ESTIMATING CARBON STOCKS OF CONIFEROUS WOODY CANOPY TREES USING AIRBORNE LIDAR AND PASSIVE OPTICAL SENSER

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ABSTRACT:

We confirmed the effectiveness of airborne LiDAR and passive optical remote sensing techniques for estimating carbon stocks of all tree organs for woody canopy two coniferous trees, Japanese red pine and Japanese cedar trees. Airborne 3-D LiDAR data and aerial photograph provided tree height and canopy area for each of the trees. Then, we examined the relationships between 1) LiDAR-derived tree height and carbon stock 2) canopy area obtained from aerial photograph and carbon stock. In addition, we made a multiplicative equation composed of both tree height and canopy area to predict the carbon stock, and examined the accuracy by comparing between the predicted and field-based values. As a result, good correlations were observed between the LiDAR-derived tree height and carbon stock in both species, while correlations were worse between canopy area obtained from aerial photograph and carbon stock in both species. The multiplicative equation offered better results than the ones of using tree height or canopy area alone, where R^2 and SE were 0.87 and 15.6 kg for Japanese red pine, and 0.85 and 7.1 kg for Japanese cedar. This shows the effectiveness of the combination of LiDAR and passive optical sensors for the carbon stock estimation.
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1. INTRODUCTION

Accurate estimation of carbon stocks in plants is important not only to study photosynthetic characteristics but also to estimate global carbon budget affected by recent increase in atmospheric CO_2 concentration that causes global changes. Field based actual measurements give accurate carbon stock, but the application is limited due to its laborious or destructive nature. Recently, remote sensing techniques such as LiDAR and passive optical sensors have been developed as indirect methods that are capable of obtaining wide area information efficiently. They have been also applied to estimating forest resources such as tree biomass, carbon stocks and structural parameters (Nelson *et al*., 1988; Omasa *et al*., 2000, 2002, 2003, 2007, 2008; Lefsky et al., 2002;Næsset *et al*., 2004; Patenaude *et al.*, 2004; Zheng *et al*., 2004; Hosoi and Omasa, 2006, 2007, 2009; Nakai et al., 2009). In terms of the carbon stock estimation, their techniques have been applied to relatively limited tree species, and the methods have not yet been sufficient for various species. Thus, the carbon stock estimation method is required to be applied for the other tree species and to be developed for the various species. In addition, as measurement methods, the combination of LiDAR and passive optical sensors is considered to be effective.

In this study, we derived structural variables of Japanese red pine (*Pinus densiflora* Siebold & Zuccarini) from airborne LiDAR and passive optical remote sensing images, and examined the usefulness of the variables for the carbon stock estimation. The carbon stock of Japanese red pine has hardly been estimated by remote sensing based method, so this species was selected in this study. In addition, for the comparison between different tree species, similar examination was also applied for Japanese Cedar (*Cryptomeria japonica* [L.f.] D. Don).

2. MATERIAL AND METHODS

2.1 Study site

The study was carried out in a mixed plantation in Ibaraki Prefecture, 40 km northeast of central Metropolitan Tokyo, Japan. The dominant tree species were Japanese cedar (*Cryptomeria japonica* [L.f.] D. Don), Japanese red pine (*Pinus densiflora* Siebold & Zuccarini), ginkgo (*Ginkgo biloba* Linnaeus), and Japanese zelkova (*Zelkova serrata* [Thunberg] Makino). From this site, 30 Japanese red pine and 15 Japanese cedar trees were chosen for this experiment.

2.2 Direct measurement of tree height and DBH

We measured the heights of the selected 30 Japanese red pine and 15 Japanese cedar trees on the ground by a range finder (Lasertape FG-21-HA, RIEGL, Austria) with an accuracy of ±5 cm. Then, Diameter at Breast Height (DBH) of each tree was also measured directly in the site for calculation of carbon stocks of trees. Circumferential lengths of each tree were measured by survey taping and DBH was obtained by dividing the length by π.

2.3 Measurement using an airborne LiDAR system

The study area was scanned in August 2005 by a LiDAR (ALTM 3100 DC, Optech Co.) mounted on a helicopter (Aero Asahi Co., Japan). The airborne LiDAR calculated the distance to a target by the time-of-flight method, and had the first-pulse and last-pulse modes, in which the first and last returned laser pulses were detected. The data of canopy surface were received by first-pulse mode (FP-mode), so the data of FP-mode were selected to generate an image of the woody outer canopy at the following process. The laser wavelength was 1,064 nm, and its repetition frequency was 50,000 Hz. The scanning frequency was set to 20 Hz. The scanning angle, the range and horizontal accuracy were 20.0°,

±15 and 13cm, and flight speed and height were 50 km/h and 400m, respectively. Together with the 3-D point cloud data collection, aerial photographs of the area were also captured as the data of passive optical remote sensing from 400m above.

2.4 Tree height estimation from 3-D LiDAR data and canopy areas from aerial photograph

A polygonal 3D-LiDAR image of the woody canopy within the study area was generated by triangulating and smoothing the FP-mode 3-D point cloud data. For the selected 30 Japanese red pine and 15 Japanese cedar trees, the heights were determined detecting the tops. In the aerial photograph, each of the selected tree canopies was segmented along their contours based on the Watershed algorithm (Wang *et al*., 2004). In this study, the area of each segment in each tree was named as the canopy area and that was calculated by counting the corresponding number of pixels in each of the segments.

2.5 Derivation of relationships between carbon stocks and variables estimated from LiDAR data and aerial photograph

Stem volume of each tree was calculated from the directly measured DBH and the tree height using an allometric equation in each species (The Forest Agency in Japan, 1998). The stem volume was converted into carbon stock of all tree organs (stem, branch, foliage and root) using the stem to total volume ratio and specific gravity obtained from the destructive field measurement data in Cannel 1982, and from the carbon fraction, 0.5, as described in the report in Ministry of the environment in Japan, 2008. For both Japanese cedar and Japanese red pine, we examined the relationships between (1) LiDAR-derived tree height and carbon stock (2) canopy area derived from aerial photograph and carbon stock. In addition to the above two relationships, we made a multiplicative equation to predict carbon stock using two variables of canopy area and tree height, as follows.

$$C_p = a \times CA^b \times H^c \qquad (1)$$

Where C_p is predicted carbon stock of all tree organs, CA is canopy area obtained from aerial photograph, and H is LiDAR-derived tree height. The coefficients of a, b and c were determined by multiple regression analysis.

3. RESULTS AND DISCUSSION

Fig.1 is an aerial photograph of a part of the study site and Fig.2 is the corresponding 3D-LiDAR image generated from 3D point cloud data obtained by the airborne LiDAR. The airborne LiDAR could offer precise 3-D model of the study area.

Fig.3 is the segmentation result in aerial photograph based on the watershed algorithm. Each canopy is indicated as green region and the boundaries of each canopy are represented as black lines. Although there were some mis-segmented areas, most of canopies were well segmented.

Fig.4 shows that the relationships between tree height estimated using airborne LiDAR and the carbon stock of all tree organs of (a) Japanese red pine and (b) Japanese cedar. Power functional relationships are shown in the figure. R^2 and Standard Error (SE) of the relationships were respectively 0.85, and 15.1 kg for Japanese red pine and 0.68, and 21.0 kg for Japanese cedar. Good correlations between the LiDAR-derived tree height and carbon stocks were obtained at both species.

Figure 1 Aerial photograph of a part of the study site obtained by optical remote sensing.

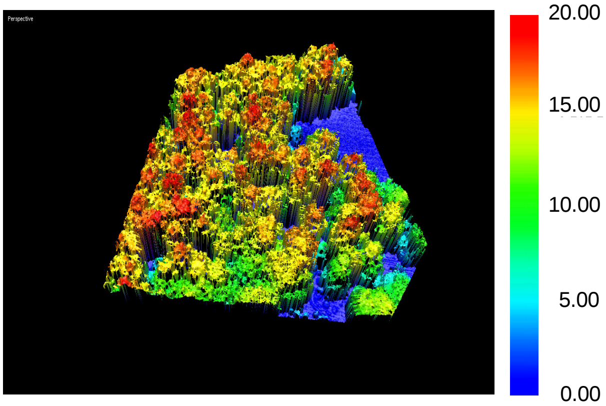

Figure 2 3D-LiDAR image generated from FP-mode 3D point cloud data.

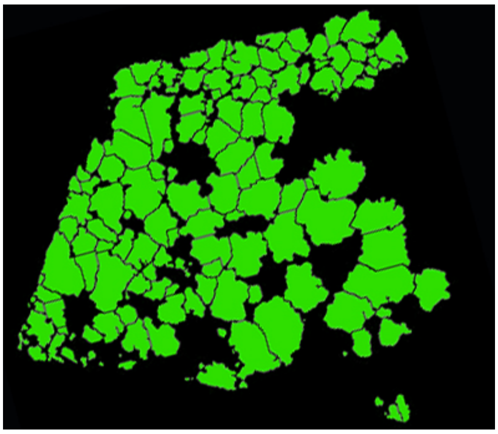

Figure 3 Segmentation result in aerial photograph based on the watershed algorithm. Each canopy is indicated as green region. Boundaries of each canopy are represented as black lines.

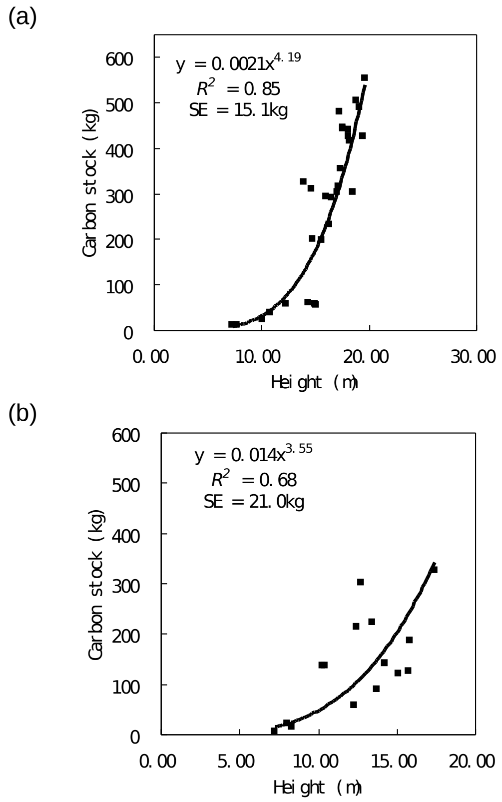

Figure 4 Relationships between the tree height estimated using airborne LiDAR and the carbon stock of all tree organs. (a) Japanese red pine and (b) Japanese cedar.

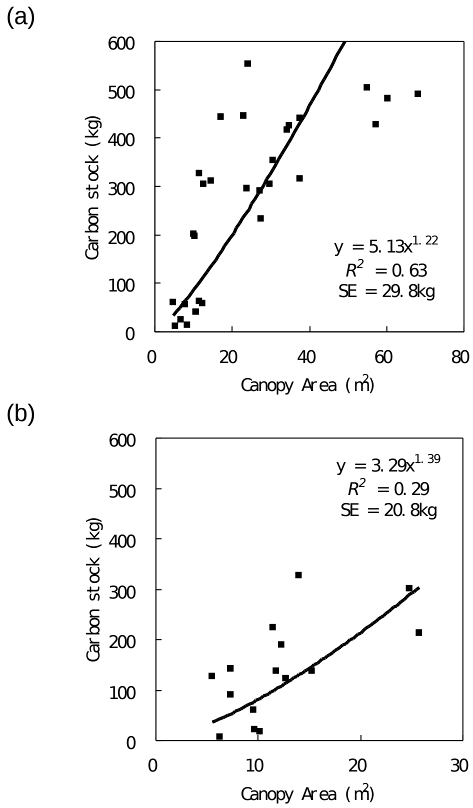

Figure 5 Relationships between the canopy area calculated by the aerial photograph and the carbon stock of all tree organs. (a) Japanese red pine and (b) Japanese cedar.

Fig.5 shows the relationships between canopy area calculated by aerial photograph and carbon stock of (a) Japanese red pine and (b) Japanese cedar. Power functional relationships were also shown in the figure. R^2 and SE of the relationships were respectively 0.63 and 29.8 kg for Japanese red pine and 0.29 and 20.8 kg for Japanese cedar. In both species, correlations between canopy areas and carbon stock were worse than the cases in Fig.4. It was also observed that canopy area of Japanese red pine varied more widely than Japanese cedar.

Coefficients *a*, *b* and *c* in Eq.(1) for Japanese red pine were respectively $10^{-2.21}$, 0.35 and 3.42, and for Japanese cedar respectively $10^{-2.76}$, 1.12 and 3.29. Fig.6 shows the comparisons of carbon stock between the predicted and field-based values of (a) Japanese red pine and (b) Japanese cedar. R^2 and SE of stem volume were 0.87 and 15.6 kg for Japanese red pine, and 0.85 and 7.1 kg for Japanese cedar. In terms of the values of R^2, it was shown that carbon stock can be predicted more accurately from Eq.(1) composed of both tree height and canopy area than the use of tree height or canopy area alone.

It was shown in Fig.4 that LiDAR-derived tree height alone can offer accurate estimation of the carbon stock. For details, some errors were observed above height of 13m in Fig.4, where the regression curves become steep. Because of the steep curve, a little difference of tree height would have caused the error of the carbon stock estimation.

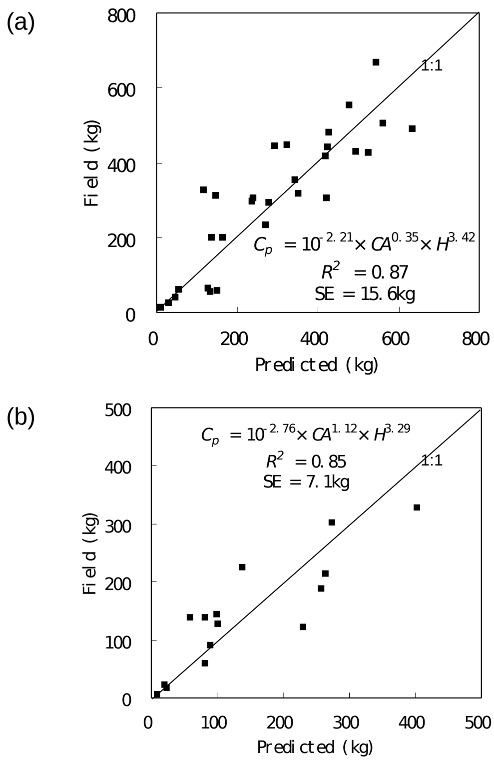

Figure 6 Comparisons of stem volume between the predicted and field-based carbon stock. (a) Japanese red pine (b) Japanese cedar.

Canopy area was chosen as a variable that represents horizontal canopy structure and it seemed to perform well the carbon stock estimation. However, even if trees have the same amount of carbon stock, canopy area can have different values depending on the 3-D structure, such as blanching pattern or foliage distribution. This would explain poor correlation between the canopy areas and the carbon stock. Due to this reason, it seems to be difficult to estimate the carbon stock accurately from the canopy area alone. In terms of species difference, canopy area of Japanese red pine varied more widely than Japanese cedar. This would mean that Japanese red pine has more structural variability than Japanese cedar.

At the result of multiple regression analysis, T-values of tree height and canopy area were 7.19 and 2.16 for Japanese red pine, and 7.23 and 4.10 for Japanese cedar. T-value of tree height is higher than that of canopy area for each species, so it shows that the tree height more affects the carbon stock estimation than canopy area.

4. CONCLUSION

It can be concluded that the proposed multiplicative equation composed of tree height from 3-D LiDAR data and canopy areas from aerial photograph is better for estimating carbon stock of the present two coniferous trees than using the tree height or canopy area alone. This shows the effectiveness of the combination of LiDAR and passive optical sensors for carbon stock estimation. In the future, more works should be conducted for more species to well utilize the findings obtained in the present study.

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