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Accurate Estimation of Forest Carbon Stocks by 3-D Remote Sensing of Individual Trees

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Forests are one of the most important carbon sinks on Earth. However, owing to the complex structure, variable geography, and large area of forests, accurate estimation of forest carbon stocks is still a challenge for both site surveying and remote sensing. For these reasons, the Kyoto Protocol requires the establishment of methodologies for estimating the carbon stocks of forests (Kyoto Protocol, Article 5). A possible solution to this challenge is to remotely measure the carbon stocks of every tree in an entire forest. Here, we present a methodology for estimating carbon stocks of a Japanese cedar forest by using a high-resolution, helicopter-borne 3-dimensional (3-D) scanning lidar system that measures the 3-D canopy structure of every tree in a forest. Results show that a digital image (10-cm mesh) of woody canopy can be acquired. The treetop can be detected automatically with a reasonable accuracy. The absolute error ranges for tree height measurements are within 42 cm. Allometric relationships of height to carbon stocks then permit estimation of total carbon storage by measurement of carbon stocks of every tree. Thus, we suggest that our methodology can be used to accurately estimate the carbon stocks of Japanese cedar forests at a stand scale. Periodic measurements will reveal changes in forest carbon stocks.

Introduction

Accurate estimation of carbon stocks in forests is crucial to understanding the global carbon budget and climate change, because forests are one of the most important carbon sinks on Earth. However, because of the complex structure, variable geography, and large area of forests, accurate estimation of forest carbon stocks is still a challenge. In many cases, forest carbon stocks are estimated from limited site data. The representativeness of site data is always uncertain because of the heterogeneity of forests. Consequently, remote sensing technology is expected to provide a solution to this challenge. Remote sensing typically involves images from a passive optical system, such as aerial photography or the Landsat Thematic Mapper (*1*), or, to a lesser degree, active radar sensors (*2*). These types of sensors have allowed extraordinary advances in the modeling, mapping, and understanding of ecosystems (*2*−*4*). However, they have significant limitations for forest applications, because their sensitivity and accuracy have repeatedly been shown to decrease as above-ground biomass increases (*2*, *4*). They are also limited by their ability to produce only 2-dimensional images, which cannot fully represent the 3-dimensional spatial features of forests. Therefore, currently available remotely sensed data can provide only a rough average result, and verification is always a problem. Because of these reasons, the Kyoto Protocol requires the establishment of methodologies for estimating the carbon stocks of forests (Kyoto Protocol, Article 5).

Meanwhile, lidar (light detection and ranging) is an emerging active remote sensing technology, and its applications to 3-D terrestrial observation are developing rapidly (*5*−*7*). Since the middle of the 1980s, the nonscanning airborne lidar has been applied to estimate the average height of forest trees and forest biomass (*8*). In the middle of the 1990s, the scanning lidar became available and then this technology was applied for forest measurement (*9*−*11*). Because of the low scanning rate or high flight speed, however, currently available scanning lidar systems with a small footprint (laser spot on the ground) of laser beam cannot cover the entire land surface (*5*, *10*, *12*). Airborne lidars with a large footprint and a large scan width are expected for forest remote sensing on a regional scale but these limit the image resolution (*9*, *11*, *13*). As a result, comprehensive information on individual trees in the woody forest cannot be collected, and tree height is usually underestimated (*9*, *10*).

Consequently, we assume that if the whole ground surface is scanned by a laser beam with small footprint, the canopy surface of individual trees in the woody forest can be measured at a high spatial resolution and the digital image of canopy height can be represented in a small mesh size. To achieve this goal, we designed a methodology and carried out extensive experiments with a high-resolution scanning lidar system loaded in a low-flight-speed helicopter. These efforts ensure that the entire canopy surface can be scanned at high resolution. By these efforts, we have accurately measured the canopy height of individual trees (*14*). The object of this study is to further improve the spatial resolution of canopy surface and to estimate the carbon stocks of Japanese cedar at the stand scale by entire individual tree measurements with the high-resolution 3-D scanning lidar.

Experimental Section

Field Sites. We studied a Japanese cedar (*Cryptomeria japonica*) forest located in Akita prefecture, Japan, because this type of forest covers a large area in Japan. The Japanese cedar trees were planted about 50 years ago. Because the undergrowth has been cleared away regularly, only Japanese cedar trees have grown in this forest.

Scanning Lidar Measurements. Surfaces of both the forest canopy and the ground were measured from a helicopter by using a high-resolution scanning lidar system (ALTM 1025 special model; Optech Co. and Aero Asahi Co.). This lidar system had the following characteristics. (i) Almost all surface area could be scanned by a laser beam of small footprint. (ii) Precise grid data could be obtained by rectangular scan using a garbomirror scanner. (iii) There were two operational

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modes, first-pulse mode (FP-mode) for measuring the canopy surface and last-pulse mode (LP-mode) for measuring ground surface. By using a time interval meter, the elapsed time (time-of-flight) between the emitted pulse and the returned pulse was measured. At each measuring point, FP-mode had the shortest elapsed time and LP-mode had the longest one. During measurement, the flight speed was 50 km h^{-1}, and the flight height was 160−200 m. The footprint size on the ground was 20−30 cm, and the distance between the centers of neighboring footprints on the ground was 10−15 cm for scan direction and 28 cm for flight direction (the scan width). The geographic position was determined with a helicopter-borne internal measurement unit (IMU) and high-resolution Global Positioning Systems (GPSs) both in the helicopter and on the ground.

Ground Measurements. On the ground, an area in the lidar-scanning site was selected to measure tree heights, stem diameter at 1.2 m height, and tree positions. This area was isolated from other forested areas and the trees included are fewer (710 m^2, 62 standing trees). Consequently, the comparison between data measured on the ground and lidar-derived data was much easier. The tree height was measured by a portable range finder with accuracy of 5 cm (RIEGL, FG21-HA). The stem diameter was measured using a measuring tape.

Generation of FP-Mode DEM, DSM, and DCHM. Digital elevation model (DEM, a mesh size of 10 × 10 cm) was obtained by interpolation of measured lidar data using software made by TopScan and modified by Aero Asahi Co. The canopy surface was shown by a DEM made from FP-mode data. The ground surface was estimated from a DEM made from LP-mode data and was used as the digital surface model (DSM). The digital canopy height model (DCHM), which shows the woody canopy height, was obtained by subtracting the DSM from the FP-mode DEM (*14*).

Analysis of DCHM. The DCHM images were analyzed to obtain tree height, canopy outline, and the total carbon stocks of each tree with software (such as ERDAS IMAGINE) written by the authors and others. The DCHM images usually included spike noises, which could seriously affect the accuracy of final results. To delete these noises, the image was pretreated by a median filter with a mask size of 3 × 3 pixels. Our early study showed that compared with filters of different types and sizes, a median filter of 3 × 3 pixels was suitable for tree-height estimation (*14*). After the median filtering, the tree height was automatically determined by filtering for searching the highest point in the canopy surface of each tree. The canopy outline of each tree was calculated by image processing for edge extraction from the DCHM image.

Estimation of Carbon Stocks. The stem carbon stocks of each tree in the isolated area were estimated from measured data of tree height and stem diameters at 1.2-m heights by using a biomass table of Japanese cedar, and then biomass was converted into carbon stocks by multiplying a ratio of 45% (*15, 16*). A regression equation for estimating the stem carbon stocks from tree height was established using both the field data and all other available data on Japanese cedar in Japan (212 sets of data) (*17*). Another regression equation for estimating the carbon stocks of branches, foliage, and roots from tree height was made using data collected all over Japan (53 sets of data) (*17*). On the basis of these equations, the total carbon stock of each tree was estimated. The tree heights in these data sets ranged from 3 to 30 m.

Results and Discussion

Figure 1 shows a FP-mode DEM image at an area (about 90 × 50 m^2) in the field site. The elevation of surfaces of canopy and ground ranged from 85.0 to 110.0 m. Spike noises caused by lack of lidar scanning data were found. This figure shows

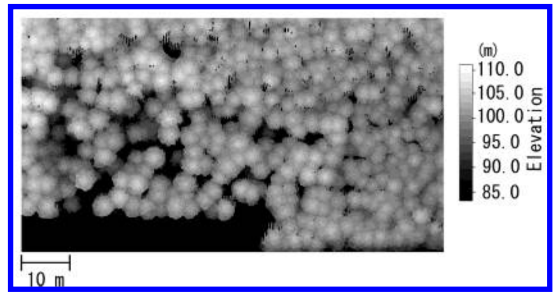

FIGURE 1. FP-mode DEM image at an area (about 90 × 50 m^2) in a Japanese cedar (*Cryptomeria japonica*) forest. The canopy surface of each tree and the top were found clearly.

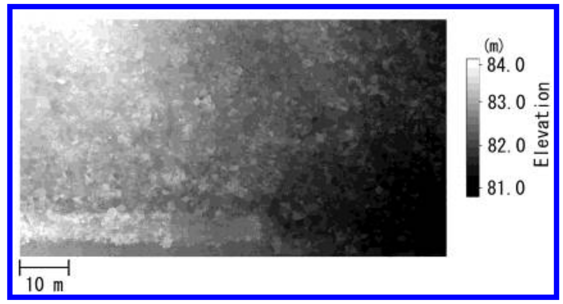

FIGURE 2. DSM image, ground surface estimated as a DEM, at the area shown in Figure 1.

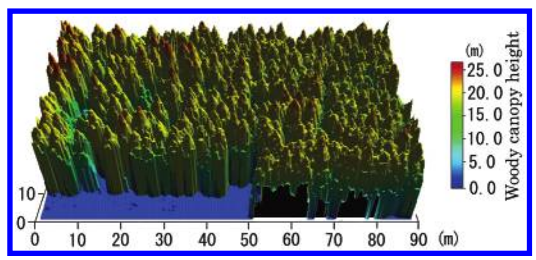

FIGURE 3. 3-D View of DCHM obtained by subtracting the DSM in Figure 2 from the FP-mode DEM in Figure 1. The DCHM shows the woody canopy height of Japanese cedar trees.

that the canopy surface of each Japanese cedar (*Cryptomeria japonica*) tree and the top are detected clearly. Ground surface is represented as the black area in the DEM image.

Figure 2 shows a DSM image of the same area. The ground surface slopes down from the left to right and the elevation varies from 81.0 to 84.0 m. Unevenness of the ground surface and the undergrowth is found as patchiness with difference in height of several tens of centimeters.

Figure 3 shows a 3-D view of DCHM obtained by subtracting the DSM in Figure 2 from the FP-mode DEM in Figure 1. Spike noises are deleted by a 3 × 3 m median filter. The ground surface is converted to a flat level and, consequently, the woody canopy height of Japanese cedar trees is revealed three-dimensionally.

Figure 4 shows an image of the highest point (cross) of each tree overlapped on the DCHM image. Image processing reveals the number of trees and tree heights. The trees in this image are Japanese cedars, a conifer. The position of the highest point of the tree corresponds with the position of the tree stem. Analysis of this image detected 394 trees, 6 trees were unfound, and 5 nonexistent trees are detected due to noise in comparison with treetops found by human eye in the DCHM image.

Meanwhile, in an isolated area (710 m^2) near the area shown in Figure 4, lidar-derived data are compared with ground-measured data. Ground measurement shows that there are 62 standing trees in the area. However, 3 of them are not revealed by our lidar-derived data because these trees

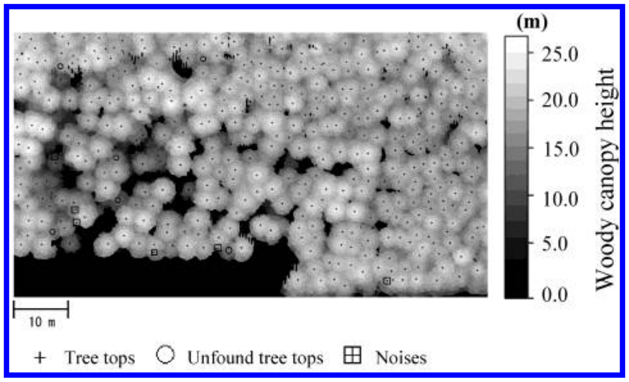

FIGURE 4. Highest point (cross) of each tree overlapped with the DCHM image. The dark areas are uncovered ground surface. Unfound trees and noises are also shown.

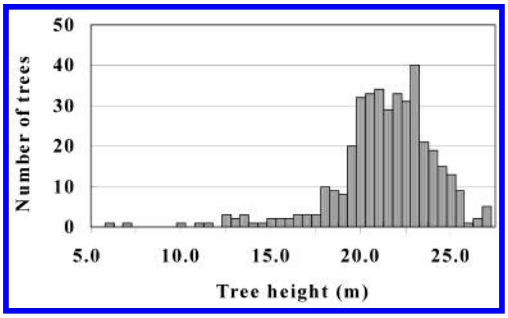

FIGURE 5. Distribution of tree heights in the area shown in Figure 4. The tree height was determined from the DCHM image.

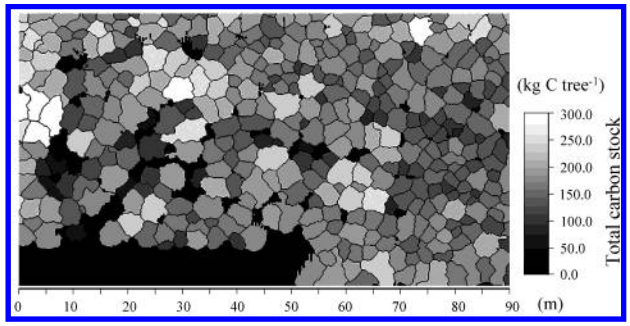

FIGURE 6. Total carbon stocks (stem, branches, foliage, and roots) of each tree in the area. Each gray level represents total carbon stocks of one tree and covers the area occupied by that tree's canopy.

are growing under other large trees. Because this Japanese cedar forest has been managed in similar ways, this result may be applicable to the entire area in the same forest. The lidar-derived height shows that the estimated error ranges from −25 to −42 cm with a root-mean-square error (RMSE) of 37.5 cm, which corresponds to −1.0% to −2.3% of the tree height measured by the portable range finder. This error may be caused by the undetectable treetops with thin branches and the unevenness of the ground surface and undergrowth shown in Figure 2. By the same lidar system, we have shown errors of less than 47 cm (RMSE = 19 cm) for coniferous trees (including Japanese cedar) and 40 cm (RMSE = 12 cm) for broadleaf trees in an other Japanese woody area (*14*). The accuracy of the lidar measurement did not depend on the tree height. Though this accuracy is satisfactory for many application purposes, we are going to further improve it in future work.

Figure 5 shows a histogram of tree heights in the forest area shown in Figure 4. Heights range from 6.0 to 27.0 m. The average height is 21.3 m, and most heights (90%) are in the range of 18.5 to 26.0 m. This kind of information will be helpful for understanding the structure and function of forest.

Analysis of our field data and of all other available data on Japanese cedar in Japan (*17*) shows that the carbon stocks of a tree stem (C_{stem}, kg C tree^{-1}) can be well estimated by $C_{stem} = 0.0119H^{2.9696}$ ($R^2 = 0.933$), and the carbon stocks of branches, foliage, and roots (C_{BFR}, kg C tree^{-1}) can be well estimated by $C_{BFR} = 0.0075H^{2.9516}$ ($R^2 = 0.864$), where H is tree height (m). On the basis of these equations, the total carbon stocks of each tree in the forest were calculated and are given in Figure 6. The gray level inside each canopy outline represents the total carbon stock of one tree and covers the area occupied by that tree's canopy. The maximum carbon storage per tree is <300 kg, and most values lie in the range of 110 to 300 kg. The total carbon storage in the image area (90 m × 50 m) is 69 300 kg, and the average carbon storage is 175.9 kg C tree^{-1}. Because the equations were established by using the data of 3−30 m tree height, using them to estimate carbon stocks for trees over 30 m may not be very accurate.

Accurate measurement of tree height is important, because biomass and forest timber stocks are universally estimated from tree heights or stem diameters (*8*, *11*, *15*). However, the conventional methods of forest site surveys measure only a limited number of trees. These limited data are then used to estimate the heights of all trees in a forest. Owing to the complex structure of forests and variable geography, this method is inaccurate. On the other hand, mapping of topographic features is the largest and fastest growing area of application for lidar remote sensing (*5*−*7*). However, even the newest works on lidar remote sensing are still not accurate enough to measure small individual trees such as Japanese cedar trees because of low spatial resolution (*12*, *13*). In contrast, our high-resolution lidar remote sensing can provide accurate measurements of every tree in a Japanese cedar forest, allowing measurements of individual trees at stand level. Furthermore, we also determined the accurate tree height by filtering for searching the highest point in canopy surface of each Japanese cedar tree automatically.

Our results have revealed a fairly allometric relationship between tree height and carbon stocks. This allometric relationship permits estimation of total carbon storage by measurement of carbon stocks of every Japanese cedar tree. Thus, we suggest that our methodology can be used to accurately estimate the carbon stocks of forests at a stand scale. Periodic measurement will reveal changes in carbon stocks of the forest. However, we have not yet applied it for Japanese cedars over 30 m in height, other conifers, or broadleaf forests. Our designed software for image analysis is not powerful enough to analyze a large amount of images for a regional area including various species of trees. With the efforts of many scientists, we believe that these challenges will be overcome gradually in the future.

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