An analysis of the relationships between tree growth and crown information derived from airborne LiDAR data

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Abstract

The objective of our study was to estimate the relationship between crown information and individual tree growth using airborne light detection and ranging (LiDAR) data. We established two study plots in the University of Tokyo Forest in Chiba for the analysis of canopy information. We conducted a linear regression analysis between the crown lengths and widths obtained from ground surveys and those obtained from airborne LiDAR data. The crown lengths and crown widths obtained from airborne LiDAR data were correlated with those obtained from ground surveys (R^2=0.46, R^2=0.56). Next, we compared the crown surface area derived from airborne LiDAR data to tree growth observed in the study plot. The crown surface areas obtained from airborne LiDAR data were highly correlated with tree growth obtained from ground surveys (R^2=0.95). Thus, airborne LiDAR accurately measured individual tree growth. We also compared tree growth to the proportion of crown surface area to stem surface area calculated from a stem curve based on a field survey. An exponential regression between tree growth and the proportion of crown surface area to stem surface area was carried out, resulting in a coefficient of determination of 0.74.

Keywords: airborne LiDAR, crown, even-aged stands, stem, tree growth

1. Introduction

A forest grows due to the photosynthesis of its trees (Arain and Restrepo-Coupe 2005). Forest growth decreases as the respiration of trees increases (Bosc *et al*. 2003). This suggests that one can predict forest growth based on the balance between the photosynthesis and respiration of trees.

The main parts of a tree involved in photosynthesis and respiration are the canopy and wood including the stems, branches, and roots, respectively. To estimate forest resources, one can collect direct, ground-based data on woodiness, such as the diameter at breast height (DBH) and the number of stems. Various growth models have been developed based on stem information, including the tree height and DBH (Castedo-Dorado *et al*. 2007; Qin *et al*. 2007). However, it is difficult to measure a crown structure that is high and complex. It is even more difficult to measure crown information over a wide area. Thus, no growth models that include crown information have been developed for Japanese mountainous areas at the regional scale.

Previous studies have suggested the utlility of remotely sensed data for measuring forest resources such as stand age (Farid *et al*. 2006), tree height (Hirata 2005; Takahashi *et al*. 2005; Næsset and Bjerknes 2001), and forest biomass (Labrecque *et al*. 2006). In addition, airborne light detection and ranging (LiDAR) data enable us to obtain a wide range of canopy information, including leaf area (Roberts *et al*. 2005), canopy fuel (Andersen *et al.* 2005), and canopy structure (Coops *et al*. 2007).

As mentioned above, it is important to analyze the relationship between woody information and canopy information in developing a growth model that considers the balance of respiration and photosynthesis. However, few previous studies have analyzed the relationship of crown information estimated from LiDAR and woody information measured by a ground survey in Japan.

The objective of our study was to model tree growth as a function of the crown surface area derived from airborne LiDAR data. First, we examined the accuracy of crown information derived from airborne LiDAR for calculating the crown surface area. We then conducted a linear regression analysis of the crown lengths and widths obtained from ground surveys and those obtained from airborne LiDAR data. Next, we compared the tree growth observed in the study plot to the crown surface area derived from airborne LiDAR data and the proportion of crown surface area to stem surface area calculated from a stem curve based on a field survey. Finally, considering the balance of tree photosynthesis and respiration for the development of the growth model, we discuss the predicted tree growth using crown information derived from airborne LiDAR data.

2. Methods

2.1 Study area

The University of Tokyo Forest in Chiba is located in the cities of Kamogawa and Kimitsu, Chiba Prefecture, Japan, between 50 and 370 m above sea level. The terrain is undulating with steep slopes, and most soils are of the brown forest type. The forest is located in a warm-temperate zone, with an average annual temperature of 14°C. The average rainfall is 2182 mm year^{-1}. The total forest area is 2216 ha, 824 ha (37%) of which comprise sugi (*Cryptomeria japonica*) and hinoki (*Chamaecyparis obtusa*) stands, 949 ha (43%) are natural hardwood forest, and 387 ha (17%) are natural conifer forest. The remaining 57 ha (3%) are demonstration forest. Stand age varies from approximately 10 to 100 years. Many permanent plots in sugi and hinoki stands have been established within the study site. The tree height and DBH were recorded approximately every 5 years in these permanent plots.

2.2 Data correction

2.2.1 Ground survey data

We conducted a ground survey in a 27-year-old hinoki stand to check the accuracy of crown length measurements obtained from airborne LiDAR. For ground surveys, a circular sample plot 22.6 m in diameter (0.04 ha) were established in the hinoki stand. DBH, tree height, base of the crown, crown width, and tree position were measured for all standing trees in each plot. We defined the base of the crown as the branch from which the crown continues all the way to the top (i.e., slightly higher than lowermost and solitary branches). We also measured the crown width from uphill and contralateral aspects. The tree positions were measured by differential global positioning system (DGPS) receivers (Trimble Navigation), Impulse 200 LR (Laser Technology), and MapStar System Electronic Compass Module II (Laser Technology). In calculating the observed crown length, the heights to the base of the crown were subtracted from the heights of the trees. The heights to the base of the crown and the total heights of the trees were measured using VERTEXIII (Haglöf).

The tree positions were also measured in permanent plots aged 102 years to link the stem growth data and crown information obtained from airborne LiDAR.

2.2.2 Airborne LiDAR data

The ALMAPS-G4 (Asahi Laser Mapping System), which consists of the ALTM 3100 laser scanning system produced by Optech, Canada, GPS airborne and ground receivers, and an inertia measurement unit (IMU) that measures the helicopter's roll, pitch, and heading were used to acquire airborne LiDAR data. The laser scanner system transmits laser pulses at 1064 nm (near-infrared) and receives the first and last echoes of each pulse. The elapsed time between transmittance and reception is measured to calculate the distance between the system and the measured object.

Airborne LiDAR data were acquired on 14 August 2005. The flight altitude of the helicopter above the ground was approximately 500 m, and the average flight speed was approximately 19.4 m s^{-1}. The pulse repetition frequency of airborne LiDAR was 70 kHz, and the scan frequency was 27 Hz. The maximum scan angle (off nadir) was 18°. The beam divergence was 1.2 mrad. Therefore, the footprint diameter was approximately 60 cm. The interval between footprints was about 25 cm. Both first pulse and last pulse were acquired to identify forest canopy and topography data in rugged terrain.

Data from a region of interest (ROI) 200 m wide and 1700 m long were selected for this study. A digital elevation model (DEM) and a digital surface model (DSM; Fig. 1a) for the study area were prepared from the airborne LiDAR data, with a 25 cm cell size. Data for the digital canopy model,(DCM) which delineates canopy height from the ground, were calculated by subtracting the DEM from the DSM.

2.3 Data analysis

2.3.1 Estimating the crown length and width from LiDAR data

The crown cross-sectional surface of the individual trees was estimated from LiDAR data with TNTmips ver. 6.6 (MicroImages, 2001). Using the DEM and DSM data, we estimated the crown cross-sectional surface of individual trees in each plot. The crown length and crown width of each tree were estimated from airborne LiDAR data using the TNTmips ver. 6.6 (MicroImages, 2001), software of the GIS and image-processing system. First, each tree was identified using the DEM and DSM. Tree height was obtained from the DCM showing the canopy surface height from the ground height, and was calculated by subtracting the DEM, i.e., the height above sea level, from the DSM, showing the surface of the canopy. When the plot was magnified, airborne LiDAR data could identify the crown of each individual tree as a DCM (Fig. 1b). We defined each individual tree derived from airborne LiDAR data with a tree positioning map measured by a ground survey.

Second, we estimated the crown cross-sectional surface. The crown length of each tree was estimated by subtracting the height to the base of the crown from the total tree height. We measured the height to the base of the crown on the rebound point obtained from the DSM cross-sectional surface (Nakajima *et al*. 2008; in press), because we considered the opposite side of objective tree canopy from the rebound point to be the crown of the neighboring tree (Fig. 2). The direction of the DSM cross-sectional surface was estimated from the average slope aspect derived from the DEM, because there was often more space for branch and leaf expansion on the slope side of trees.

(b)

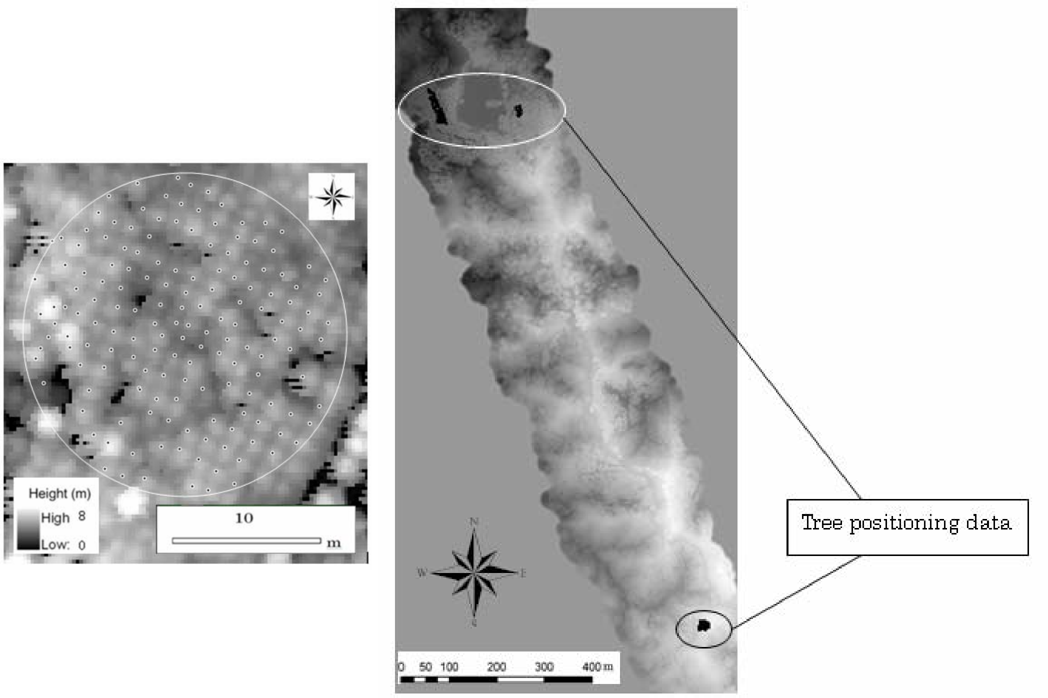

Figure 1: (a) Digital surface model and (b) digital crown model overlapped with tree positioning data

Figure 3 shows an example of a cross-sectional surface of a tree. We calculated the crown length, crown width, and width at approximately the middle point of the crown length for this figure. Third, the estimates of crown length and width from airborne LiDAR data were compared to the data measured manually on the plot. The crown lengths and widths obtained from ground surveys were regressed against the crown lengths obtained from airborne LiDAR. We then calculated the coefficient of determination. These crown information data were also used for estimating the crown surface area.

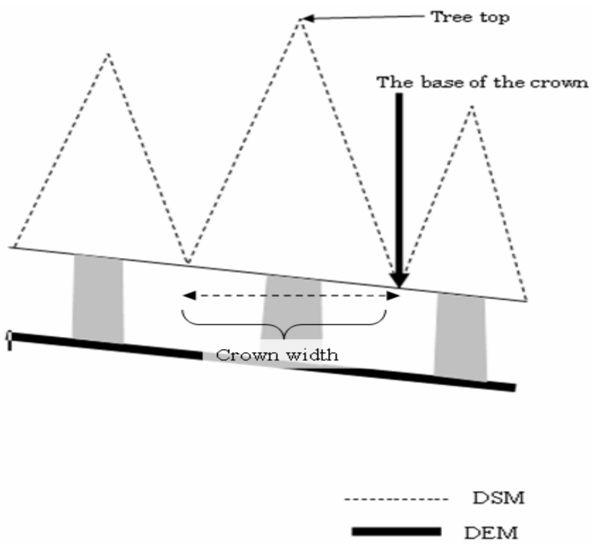

Figure 2: Position at which tree height was measured to determine the base of the crown. The base of the crown and crown width are indicated by a bold arrow and dotted arrow, respectively.

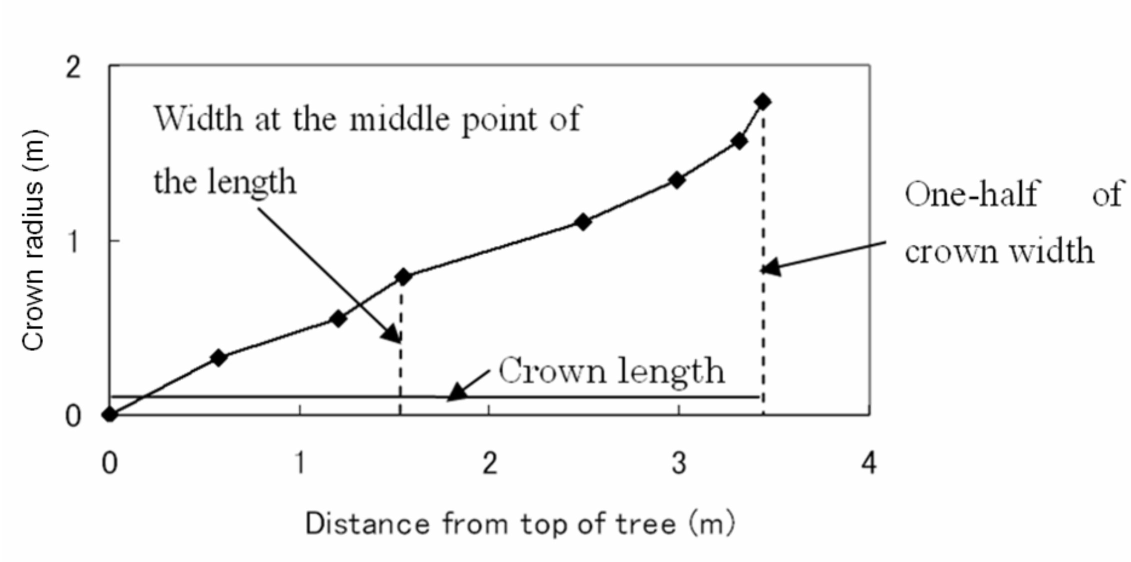

Figure 3: Example of the cross-sectional surface of a dominant tree

2.3.2 Estimation of tree growth using crown information derived from airborne LiDAR data

Finally, we obtained the relationship between the surface areas of the crown and stem using data derived from airborne LiDAR and the ground survey. In this study, we assumed that the stem surface and crown surface are the main parts of respiration and photosynthesis, respectively. This assumption is based on suggestions by previous studies that photosynthesis activity is very high on the crown surface (Kajihara 2000). Bosc *et al.* (2003) reported that the surface area of wood has a stronger relationship with respiration than with woody volume. With this assumption, we calculated the crown surface area and stem surface area and estimated the relationship of the individual tree growth and crown surface area or proportion of crown surface area to stem surface area.

2.3.2.1 Relationship between tree growth and crown surface area

In this procedure, we applied formula (1), the crown curve reported by previous studies (Kajihara 2000; Nakajima *et al.* in press), to the crown profile:

$$Y = \frac{DX}{aL + (2-a)X} \qquad (1)$$

where X: distance from the top of the tree (m)
Y: width at distance X (m)
D: crown width (m)
L: crown length (m)
a, b: parameters

The crown surface area is estimated with formula (2) showing the surface of the solid revolution of formula (1):

$$Sc = 2\pi \int_0^L Y \left\{ 1 + \left(\frac{dY}{dX} \right)^2 \right\}^{\frac{1}{2}} dX \qquad (2)$$

where S_c: crown surface area (m^2)

We calculated the crown surface area by integrating formula (2) with the Romberg quadrature and applied eight angles (45, 90, 135, 180, 225, 270, 315, and 360 degrees) of the crown around the tree top to these equations. We estimated the average value of the eight directions of crown surface area of the tree in the permanent plot. We compared the crown surface area to tree growth (m^3 $year^{-1}$) over the past 20 years calculated from the Yamamoto-Schumacher formula (Forestry Agency 1970) applied to the plots measured twice. The crown surface was regressed against the stem growth. We then calculated the coefficient of determination.

2.3.2.2 Relationship between tree growth and the proportion of crown surface area to stem surface area

We calculated the stem surface area from tree height and DBH, observed during the ground survey, and the relative taper curve (Nakajima *et al.* in press). We applied the relative taper curve estimated in the University Forest in Chiba (Nagumo and Tanaka 1981). Formula (3) is the actual taper curve:

$$Y_s = \frac{D_s \left(\frac{\alpha X}{H} + \frac{\beta X^2}{H^2} + \frac{\gamma X^3}{H^3} \right)}{\alpha \left(1 - \frac{1.3}{H} \right) + \beta \left(1 - \frac{1.3}{H} \right)^2 + \gamma \left(1 - \frac{1.3}{H} \right)^3} \qquad (3)$$

where Y_s: stem radius (m)
D_s: radius (m) at breast height (1.3 m)
H: tree height (m)
$a, ß, \gamma$: parameters

The stem surface area is estimated with formula (4) showing the surface of the solid revolution of formula (3):

$$S_s = 2\pi \int_0^H Y_s \left\{ 1 + \left(\frac{dY_s}{dX} \right)^2 \right\}^{\frac{1}{2}} dX \qquad (4)$$

where S_s: stem surface area (m^2)

We calculated the stem surface area by integrating formula (4) with the Romberg quadrature. The crown surface divided by stem surface area was regressed against the stem growth (m^3 $year^{-1}$) and was calculated as described above. We then calculated the coefficient of determination.

3. Results and discussion

3.1 Estimating the crown length and width from LiDAR data

The crown lengths and widths estimated by airborne LiDAR were plotted against those measured in the ground surveys (Fig. 4).

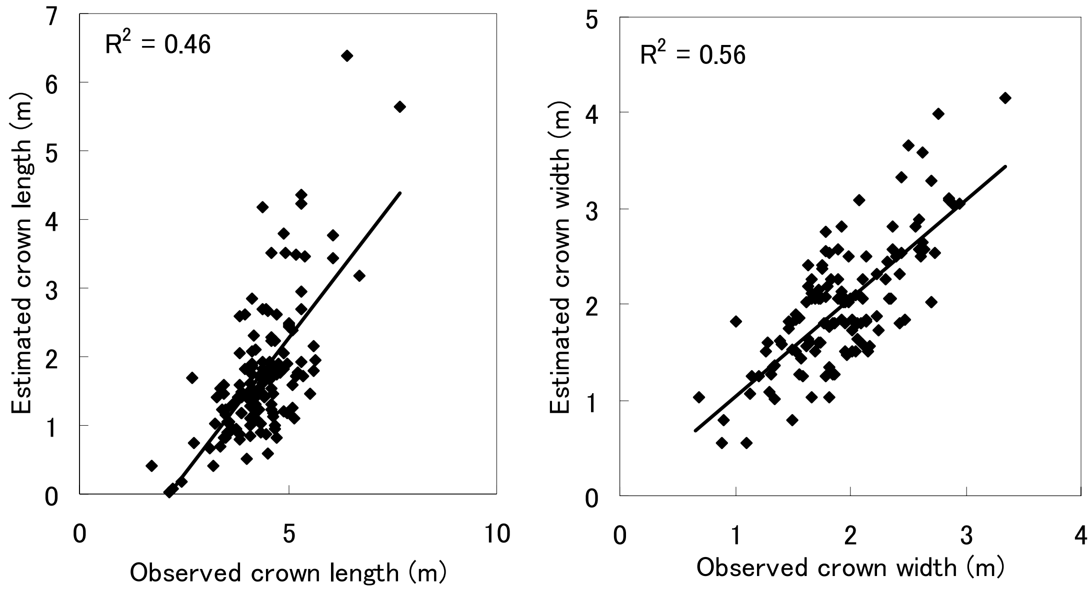

Figure 4: Crown lengths and widths estimated by airborne LiDAR

The coefficients of determination for crown length and width were 0.46 and 0.56, respectively. The first pulse of the airborne LiDAR captured the tendency of canopy size correctly because the distance between neighboring footprints was relatively narrow.

In particular, the constant and slope of the regression lines for crown length were -1.7202 and 0.7957, respectively. This result suggests the underestimation of crown length derived from airborne LiDAR data. A cause of the underestimation in this high-density sample plot (about 4000 stems ha^{-1}) could be that airborne LiDAR did not include the length of the shaded canopy. We verified the outcomes discussed above in the following way. In high-density stands, where branches shade other trees, we measured the sunlit canopy, as well as the shaded canopy, and included these data in the ground survey data because the shaded canopy was not completely dead. In other words, the length of the canopy in the survey was the sum of the sunlit and shaded canopies. However, the measurements included only the sunlit canopy, because the DSM measured by airborne LiDAR was obtained primarily from the first pulse, a laser that does not reach the shaded canopy. Therefore, differences between the crown lengths obtained from airborne LiDAR and ground surveys in high-density stands would be caused by an underestimation in airborne LiDAR, as airborne LiDAR did not include the length of the shaded canopy.

However, this difference would not be significant for predicting stand growth. Kajihara *et al.* (1989) compared the distribution of stem volume in sunlit and shaded canopies and found that a shaded canopy has no influence on the stem growth of sugi and hinoki. In other words, the surface area of the sunlit canopy per unit area has more impact on growth than that of the shaded canopy. Kajihara (1985) showed that the surface area of the sunlit canopy plays an essential role in the growth of sugi stands.

3.2 Estimation of tree growth using crown information derived from airborne LiDAR data

3.2.1 Relationship between tree growth and crown surface area

Figure 5 shows the relationship between tree growth and the crown surface area of the trees.

The coefficient of determination was 0.95. The *P* value and root mean square error (RMSE) were less than 0.01 and 0.008, respectively, suggesting a strong correlation between tree growth and crown surface area. This finding is also consistent with those of previous studies, which reported that in general, a larger crown surface area results in a greater annual increment (Kramer 1966).

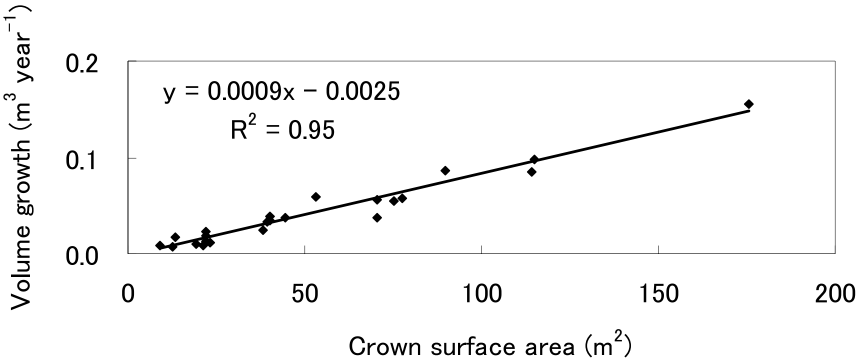

Figure 5: Relationship between individual tree volume growth and crown surface area

3.2.2 Relationship between tree growth and proportion of the crown surface area to stem surface area

Figure 6 shows the relationship between tree growth and the ratio of the crown surface area to the stem surface area of the trees. The coefficient of determination was 0.74. This result suggests a correlation between tree growth and the proportion of crown surface area to stem surface area. To predict tree growth considering both stem information and crown information, some previous studies (e.g., Cole and Lorimer 1994; Wyckoff and Clark 2005) reported that the best fit was a non-linear model. Thus, we expected that the relationship between individual tree volume and the ratio of the crown surface area to the stem surface area of the trees would be non-linear. The coefficient of determination was less than that between tree growth and crown surface area. However, this relationship (Fig. 6) might be more applicable to sugi, regardless of tree age, similar to the previous non-linear regression growth model (i.e., Cole and Lorimer 1994).

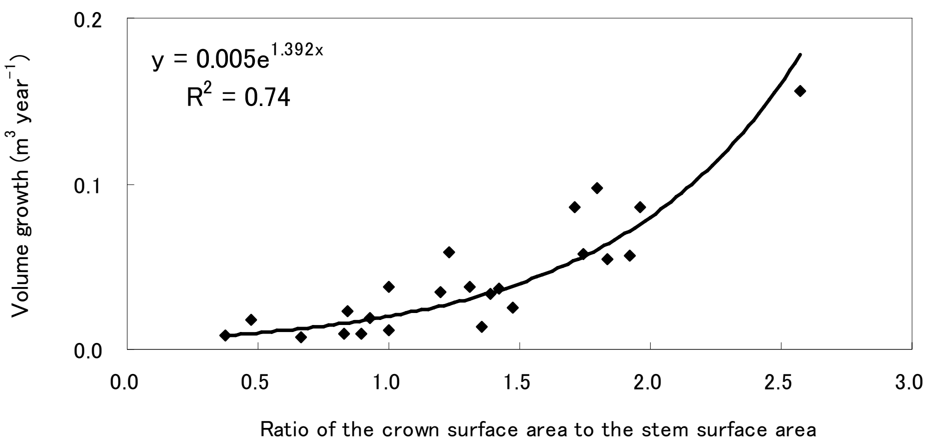

Figure 6: Relationship between individual tree volume and the ratio of stem surface area to crown surface area

As described above, we estimated the crown length by the DSM obtained from the first pulse. The first pulse reflected against the sunlit canopy does not include information on the shaded portion of the canopy, where sunlight is blocked by branches from other trees. In other words, Figures 5 and 6 suggest a strong relationship between the sunlit crown surface area and tree growth. This result is also consistent with previous reports that the shaded canopy does not contribute to tree growth (e.g., Kajihara 1985).

Note that we considered only the stem surface area as the main contributor to respiration. However, a tree respires not only on the surface of its stem but also on the surface of its branches and roots. Thus, to obtain an accurate estimation of the relationship between photosynthesis and respiration, we should compare the crown surface area to the sum of the surface area of stems, branches, and roots. Fukuda *et al*. (2003) showed the relationships between the total biomass and bole biomass of sugi depending on stand age. Given that stem biomass is highly correlated with the total biomass, it might be possible to estimate total tree growth based on stem growth models such as in Figures 6 or 7.

4. Conclusion

Airborne LiDAR was successful for acquiring precise measurements of crown lengths and widths in high-density stands. Based on these results, we estimated the relationship between tree growth and the crown surface area of individual trees. We found strong correlations between the crown surface area and tree growth. We also found that tree growth could be modeled as a function of the ratio of the crown surface area to the stem surface area.

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