total of 33 trees were harvested from ten of the study sites to establish regressions of tree height, crown length, crown volume and leaf area on *dbh*. These sample trees represented four boreal species, namely black spruce (*Picea mariana* (Mill.) BSP), white spruce (*Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.) and trembling aspen (*Populus tremuloides* Michx.). Based on the theory of allometry (ABRAHAM *et al.*, in review), a set of regression equations were developed to relate *dbh* with tree height, crown length and crown volume, and then applied to the censused *dbh* measurement to obtain these measures for all the trees in each study plot. These individual measures were then averaged or summed up to obtain observed mean canopy height (H_{obs}), mean crown depth (D_{obs}) and total canopy volume (V).

As pointed out earlier, D in Eq. (4) is a crucial variable along with mean free path (l) for estimating leaf area index using airborne laser altimetry. While H can readily be estimated by laser altimetry, such is not the case with D. However, as shown in Fig. 4, D_{obs} was found to be well correlated with H_{obs}, indicating that a laser-based estimate of canopy depth (D_{est}) can be obtained from H_{est} using the coefficient obtained from regression of D_{obs} on H_{obs}.

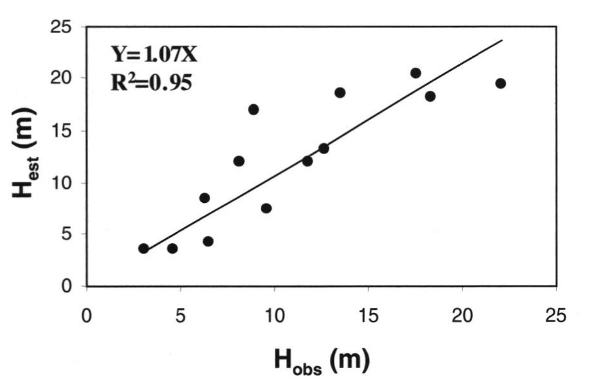

Fig. 3. Relationship between observed mean tree height (H_{obs}) and mean tree height estimated via laser altimetry (H_{est})

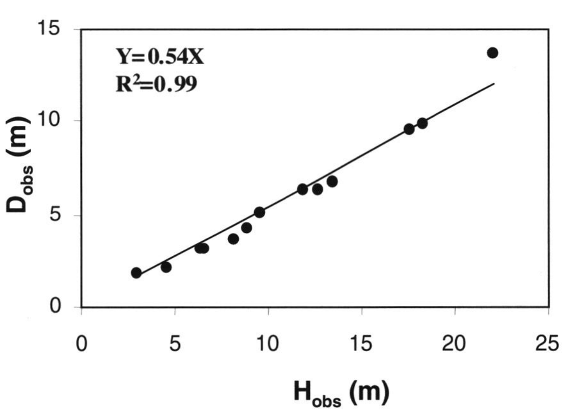

Fig.e 4. Relationship between observed mean tree height (H_{obs}) and observed mean canopy depth (D_{obs})

Leaf area in individual trees was obtained from leaf weight using the ratio of leaf area to leaf weight in sample leaves. The sample leaves were obtained from the upper, middle and lower crown of the harvested trees. Leaf areas of samples were measured using an image processing program 'NIH Image' Version 1.61 (Wayne Rasband, National Institutes of Health, USA). In large trees, for which census measurement of leaves was impractical, foliage weight was estimated from branch diameter using a regression established between them. Plot leaf area was compiled as a sum of individual tree leaf area obtained from *dbh* using allometric equations developed using the harvested trees. Leaf area thus obtained was converted to leaf area density (A_{obs}) and leaf area index (I_{obs}) for each plot by dividing them with canopy volume (V). and projected canopy area (G), respectively. Leaf area index (I_{obs}) was computed as a product of A_{obs} and D_{obs}. The characteristics of the thirteen sites in terms of the aforementioned laser altimetry and ground truthing variables are summarized in Table 1.

Validation of Theory

The postulated theory of inverse proportionality of mean free path with leaf area density (Eq. (3)) and with leaf area index (Eq. (4)) was tested using l, A_{obs} and I_{obs}. To begin with, Eq. (3) was tested by plotting A_{obs} against l to see the sign of inverse proportionality between them. Then we related A_{obs} with l in accordance with Eq. (3), in which non-linear regression was conducted using the statistical software JMP ver. 4.0 (SAS Institute, Inc., USA). The constant of proportionality c determined in this process of fitting Eq. (3) can now be utilized for estimating leaf area index from the laser altimetry data in accordance with Eq. (4).

The expected relationship between leaf area index and mean free path (Eq. (4)) was tested y examining the correspondence between observed leaf area index (I_{obs}) and its laser-based counterpart (I_{est}) at three different levels corresponding to three different levels of ALA involvement in obtaining an estimate of leaf area index, i.e.

$$I'_{est}=A_{est}D_{obs}, \tag{5}$$

$$I''_{est}=A_{obs}D_{est}, \tag{6}$$

and

$$I_{est}=A_{est}D_{est}. \tag{7}$$

In estimates (5) and (6), the airborne laser altimetry is only partially involved appearing in either one of the factors A or D, whereas estimate (7) is fully ALA based.

RESULTS AND DISCUSSION

As shown in Fig. 5, leaf area density was found to be inversely proportional to the mean free path as had been expected from the proposed theory. The constant of proportionality c obtained from regression was used to estimate leaf area density (A_{est}) from the mean free path, which we plotted against A_{obs} in Fig. 6. The figure shows that the estimated leaf area density (A_{est}) approximates the observed counterpart reasonably well though it tends to underestimate the reality as indicated by the calculated constant of proportionality of 0.92. With coefficient of determination (R^2) at 0.91, the estimated leaf area density is also well correlated with the observation.

We also found close correspondence between observed leaf area index (I_{obs}) and its laser-based estimated counterpart (I_{est}) at three different levels of comparison with varying degree of involvement of ALA-based A and D estimates. In the first level, where of the two factors determining leaf area index, i.e. leaf area density (A) and canopy depth (D), only the former is laser-based while observed values were used for the latter, the estimated leaf area index (I'_{est}) correlated well with observed ($R^2=0.93$) as shown in Fig. 7. Again in this case, estimates tended to be less than observation with the constant of proportionality at 0.79. The tendency of underestimation, however, was reduced in the second level of comparison where

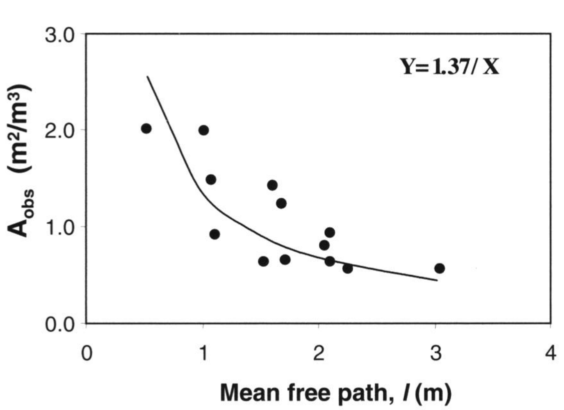

Fig. 5. Relationship between mean free path (l) and observed leaf area density (A_{obs})

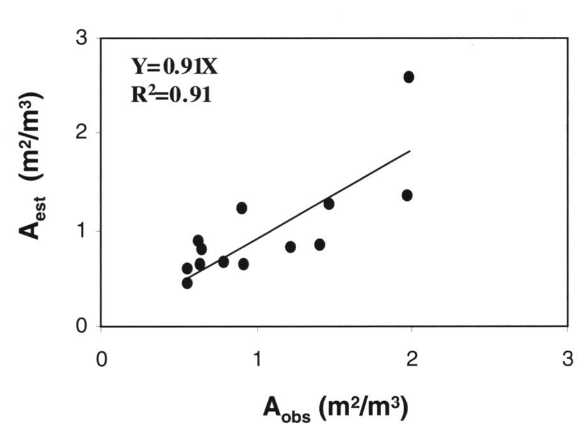

Fig. 6. Comparison of observed leaf area density (A_{obs}) with leaf area density estimated from mean free path (A_{est})

Table 1. Summary of ground and laser metrics and associated estimates of leaf area density and leaf area index

		Ground truth measures						ALA measures				LAI estimates (m^2/m^2)		
No.	Plot ID	H_{obs} (m)	D_{obs} (m)	A_L (m^2)	V (m^3)	A_{obs} (m^2/m^3)	I_{obs} (m^2/m^2)	L (m)	H_{est} (m)	D_{est} (m)	A_{est} (m^2/m^3)	I'_{est}	I''_{est}	I_{est}
1	SBTP6-N1	11.9	6.3	415	449	0.92	5.86	2.11	12.14	6.56	0.65	4.12	6.06	4.26
2	SBTP6-N2	3.0	1.8	60	30	1.97	3.59	1.02	3.43	1.85	1.34	2.44	3.65	2.49
3	SBTP5-S3	13.5	6.8	1,107	1,723	0.64	4.36	2.11	18.05	9.99	0.65	4.41	6.42	6.49
4	SBTP5-S2	8.9	4.3	352	554	0.64	2.71	1.53	16.92	9.14	0.90	3.81	5.80	8.18
5	SBTP5-S1	12.7	6.4	888	1,111	0.80	5.11	2.06	13.32	7.19	0.67	4.25	5.75	4.78
6	NBTP6-N	17.6	9.4	1,106	1,688	0.65	6.18	1.72	20.26	10.94	0.80	7.52	7.17	8.71
7	SBTP3-N	6.6	3.1	372	407	0.91	2.83	1.12	4.22	2.28	1.22	3.79	2.08	2.79
8	NBTP9-N	9.6	5.2	1,062	749	1.42	7.30	1.61	7.48	4.04	0.85	4.38	5.73	3.44
9	SBTP2-S	8.2	3.6	1,021	1,833	0.56	2.02	3.06	12.12	6.54	0.45	1.63	3.65	2.93
10	SBTP2-N	18.3	9.8	3,213	5,771	0.56	5.46	2.26	18.16	9.81	1.61	5.94	5.46	5.94
11	SBTP1-S	22.1	13.6	1,241	1,012	1.23	16.71	1.69	19.36	10.45	1.81	11.04	12.82	8.47
12	SBTP1-N	6.4	3.1	1,161	790	1.47	4.56	1.09	8.39	4.53	1.26	3.90	6.66	5.69
13	NBTB11-N1	4.6	2.1	111	56	1.99	4.11	0.53	3.45	1.86	2.58	5.35	3.70	4.82

Note: H_{obs}-mean tree height; D_{obs}-mean canopy depth; A_l-total leaf area: V-total canopy volume; A_{obs}-observed leaf area density; I_{obs}-observed leaf area index; l-mean free path; H_{est}-estimated mean canopy height; D_{est}-estimated mean canopy depth; A_{est}-estimated leaf area density; I'_{est}-LAI estimated as product of A_{est} and D_{obs}; I''_{est}-LAI estimated as product of A_{obs} and D_{est}; I_{est}-LAI estimated as product of A_{est} and D_{est}.

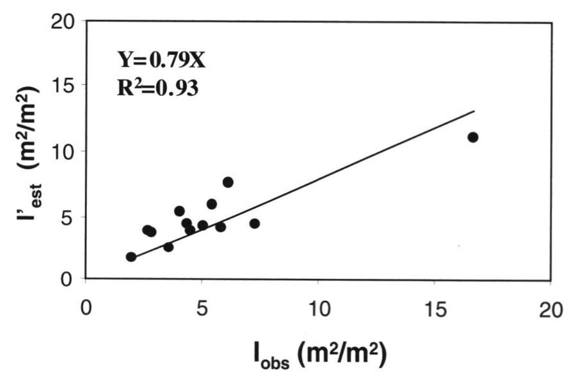

Fig. 7. Comparison of observed leaf area index (I_{obs}) with leaf area index estimated as product of estimated leaf area density (A_{est}) and observed mean canopy depth (D_{obs})

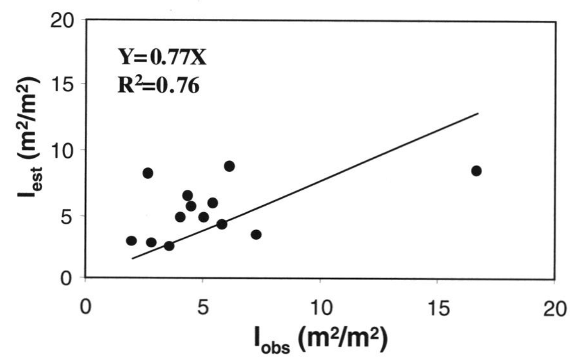

Fig. 9. Comparison of observed leaf area index (I_{obs}) with leaf area index estimated as product of estimated leaf area density (A_{est}) and estimated mean canopy depth (D_{est})

laser-based estimate was used only for canopy depth as in Fig. 8. Here, the constant of proportionality rebounded to 0.93 indicating that estimates are closer to observed values than in the first level. In both levels however, the overall variability did not differ with R^2 remaining at 0.93 in both cases. These results suggest that between A_{est} and D_{est}, it is the latter that more closely approximates reality, i.e. laser-based estimates of D tend to be closer to actual value than does laser-based estimates of A. The tendency of laser-based A and D to underestimate reality is compounded when both A_{est} and D_{est} are used to estimate leaf area index as found in the third level of comparison. Fig. 9 shows that when both laser-based variables are used, the constant of proportionality further reduces to 0.77, along with increase in variability of estimates relative to observation indicated by R^2 of 0.76.

It is natural for the coefficient of determination to deteriorate with increasing involvement of laser-based factors in the estimates of leaf area density and leaf area index. On the other hand, the reason for the consistent trend of underestimation of leaf area density and leaf area index is not very clear. One possible cause is random fluctuation in our data set, which just happened to have worked in the way it did. Another possible cause may be the discrepancy between theory and reality that the laser beams may have been blocked by leaf clusters rather than by individual leaves as postulated in the theoretical derivation. At this stage of analysis, however, we are neither very sure if this is actually the case nor ready to give more exact explanation for the underestimation.

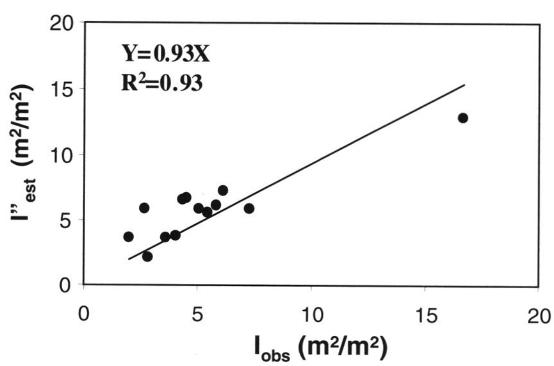

Fig. 8. Comparison of observed leaf area index (I_{obs}) with leaf area index estimated as product of observed leaf area density (A_{obs}) and estimated mean canopy depth (D_{est})

In spite of these shortcomings, it can be concluded that the estimates of leaf area density and leaf area index from airborne laser altimetry are reasonably good, especially in view of the fact that the airborne laser altimetry can cover several hundred kilometers in just a matter of a day.

The above results suggest the potential usefulness of our proposed theory in applying laser altimetry in estimating leaf area and leaf area index in boreal forest canopies. Airborne laser altimetry sensors that capture reflections for the whole vertical range of forest canopy within a single footprint are increasingly being used to study other measures of forest canopy structure than canopy heights (Blair and Hofton, 1999; Blair *et al.*, 1999, Lefsky *et al.*, 1997; Means *et al.*, 1999). On the other hand, the use of sensors that capture only the first return in each footprint is generally confined to measurement of vegetation height (e.g. Magnussen and Boudewyn, 1998; Nilson, 1996) or height along with height-related variables as stand stocking and biomass (e.g. Naesset, 1997; Nelson *et al.*, 1988). However, our results suggest that by applying mean free path theory, first-return laser altimetry data can effectively be used to estimate leaf area density and leaf area index over boreal forest canopies. To our knowledge, this is the first attempt of applying mean free path to estimate LAI in forest canopies using first-retun laser altimetry data and our results should reinforce current efforts to apply laser altimetry to measure LAI over extensive areas.

CONCLUSION

Our results verified the theory that the unobstructed sight (free path) through the foliage layer of boreal forest canopies depended on the density of foliage and that leaf area density was inversely proportional to the mean free path, making it possible to estimate the former from the latter. We also found it possible to estimate leaf area index as the product of leaf area density and canopy depth-both predictable from laser altimetry data.

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Article

CROCO : Semi-automatic Image Analysis System for Crown Condition Assessment in Forest Health Monitoring

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ABSTRACT

A semi-automatic image analysis system, CROCO, was developed for assessing tree crown condition objectively and at low cost in forest health monitoring. The system is composed of a Macintosh computer, a digital camera, the commercially available software Adobe Photoshop and the public domain software NIH Image. Most of the procedures are automated by the batch processing tool of Adobe Photoshop and a set of macro programs of NIH Image, which enable us to analyze large numbers of images rapidly and at low cost. After pre-processing, the macros automatically generate a silhouette from the color image based on the between-class variance method and calculate the index DSO as a measure of crown transparency based on two fractal dimensions. The precision of the system was examined in terms of weather conditions, camera angle (CA) and overlap rate of the target crown with other trees (OR). The results suggested that CROCO can provide a consistent measure of DSO irrespective of either cloudy or sunny conditions, if photographing conditions satisfy the criteria of CA less than about 45 degrees and OR less than about 50% of crown width. CROCO may be used as a control assessment to detect and correct observer bias.

Keywords: image analysis, crown transparency, forest health monitoring, precision, NIH Image, Adobe Photoshop

INTRODUCTION

In Europe, the increasing concerns about the effects of air pollution on forests led to the establishment of an unprecedented large-scale international program for the assessment and monitoring of forest health (De Vries *et al.*, 2000). Since 1986, large numbers of individual trees, e.g. 374,634 trees distributed on 18,321 plots over 31 countries in 1999, have been assessed annually in the systematic sampling plots (Lorenz *et al.*, 2000). The key parameter is crown transparency (defoliation) of individual trees that is defined as the relative amount of needle/leaf loss or light passing through the crown in comparison to reference trees with full foliage in the vicinity. However, crown transparency is estimated visually by observers from the ground, and therefore, prone to observer error (Dobbertin *et al.*, 1997; Ferretti, 1998; Innes, 1988; Innes *et al.*, 1993; Gertner and Köhl, 1995; Ghosh *et al.*, 1995; Landmann and Bouhot-Delduc, 1995; Strand, 1996; Solberg and Strand, 1999). One of the major problems is the existence of systematic differences between countries, causing sharp changes in the crown transparency estimates at the country borders, and making it very difficult to find possible relationships between crown transparency and natural and anthropogenic stress factors (De Vries *et al.*, 2000; Klap *et al*, 2000).

Image analysis of tree crown photographs may provide more objective measures than the visually estimated crown transparency. Due to large sample sizes in the monitoring program, image analysis should be done as cheaply and automatically as possible, while maintaining a high standard of precision. However, the image analysis methods proposed previously need time-consuming manual tasks for interactive thresholding or selecting the areas to be analyzed (Lee *et al.*, 1983; Strand, 1990; McKennan, 1995; Mizoue and Masutani, 1993; 1994). Recently, Mizoue and Inoue (2001) found that the automatic thresholding algorithm proposed by Otsu (1979) can be successfully used for generating a crown silhouette image from the original color one. Moreover, I proposed a new index DSO as a measure of crown transparency, which is calculated automatically from the silhouette image as follows:

DSO= Ds - Do,

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where Ds and Do are fractal dimensions of the silhouette and outline images of a tree crown, respectively. The DSO value has a curvilinear relation to crown transparency scores of the British (Innes, 1990) and Swiss (Bosshard, 1986) standard photographs for the visual assessments, whereas Ds and Do themselves cannot necessarily specify a level of crown transparency (Mizoue, 2001). In addition, DSO has a linear relation with actual foliage biomass density and stem volume increment for *Chamaecyparis obtusa* Endl. (Mizoue and Masutani, 2002). These results suggest that DSO is useful as an objective measure of crown condition. Based on these findings, I have developed a low-cost and semi-automatic image analysis system to assess tree crown condition, namely CROCO, using two widely available image processing software packages for a Macintosh computer. One objective of this paper is to provide an overview of the procedures for CROCO.

In viewing a given crown from the ground, the crown appearance varies with several factors. In the European program, the manual for visual assessment (Eichhorn, 1998) recommended that tree crowns should be assessed from a distance of one tree length from the target tree, i.e. at an elevation angle of 45 degrees, in full daylight. However, in practice the assessments are made at various viewing angles depending on forest stand structures under various weather conditions. In addition, an entire crown cannot necessarily be seen from the ground and the visibility is often limited by neighboring trees (Ferretti, 1997). Therefore, it is important to clarify how much these factors influence the results (DSO) when the CROCO system is used. Another objective of this paper is to examine the precision of CROCO in terms of weather conditions, camera angles and overlap rate with other trees.

THE SYSTEM

The system comprises a Macintosh computer, a digital camera, the commercially available software Adobe Photoshop (version 4.0J, Adobe Systems) and the public domain software NIH Image developed at the US National Institute of Health and available on the Internet at http://rsb.info.nih.gov/nih-image/index.html (Rasband and Bright, 1995). The image processing involves 4 steps: 1) image acquisition, 2) pre-processing, 3) thresholding and 4) calculation of DSO (Fig. 1).

Image Acquisition

In this study, a high-resolution digital camera (DS-505A, Fujix) equipped with an auto focus lens (AF Zoom-Nikkor 35-135mm f/3.4-4.5, Nikon) was used. The camera can be equipped with a variety of Nikon interchangeable F-mount lenses. Images are captured in 24-bit color by a charge-coupled device (CCD) with 1200 rows and 1500 columns and recorded directly to an image memory card in JPEG compression format. The card (HG-15, Fujix) can store up to 84 compressed images.

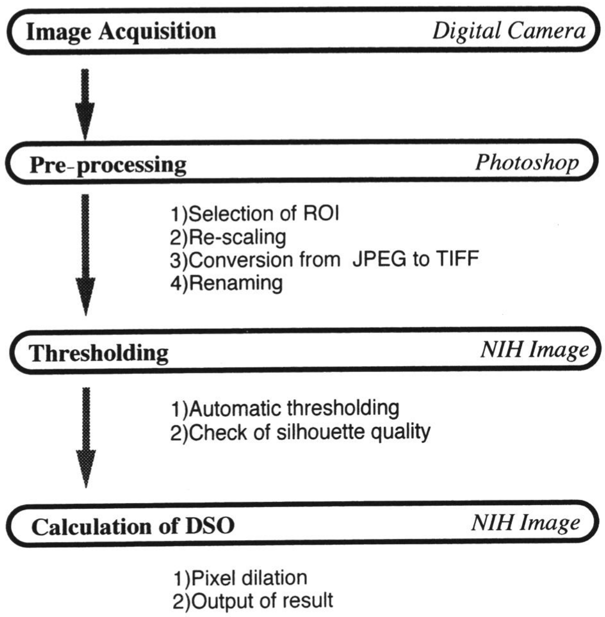

Fig. 1 Flowchart for CROCO system

Images are saved to a computer immediately by inserting the card into the card slot of the computer and dragging them to the hard-disk. Of course, normal film cameras and scanning devices for films or prints can also be used if a digital camera is not available, but they would be much less cost-effective for analyzing large numbers of samples.

Pre-processing

Adobe Photoshop is used for pre-processing of the original color images. First, a rectangular region of interest (ROI), where the crown of interest is enclosed but the parts overlapping the neighboring trees are excluded, is selected using the mouse (Fig. 2a), and the region other than the ROI is cropped away (Fig. 2b). To facilitate the subsequent processing, the image is re-scaled so that the larger side of the rectangle is 500 pixels. If there are other objects such as branch tips of neighboring trees within ROI, those parts are erased using the mouse (Fig. 2c). Then, the image file is converted from JPEG to TIFF format, since NIH Image used in the subsequent steps cannot deal with JPEG images. The re-scaling and conversion of file format referred to above are performed automatically for a series of images in a folder, using the batch-processing tool of Adobe Photoshop. Last, the file names of a series of images are changed so that these are composed of a common prefix and a suffix of a numerical sequence, such as 'photo1', 'photo2', 'photo3' etc, since such file names are required for the batch processing in the following steps.

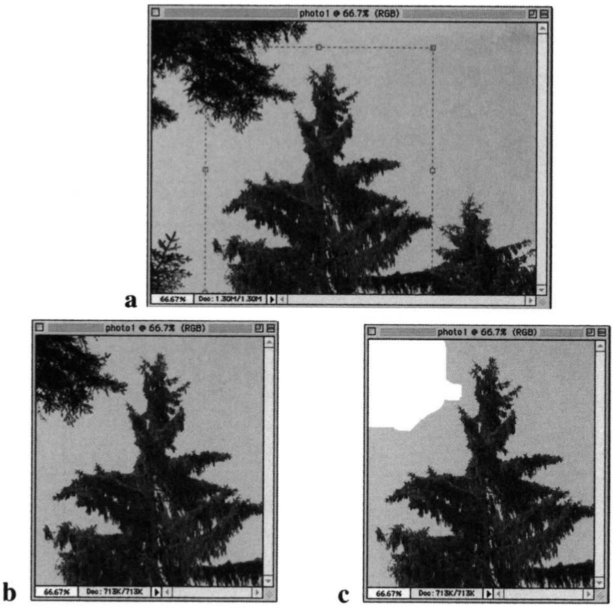

Fig. 2 Pre-processing of image using Photoshop
Note: a: selecting a region of interest (ROI); b: cropping away areas other than ROI; c: erasing other objects.

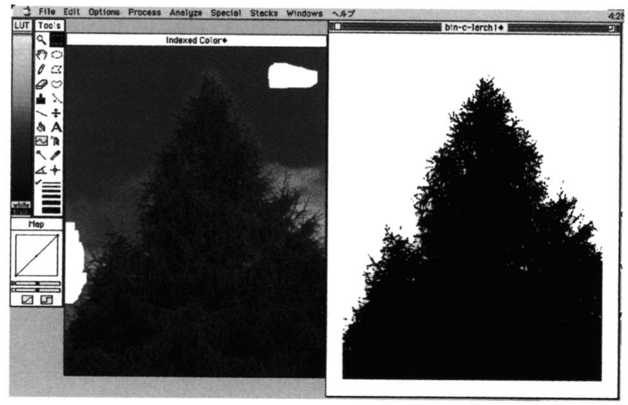

Fig. 3 Example of the macro CHECK.
Note: The crown image is Japanese larch (*Larix Kaempferi* CARR.) with 5% crown transparency in the British standard photographs (INNES, 1990 with permission)

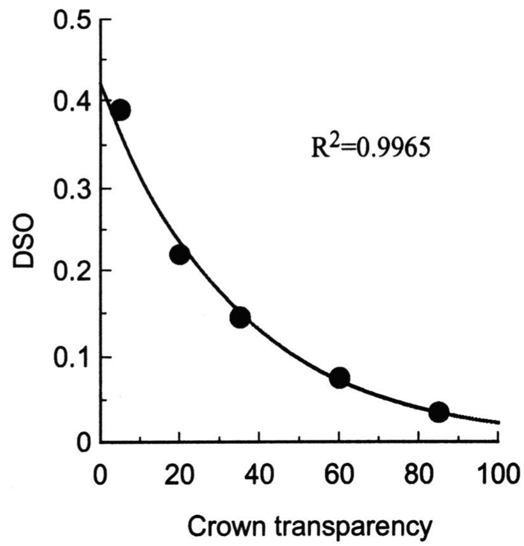

Fig. 4 An example of the relation between DSO and crown transparency obtained from the British standard photographs for Norway spruce (INNES, 1990)

Thresholding

The automatic thresholding algorithm based on the between-class variance (OTSU, 1979) can be applied to the blue-filtered grey images of tree crowns (MIZOUE and INOUE, 2001). Using the Pascal-like macro language of NIH Image, I have developed a macro 'THRESHOLD', which subsequently implements the automatic thresholding for a series of color images. THRESHOLD first displays dialog boxes. Once we input the common file name and the total number of image files in a folder, the silhouettes are generated from the original color images automatically. Since automatic thresholding may occasionally produce obviously bad silhouettes when foliage is brightly reflective (MIZOUE and INOUE, 2001), a macro 'CHECK' was developed to check the quality of the silhouettes generated by THRESHOLD. CHECK also begins with the dialog boxes where the common file name and the total number of image files are inputted, and then both the original color image and the generated silhouette are displayed on the monitor simultaneously (Fig. 3). If the silhouette is clearly bad, the user should click the mouse while keeping the 'shift' key down, and then its file name is automatically recorded in a text file. On the other hand, if the silhouette is appropriate, the user should just click the mouse. Once the mouse is clicked, the next image is automatically displayed and therefore this process can be easily repeated for a series of images. If clearly inadequate silhouettes are detected, we have to apply interactive thresholding using the look-up table tool of NIH Image (MIZOUE and INOUE, 2001) or modify the original color images manually by changing contrast or painting and then implement THRESHOLD and CHECK again.

Calculation of DSO

A macro 'CALCULATE' was developed to automatically calculate the index DSO as a measure of crown transparency from the silhouette generated by THRESHOLD. Once the user enters the name and number of files, CALCULATE subsequently processes a series of the silhouette images and records the resulting DSO values in a text file. DSO is calculated from two fractal dimensions (MANDELBROT, 1983), Ds for the silhouette and Do for the outline (DSO = Ds - Do), estimated by the pixel dilation method (MIZOUE, 2001). Fig.4

shows a typical example of the relation between DSO and crown transparency (CT) for Norway spruce (*Picea abies* (L.) KARST.) in the British standard photographs for visual assessment (INNES, 1990), indicating that DSO decreases exponentially with increasing CT, with DSO being close to 0 at CT=100 (MIZOUE, 2001).

PRECISION OF THE SYSTEM

Weather Conditions

To examine the effects of weather conditions on DSO, crown photographs of 21 trees including 9 species in the Hakozaki campus of Kyushu University, Fukuoka, Japan (HKU) and 24 trees including 6 species around the Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland (SFI) were taken under still, cloudy (28 May 1998 in the HKU, 2 August 1999 around the SFI) and sunny (31 May 1998 in the HKU, 15 August 1999 around the SFI) conditions, using the digital camera (Table 1). Fig. 5 shows the DSO values for the two sky conditions. There was a strong correlation between them ($r=0.991$, $p<0.0001$) and the mean deviation of DSO under cloudy conditions from one under sunny conditions was only slight (-0.014) although the difference was significant ($p<0.0001$).

HANISH and KILZ (1990) showed photographs where the crowns looked more transparent under cloudy or backlight conditions than under sunny conditions or when viewed from the same direction of the sun's ray. INNES (1988) indicated that in darker conditions, one tended to underestimate crown transparency. On the other hand, the results of this study

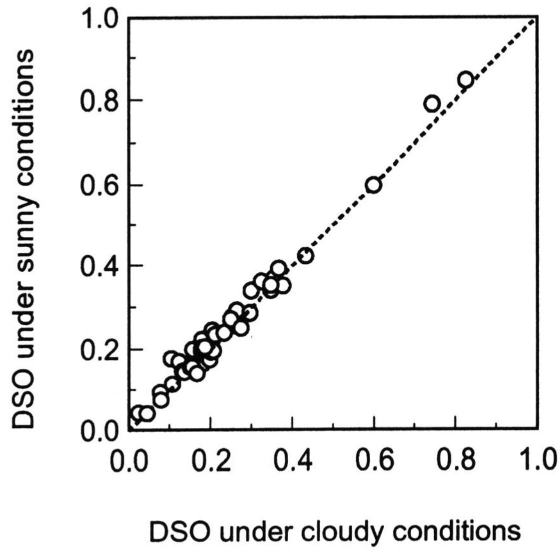

Fig. 5 Comparison of DSO between cloudy and sunny conditions
Note: The broken line indicates 1:1.

Table 1 Sample trees for examining the effect of weather conditions, camera angle and overlap rate

Species	Weather conditions		Camera angle		Overlap rate
	Sample size	Place	Sample size	Place	Sample size
Picea abies (L.) KARST.	11	SFI	4	BAS	28
Fagus sylvatica L.	5	SFI	3	BAS	4
Larix decidua MILL.	3	SFI	1	BAS	1
Quercus spp.	3	SFI			2
Betula spp.	1	SFI			3
Pinus sylvestris L.	1	SFI			3
Abies alba MILL.			3	BAS	4
Acer pseudoplatanus L.			1	BAS	3
Populus spp.					3
Pseudotsuga menziesii FRANCO					2
Larix kaempferi CARR.					1
Picea sitchensis (BONG.) CARR.					1
Pinus Thunbergii PARL.	9	HKU	2	HKU	
Ailanthus altissima (DESF.) RWINGLE	3	HKU			
Ginkgo biloba L.	3	HKU			
Cedrus deodara LOUD.	1	HKU			
Cinnamonum Camphora (LINN.) SIEB.	1	HKU	1	HKU	
Metasequoia glyptostroboides HU et CHENG	1	HKU	1	HKU	
Robinia Pseudo-acacia L.	1	HKU			
Juniperus chinensis var.*procumbens* (SIEB.) ENDL.	1	HKU			
Araucaria cunninghamii SWEET	1	HKU	2	HKU	
Total	45		18		55

Note: HKU, the Hakozaki campus of Kyushu University,Fukuoka,Japan; SFI, Swiss Federal Institute for Forest,Snow and Landscape Research, Birmensdorf, Switzerland; BAS, Balsthal, Canton of Aargau, Switzerland.

showed that there were not large differences in DSO between cloudy and sunny conditions (Fig. 5). However, it should be noted that the most important factor for successful automatic thresholding is high contrast between objects and background (WEAVER and AU, 1997). Thus extremely bad lighting conditions, such as under very dark sky or with direct sun rays entering into the camera lens, should be avoided.

Camera Angle

Each of 6 trees including 4 species in the HKU and 12 trees including 5 species around Balsthal, Canton of Aargau, Switzerland (BAS) was photographed with different camera angles (CA) on 3 November 1998 and 29 June 1999 respectively to examine the effects of camera angles (Table 1). CA was measured as a vertical angle from horizon to tree tip (Fig. 6). Fig. 7 shows that DSO generally tended to increase with increasing CA. This indicates that the crowns appear denser as viewed from the position closer to the trees because larger DSO means lower crown transparency (Fig. 4). However, at CA less than about 45 degrees, the DSO values were relatively constant for all sample trees including various species (Fig. 7).

HANISH and KILZ (1990) also showed crown photographs taken at different camera angles (CA) and indicated that the crown appeared denser as CA increased. They indicated that the best elevation angle for the visual assessment was about 30 to 45 degrees. Similarly, in applying CROCO, crown photographs should be taken with CA less than about 45 degrees since DSO values were relatively constant at CA less than 45 degrees (Fig. 7).

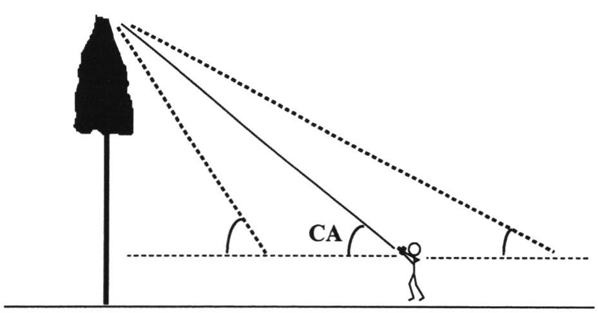

Fig. 6 Photographing the crown at different camera angles (CA)

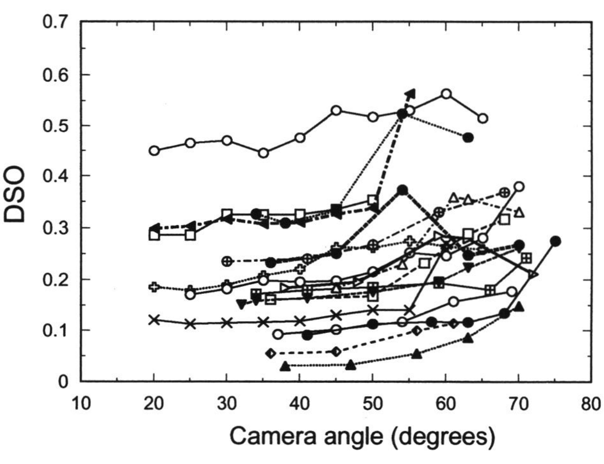

Fig. 7 Effect of camera angles (CA) on DSO

Overlap Rate

The crown photographed from the ground often overlaps other trees on one side or both sides. In the system presented in this study, the region of interest (ROI) has to be selected so as to exclude the overlapping portions as shown in Fig. 8 and the portions other than the ROI have to be cropped away, since it is impossible to extract the silhouette of only the target crown from the overlapping portions. To examine the effects of overlap rate on DSO, 55 crown images including 12 species without other overlapping trees were used and the ROI was reduced experimentally from the lateral edge(s). The sample images were selected from the slides taken in Switzerland and the British (INNES, 1990) and Swiss (BOSSHARD, 1986) standard photographs (Table 1).

In further detail, the outer portions of the silhouette were cropped away perpendicularly at the points apart from the crown edge(s) by varying overlap rates (OR) of the crown radius, with OR being changed to be 10, 25, 50, 75 and 100% (Fig. 9). Two tests were performed; one reducing ROI on only one side of the crown (OR = 10, 25, 50, 75, 100) and averaging the resulting DSO values obtained from two (right and left) one-side reductions (the one-side test), and another reducing ROI on both sides simultaneously (OR = 10, 25, 50, 75) (the both-side test).

Fig. 10 shows mean deviation in DSO and its 95% confidence interval for the images with increased overlap rate (DSO_i) from DSO for the entire crown images without overlap (DSO_n). The statistical test indicates that DSO_i was significantly ($P<0.05$) overestimated as compared to DSO_n except for 10%

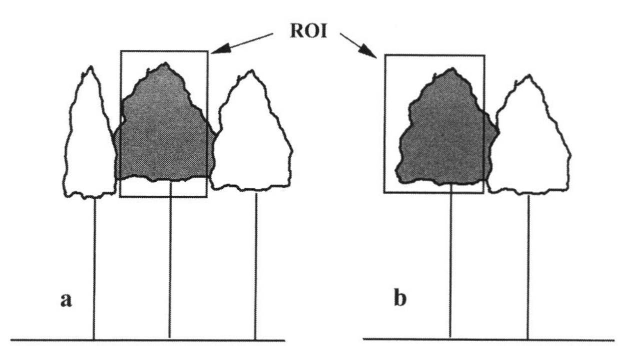

Fig. 8 Crown overlapping with other trees on both sides (a), and one side (b)
Note: The ROI has to be selected so as to exclude the overlapping portions.

OR for both of the two tests and 25% OR for the one-side test. The mean deviation increased with increasing OR, and the deviation was smaller for one-side than for both-side overlap (Fig. 10). Fig. 11 shows the relationships between DSO_i and DSO_n for the 25, 50 and 75% OR, indicating that there were strong linear relations between them. The coefficients of determination were more than 0.97 except the 75% OR on the both-sides test (Table 2).

This overestimation in the DSO due to excluding the outer portions can be explained by the general impression that outer parts of the crown silhouette projected horizontally to the two dimensional plane appear more transparent than the inner parts. This is because the inner parts of the crown silhouette are composed of more foliage and branches than the outer parts. The strong linear relations between DSO_i and DSO_n shown in Fig. 11 suggest that the overestimation can be accurately corrected using the regression lines shown in Table 2. However, when the overlap rate is 75% on both sides of the crown, the correction would not be expected to be accurate due to its relatively low coefficient of determination (Table. 2). Therefore, we should not apply CROCO to sample trees whose overlap rate with other trees is more than 50% of the crown width.

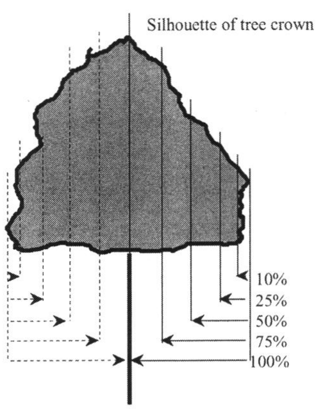

Fig. 9 Experimental method to change the overlap rate.

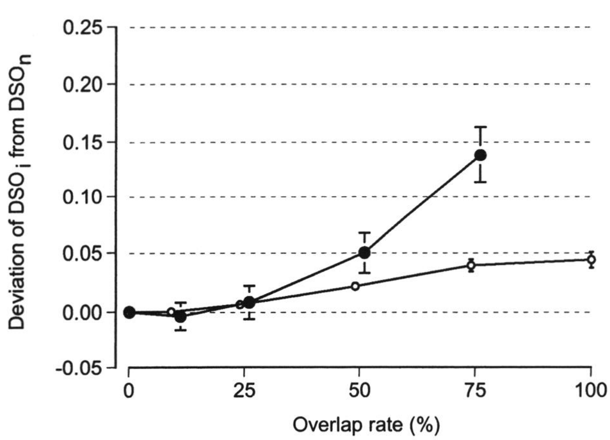

Fig. 10 Mean deviation and 95% confidence intervals of deviation in DSO for the images with increased overlap rate (DSO_i) from that for the entire crown images (no overlap) (DSO_n)

Note: Closed and open circles indicate the both-side and one-side tests, respectively.

CONCLUSIONS

This paper first presented an overview of the procedures for the CROCO system developed for assessing crown condition objectively and cost-effectively in forest health monitoring. One advantage of CROCO is that it uses the public domain software NIH Image and the widely-used Adobe Photoshop for personal computers. Although NIH Image was designed for only the Macintosh platform, a Windows version of NIH Image, called Scion Image for Windows, is freely available from http://www.scioncorp.com/. Adobe Photoshop is also available on Windows. Therefore, the system can be built readily without requiring any specialized equipment. Another advantage of the system is that most of the image processing is automated using the batch processing tool of

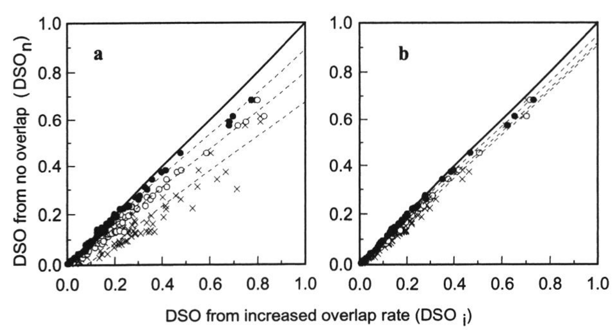

Fig. 11 Relationship between DSO from increased overlap rate (DSO_i) and one from no overlap (DSO_n) for the both-side test (a), and the one-side test (b)

Note: Closed circles, open circles and crosses indicate 25, 50 and 75% overlap rate of crown radius, respectively.

Table 2 Parameters of regression lines of DSO from the entire crown (DSO_n) against one from increased overlap rate (DSO_i) [DSO_n= a DSO_i+b]

Overlap Rate (%)	Parameter a	Parameter b	R^2
both side			
25	0.8828	0.0088	0.9947
50	0.8091	-0.0110	0.9878
75	0.7334	-0.0583	0.8883
one side			
25	0.9465	0.0035	0.9984
50	0.9256	-0.0070	0.9968
75	0.9344	-0.0255	0.9876
100	0.9770	-0.0039	0.9718

Photoshop and the macro language of NIH Image, which enable us to analyze large number of images rapidly and at low cost.

Second, the precision of the system was examined in terms of weather conditions, camera angle (CA) and overlap rate (OR) with other trees. The system produces consistent results between sunny and cloudy conditions. This indicates its practical usefulness, since it is impossible to take a photograph of a given crown under a specific sky condition in a survey of large numbers of sample trees. On the other hand, the DSO values cannot be estimated precisely unless the visibility of the target crown from the ground satisfies the levels of CA less than about 45 degrees and OR less than about 50% of crown width. This suggests that CROCO cannot be used for all sample trees, since the systematic sample plots adopted in the European programs include trees with poor visibility, whereas field observers may be able to recognize or imagine the crown transparency of the target tree from the overlapping portions with other crowns, from the small non-overlapping parts of the crown, or with steep viewing angles (FERRETTI, 1997). In addition, there may be some factors affecting the precision of CROCO other than weather conditions, camera angle and overlap rate. Further research will be needed to test the effects of other factors such as camera types, image-file formats and camera azimuth.

A possible way to use CROCO is as a control assessment to detect and correct observer bias among different field teams. The European monitoring program recommends repeated assessment by control teams for parts of sample trees assigned to field teams (EICHORN, 1998). This control assessment allows the quantification of observer error among different field teams and the correction of observer bias if the control teams are unbiased (GHOSH and INNES, 1995). However, the problem is that the control observers themselves cannot necessarily provide unbiased estimates (GHOSH *et al*, 1995). On the other hand, combining field observation and CROCO estimates for sub-sample trees with good visibility (CA less than about 45 degrees and OR less than about 50% of crown width) may be a more reliable method to correct observer bias, since in this case CROCO can be expected to estimate the DSO value precisely and reproducibly as an objective measure of crown transparency.

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Article

Error in Stem Volume Estimation using Tree Height and Several Upper-Stem Diameters of Standing Tree Measured with a Spiegel Relascope and Wheeler Pentaprism Caliper - In a 29-year-old Stand of Japanese Cypress (*Chamaecyparis obtusa* ENDL.) -

Yoshiaki WAGUCHI*

ABSTRACT

This paper describes the error in stem volume when estimated using standing tree height (h_s) measured with a wide-scale Spiegel Relascope and upper-stem diameters at i/10 of h_s from the ground level ($d_{w0.ihs}$, i = 3, 5, 7) measured with a Wheeler Pentaprism Caliper. To measure tree height and upper-stem diameter, 15 sample trees in a 29-year-old stand of Japanese cypress (*Chamaecyparis obtusa* Endl.) were selected. The mean, standard deviation and range (minimum ~ maximum) of error in h_s were -0.33m, 0.31m and -0.8~0.5m, respectively. The means, standard deviations and ranges (minimum ~ maximum) of error in $d_{w0.ihs}$ (i = 3, 5, 7) were 0.31cm, 0.57cm and -0.3~1.3cm for $d_{w0.3hs}$, 0.37cm, 0.69cm and -0.9~1.2cm for $d_{w0.5hs}$, -0.34cm, 0.79cm and -1.6~1.1cm for $d_{w0.7hs}$, respectively. Such errors were common or slightly worse in both tree height and upper-stem diameter measurements. The mean, standard deviation and range (minimum ~ maximum) of error in stem volume estimated using hs and $d_{w0.ihs}$ (i = 1,3, 5, 7,9) were 0.0023m^3, 0.0084m^3 and -0.0097~0.0201m^3, respectively.

Keywords: error, stem volume, tree height, upper-stem diameter, standing tree

INTRODUCTION

The stem volume of a standing tree can be estimated by measuring its height and several upper-stem diameters. However, accurate measurements of tree height and upper-stem diameters are difficult to obtain, and often include significant error, causing error in estimates of stem volume. Although a number of studies have reported on the accuracy of standing tree height and upper-stem diameter measurements (WHEELER, 1962; SUGAHARA, 1972; RENNIE, 1979; YOSHIDA, 1991; HIRATA *et al.*, 1992; CLARK *et al.*, 2000), none have yet shown the degree of error in estimates of stem volume.

This paper describes the error in stem volume when estimated using standing tree height measured with a wide-scale Spiegel Relascope and several upper-stem diameters measured with a Wheeler Pentaprism Caliper.

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MATERIALS AND METHODS

This study was conducted in a 29-year-old stand of Japanese cypress (*Chamaecyparis obtusa* Endl.) at Murou Village, Nara Prefecture. The stand area and tree density were 0.47ha and 2,576 trees/ha, respectively. The height and stem diameter of 15 randomly selected sample trees were measured. Tree height (h_s) was measured with a wide-scale Spiegel Relascope using the percentage scale. A 5-meter pole was placed upright against the tree stem for measurement. Diameter at breast height (dbh) and diameter at 1/10 of hs from the ground level ($d_{0.1hs}$) were measured with a caliper, and upper-stem diameter at i/10 of hs from the ground level ($d_{w0.ihs}$, i = 3, 5, 7) was measured with a Wheeler Pentaprism Caliper. The measurement position for each diameter was determined with a graduated pole. Then each sample tree was felled, and the actual tree height (h) and upper-stem diameter at i/10 of h from the ground level ($d_{0.ih}$, i = 1, 3, 5, 7) were measured with a tape and the caliper, respectively. The actual upper-stem diameter at i/10 of h_s from the ground level ($d_{0.ihs}$, i

= 3, 5, 7) was also measured with the caliper.

The tree height measurement error (eh) was calculated as h_s - h. The upper-stem diameter measurement error excluding the tree height measurement error ($ed_{0.ihs}$) was calculated as $d_{w0.ihs}$ - $d_{0.ihs}$ (i = 3, 5, 7); the measurement error including the tree height measurement error ($ed_{0.ih}$) was calculated as $d_{w0.ihs}$ - $d_{0.ih}$ (i = 3, 5, 7). The standing tree stem volume (v_e) was estimated by sectional measurement method using HUBER' s formula (OSUMI, 1987), h_s, and $d_{w0.ihs}$ (i = 1, 3, 5, 7, 9). Since $d_{w0.1hs}$ was not measured with the Wheeler Pentaprism Caliper, $d_{w0.1hs}$ was treated as $d_{0.1hs}$. The same formula was used to calculate actual stem volume (v) using h and $d_{0.ih}$ (i = 1, 3, 5, 7, 9). The diameter at 9/10 of h_s or h from the ground level ($d_{w0.9hs}$ or $d_{0.9h}$) was estimated assuming a cone from the tree apex to 7/10 of h_s or h from the ground level. The stem volume estimation error (ev) was calculated as v_e - v.

RESULTS AND DISCUSSION

Tree Height Measurement Error

The means, standard deviations and ranges (minimum ~ maximum) of dbh and h in this study were 13.79cm, 1.63cm and 11.1~17.1cm for dbh, 13.71m, 1.20m and 11.3~15.7m for h, respectively, and moreover, those of eh in this study were -0.33 m, 0.31m and 0.8~0.5m, respectively.

YOSHIDA (1991) investigated error in tree height measurement with a Spiegel Relascope in 13 stands of Japanese cedar (*Cryptomeria japonica* D. DON) at mean tree heights between 10.0m and 23.2m. The mean and variance of the measurement errors were -0.12m and 0.805m^2, respectively. TAKAHASHI *et al.* (1997) measured heights of 20 trees ranging from 15m to 20m with a Blume-Leiss altimeter in stands of Japanese cedar that was 31 to 35 years old. The mean and standard deviation of the differences between actual heights and Blume-Leiss altimeter measurements were -0.33m and 0.52 m, respectively. Furthermore, HIRATA *et al.* (1992) measured tree heights with a measurement stick and a tape in an evergreen broad-leaved forest. In trees over 11m high, the mean and variance of the differences between tape measurements and stick measurements were 0.20m and 0.283 m^2, respectively.

The accuracy of our study is comparable to that of these other studies. Therefore, the present error is common in tree height measurements. In addition, this result indicates that different measurement instruments have similar measurement accuracy.

Upper-stem Diameter Measurement Error

The means, standard deviations and ranges (minimum ~ maximum) of $d_{0.ih}$ (i = 1, 3, 5, 7) in this study were 14.07cm, 1.57cm and 11.8~17.6cm for $d_{0.1h}$, 12.53cm, 1.29cm and 10.4~14.9cm for $d_{0.3h}$, 10.45cm, 1.11cm and 8.8~12.5cm for $d_{0.5h}$, 7.44cm, 0.90cm and 5.6~8.8cm for $d_{0.7h}$, respectively. Table 1 shows the means, standard deviations, and minimum and maximum values of $ed_{0.ihs}$ and $ed_{0.ih}$ (i = 3, 5, 7) in this study.

Table 1 Means, standard deviations, and minimum and maximum values of upper-stem diameter measurement errors

	i		
	3	5	7
$ed_{0.ihs}$(cm)			
mean	0.31	0.37	-0.34
standard deviation	0.57	0.69	0.79
minimum	-0.3	-0.9	-1.6
maximum	1.3	1.2	1.1
$ed_{0.ih}$(cm)			
mean	0.45	0.53	0.01
standard deviation	0.57	0.75	0.84
minimum	-0.2	-0.9	-1.4
maximum	1.5	1.4	1.3

SUGAHARA (1972) measured stem dbhs ranging from about 10cm to 40cm with a caliper and a Wheeler Pentaprism Caliper in a natural stand of Japanese red pine (*Pinus densiflora* SIEB. et ZUCC.). The mean and standard deviation of the differences between caliper measurements and Wheeler Pentaprism Caliper measurements were -0.20cm and 0.96cm, respectively. KAJIHARA (1984) measured stem diameters ranging from 10cm to 20cm at 1/10 of tree height from the ground level with a Wheeler Pentaprism Caliper in two Japanese cedar stands. The mean and standard deviation of the differences between actual diameters and Wheeler Pentaprism Caliper measurements in one stand were -0.09cm and 0.44cm, and those in the other stand were -0.15cm and 0.47cm, respectively. Furthermore, WHEELER (1962) measured upper-stem diameters at two heights (1.4m and 5.3m) of 10 trees with a Wheeler Pentaprism Caliper. Measurements were within ±1.3cm of wooden caliper measurements.

The values of $ed_{0.ihs}$ in this study are slightly worse than the accuracy of diameter measurement obtained by both SUGAHARA (1972) and KAJIHARA (1984), but generally similar to that obtained by WHEELER (1962). Accordingly, these results indicate that the present error is commonly equal to or slightly worse in measurements of upper-stem diameter made using a Wheeler Pentaprism Caliper.

The differences between $ed_{0.ihs}$ and $ed_{0.ih}$ are sufficiently small because the differences (eh) between h_s and h are also small.

Stem Volume Estimation Error

The mean, standard deviation and range (minimum ~ maximum) of v in this study were 0.1158m^3, 0.0338m^3 and 0.0650~0.1808m^3, respectively, and moreover, those of ev in this study were 0.0023m^3, 0.0084m^3 and -0.0097~0.0201m^3, respectively.

To examine the accuracy, ev was compared with the estimation error of YAMAMOTO's volume formula (OSUMI, 1987) as

$$V = a D^b H^c$$

where V, D, and H are stem volume, dbh, and tree height, respectively, and a, b, and c are parameters. These parameters were estimated using the least squares method and v, dbh, h of all sample trees. The values of a, b, and c were 1.100*10^{-4}, 1.877, and 0.768, respectively (R^2 = 0.961, P<0.001). The stem volume of every sample tree (v_f) was estimated using the formula, dbh, and h_s. To calculate the estimation error of the volume formula (ev_f), v was subtracted from v_f.

The mean, standard deviation and range (minimum ~ maximum) of ev_f were -0.0020m^3, 0.0069m^3 and -0.0141~0.0102 m^3, respectively. The mean and range of ev had a slightly positive bias, while those of ev_f had a slightly negative bias. However, the absolute mean and the standard deviation of ev were similar to those of ev_f. Values of ev_f might be small as the formula is based on the actual values of all sample trees. Consequently, ev values might also be considered small.

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