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Application of Portable Terrestrial Laser Scanner to a Secondary Broad-Leaved Forest

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Abstract

In order to conduct further verification of measuring broad-leaved forests using a low-cost portable Terrestrial Laser Scanner (TLS), the present study measured a secondary broad-leaved forest of the Funyu experimental forest, Utsunomiya University, Japan. Then, DBH, height, top end diameter, sweep, and stem volume were analyzed and compared with results of coniferous plantation forests using terrestrial LiDAR. RMSE of DBH was 1.91 cm, which was higher than that of coniferous plantation forests. However, DBH was typically rounded to 2 cm; therefore, RMSEs of DBH were within the allowable range. Furthermore, species did not affect the accuracy of DBH mensuration. The RMSE of height was 2.26 m, which was similar to 2.29 m of the 32-year-old coniferous plantation forest with high stand density. RMSE of height outside the plot was higher than that inside the plot because distances from the portable TLS to trees were too short to measure the heights of trees. The log detection rate was 79.22% in the present study, whereas it was 85.23% in the coniferous plantation forest. RMSE of top end diameter was lower than that of the coniferous plantation forest because the broad-leaved trees were extracted manually in the present study, whereas coniferous trees were extracted automatically. Errors in top end diameters increased with increasing top end heights because the number of points decreased. The RMSE of sweep was much higher than that of coniferous plantation trees. The RMSE of stem volume was 14.3%, which was lower than that of the coniferous plantation forest, despite the low-cost portable TLS, because of lower RMSEs of top end diameters and shorter distances from the portable TLS.

Keywords: Broad-leaved forest, DBH, Height, Portable TLS, Stem volume

1. Introduction

Japan depends on the import of oil, coal, and natural gas for the majority of its energy supply. The country's energy self-sufficiency rate was just 5% in 2010 (Forestry Agency of Japan, 2013). To secure a stable supply of energy, alternatives to fossil fuels, such as renewable energy sources including solar, wind, river, geothermal heat, and biomass, need to be developed. Among various biomass resources in Japan, woody biomass attracts much attention because of its abundance and the potential for its energy use to contribute towards revitalizing forests and forestry product industries, which have been depressed for the last 30 years.

In July 2011, the Feed-in Tariff (FIT) Scheme for Renewable Energy Use was introduced in Japan, in accordance with new legislation, entitled the Act on the Purchase of Renewable Energy-Sourced Electricity by Electric Utilities. Under the FIT program, electricity generated from woody biomass must be procured at a fixed price (without tax) for over 20 years for (a) unused materials such as thinned wood and logging residue (at USD0.32/kWh), (b) general materials such as sawmill residue (at USD0.24/kWh), and (c) recycled materials such as construction waste wood (at USD0.13/kWh) (ANRE, 2012). Furthermore, the price of USD0.40/kWh for unused materials with less than 2 MW of direct combustion was set in order to promote the use of thinned wood and logging residue from a large number of small, fragmented, and scattered forests, starting in April 2015.

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Incentives have promoted the use of power generated from unused materials, and they are expected to increase the use of thinned wood and logging residue from 2 million m^3 in 2014 to 8 million m^3 in 2025 based on the forest and forestry basic plan of Japan established in May 2016 (Forestry Agency of Japan, 2016). Timber supply and demand are also expected to increase from 24 and 76 million m^3 in 2014 to 40 and 79 million m^3 in 2025, respectively. Therefore, the self-sufficiency rate of timber is expected to increase from 31% in 2014 to 50% in 2025. Timber supply from coniferous and broad-leaved forests occupied 89% and 11%, respectively, whereas stocks of those forests occupied 71% and 29%. Broad-leaved forests were used for firewood and charcoal production until the 1960s. However, those forests have been lagging in terms of tending operations since then. Therefore, harvesting and regeneration operations of broad-leaved forests are expected to maintain the relevant ecological, economic, and social functions of broad-leaved forests, as well as to increase timber supply.

In order to establish a forest management plan, it is crucial to inspect stand conditions. Light Detection And Ranging (LiDAR) technology is commonly used to obtain basic information about terrain and vegetation. Airborne LiDAR can measure crown surfaces and calculate the height and number of trees. Stem volumes and stand volumes can then be estimated using data including crown volume, tree height, and the number of trees (Ito et al., 2011). However, airborne LiDAR cannot directly measure stem shape or volume (Kato et al., 2014b). In contrast, terrestrial LiDAR has been used to obtain detailed descriptions of stem shape, such as taper, sweep, and lean (Murphy et al., 2010).

The previous study (Aruga et al. 2016) verified terrestrial LiDAR data measured for 32- and 62-year-old Japanese cypress (*Chamaecyparis obtusa*) and Japanese cedar (*Cryptomeria japonica*), respectively, of the Funyu experimental forest, Utsunomiya University, Japan. Root mean square errors (RMSEs) of Diameter at the Breast Height (DBH) and height were 1.33 cm and 2.29 m in the 32-year-old forest and 1.35 cm and 1.41 m in the 62-year-old forest, respectively. Average extracted volumes measured manually and with terrestrial LiDAR were 0.62 and 0.70 m^3/stem. The difference was -0.08 m^3/stem (13%). Omasa et al. (2002) measured 24 stems in a Japanese larch (*Larix leptolepis*) plantation forest. As a result, the RMSE of DBH was 0.73 cm. Urano and Omasa (2003) measured 40 stems in Japanese cedar (*Cryptomeria japonica*) plantation forests. As a result, the RMSE of DBH was 0.61 cm. Acuna et al. (2009) measured 42 stems in Radiata pine plantation forest. As a result, the extracted volumes measured manually and with terrestrial LiDAR were 1.81m^3/stem and 1.76 m^3/stem, respectively. The difference was 0.05 m^3/stem (3%).

These studies measured coniferous plantation forests, which are easier to measure than secondary broad-leaved forests because of the straight shape of trees and simple stand structures. Kato et al. (2014a) measured 510 stems in broad-leaved and coniferous forests. As a result, the RMSEs of DBH were between 1 and 4 cm, according to distances from the portable Terrestrial Laser Scanner (TLS), and the RMSEs of height were between 0.2 and 1.2 m. The RMSEs of DBH determined by Kato et al. (2014a) were higher than those of other studies because of measuring broad-leaved forests using a low-cost portable TLS.

In order to conduct further verification of measuring broad-leaved forests using a low-cost portable TLS, the present study measured a secondary broad-leaved forest of the Funyu experimental forest, Utsunomiya University, Japan. Then, DBH, height, top end diameter, sweep, and stem volume were analyzed and compared with results of coniferous plantation forests using terrestrial LiDAR.

2. Materials and Methods

The study site was a 50-year-old broad-leaved forest that included *Quercus serrate*, *Magnolia obovata*, *Castanea crenata*, and *Cerasus jamasakura* (Figures 1, 2). Three trees were measured at 10 locations of a portable TLS in a 15x20-m plot, whereas seven trees were measured from every 2-3 locations of a portable TLS outside the plot. In the plot, stand density was 533 stems/ha. Average DBH and height were 25.13 cm and 17.19 m, respectively. According to 10 trees measured using portable TLS, average DBH and height were 23.40 cm and 18.49 m, respectively (Table 1). After measuring 10 trees using portable TLS, the trees were cut down and bucked by 2 m from the breast height (1.2 m in this area). Then, the top end diameter and sweep of logs were measured and compared with portable TLS.

Portable TLS used in the present study was SIKC LMS511 (Figure 3), whereas the terrestrial LiDAR used in the previous study (Aruga et al., 2016) was TRIMBLE TX5. Maximum distances of the portable TLS and terrestrial LiDAR were 50 and 120 m, respectively. Beam width, measured velocity, and resolution of portable TLS were 4.7 mrad, 37,000 Hz, and 0.167°, whereas those of terrestrial LiDAR were 0.19 mrad, 122,000-976,000 Hz, and 0.009°. Therefore, portable TLS should be used within shorter distances than terrestrial LiDAR. Minimum and maximum distances from portable TLS to trees were 1.37 and 7.45 m, respectively, and the average distance was 3.27 m in the present study, whereas the average was 20.54 m in the previous study (Aruga et al., 2016). According to increased distances, the number of the scan points decreased (Figure 4).

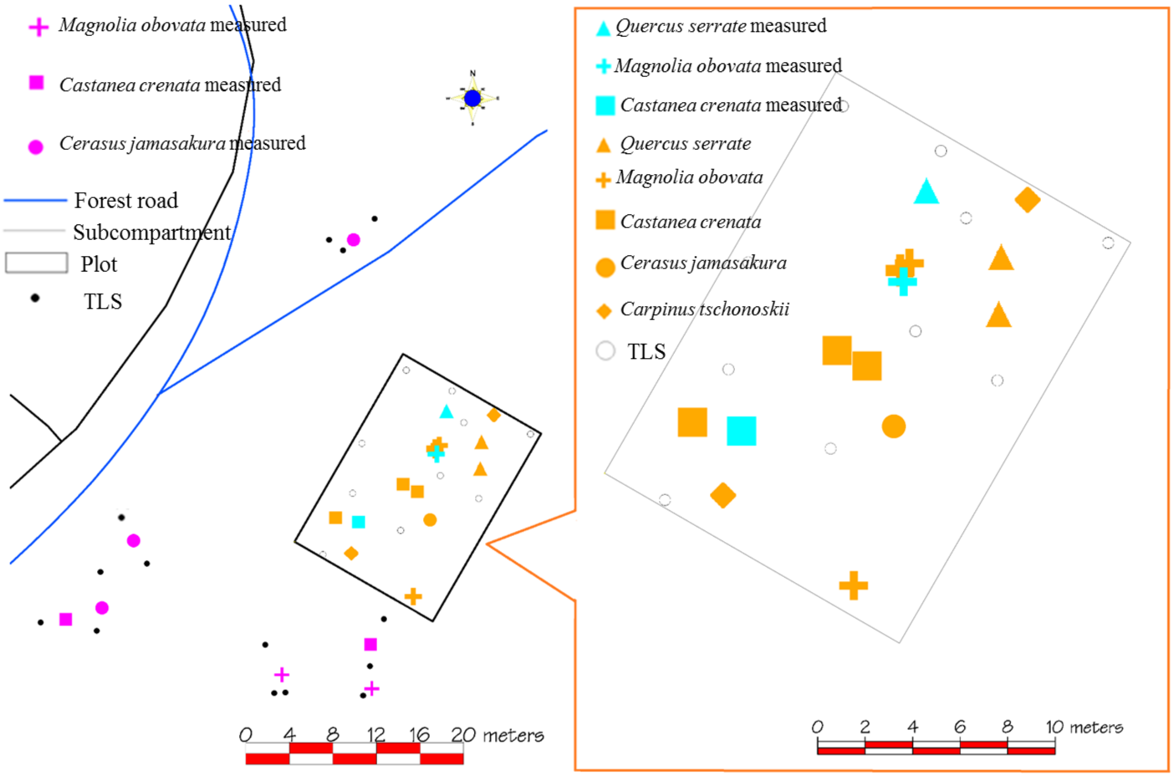

Figure 1. Study site

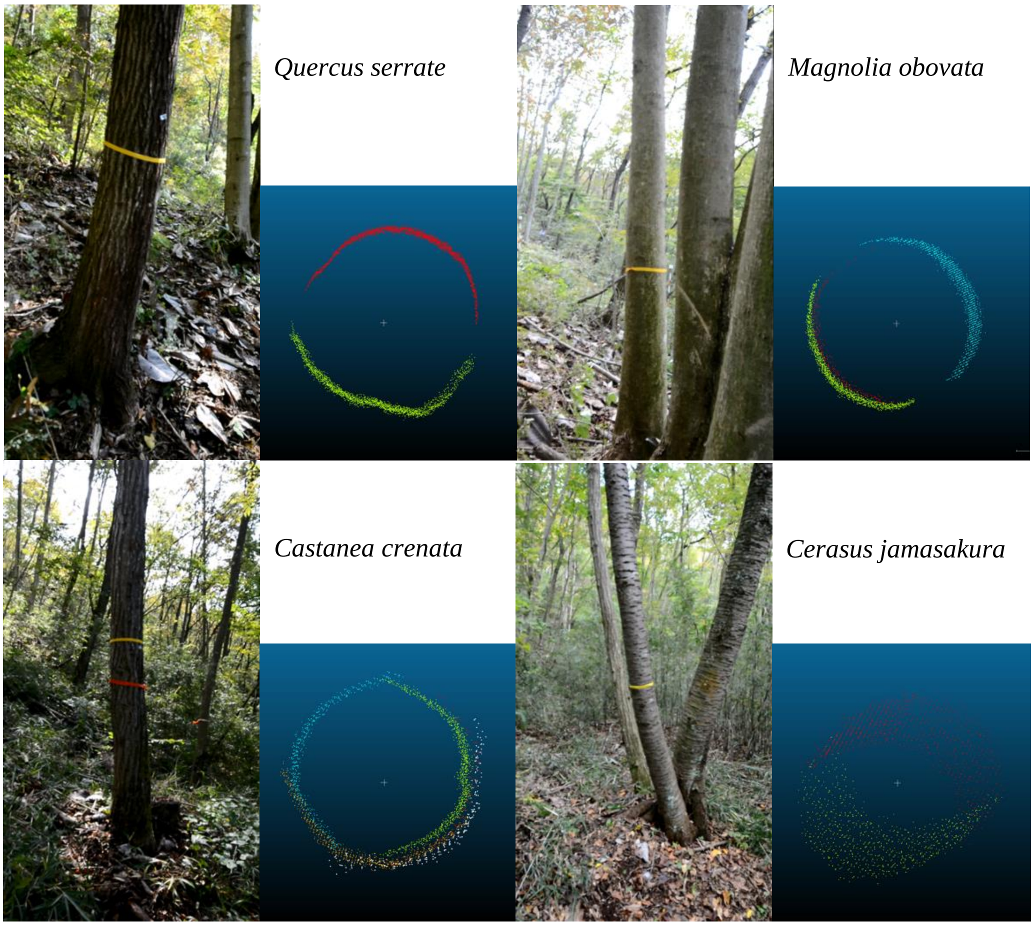

Figure 2. Trees and point clouds at the breast height

Table 1. DBH, height, and stem volume

	No.	Average DBH (cm)	Average Height (m)	Average Volume (m^3)	Error DBH (cm)	Error Height (m)	Error Volume (m^3)	RMSE DBH (cm)	RMSE Height (m)	RMSE Volume (m^3)
Inside	3	27.70	21.91	0.640	-1.11	1.45	-0.055	1.79	1.52	0.099
Outside	7	21.56	17.03	0.342	0.39	-1.02	0.008	1.96	2.26	0.034
Quercus serrate	1	32.80	21.62	0.858	-0.40	1.03	0.053	0.40	1.03	0.053
Magnolia obovata	3	22.70	19.08	0.421	0.87	-0.52	-0.033	2.94	1.37	0.043
Castanea crenata	3	20.83	17.89	0.348	-0.82	-0.70	-0.039	1.60	2.97	0.087
Cerasus jamasakura	3	23.53	17.47	0.382	-0.10	-0.06	0.017	0.95	1.77	0.047
Total	10	23.40	18.49	0.431	-0.06	-0.28	-0.011	1.91	2.06	0.061

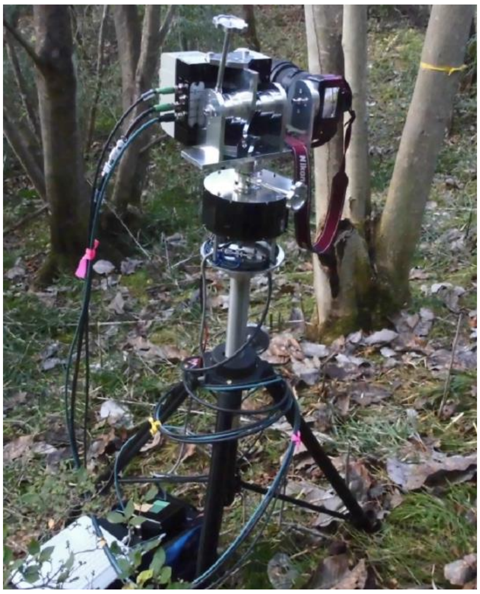

Figure 3. Portable TLS

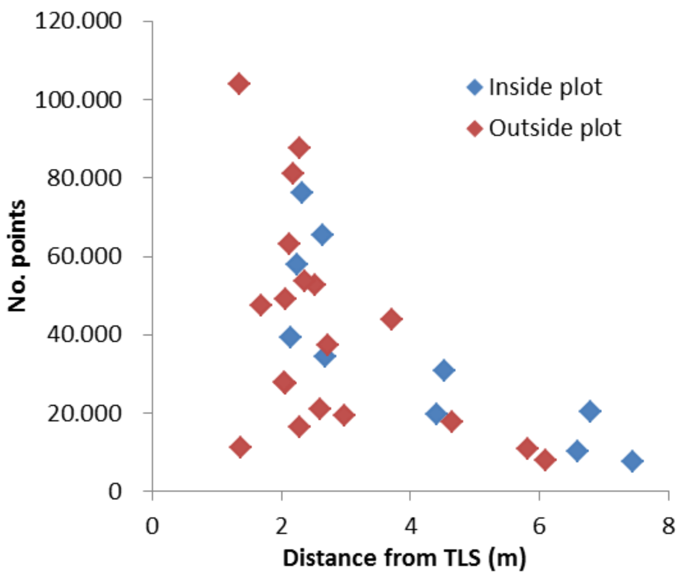

Figure 4. Distance and No. points

Since secondary broad-leaved forests have complex structures, the broad-leaved trees were manually extracted from point clouds of the portable TLS in the present study (Figure 5), whereas coniferous trees were extracted automatically (Endo et al., 2012). Then, a 10-cm slice was taken through the laser scan point cloud; circle fitting of the scan points using the least squares method within the slice was used to determine the center and diameter each 10 cm slice.

3. Results

3.1. DBH and Height

Average errors (manual–TLS) of DBH and height were -1.11 cm and 1.45 m in the plot and 0.39 cm and -1.02 m outside the plot, respectively (Table 1, Figure 6). The RMSEs of DBH and height were 1.79 cm and 1.52 m in the plot and 1.96 cm and 2.26 m outside the plot, respectively.

RMSEs of DBH and height were 1.33 cm and 2.29 m in the 32-year-old coniferous plantation forest, and 1.35 cm and 1.41 m in the 62-year-old coniferous plantation forests, respectively (Aruga et al., 2016). Therefore, RMSEs of DBH of the broad-leaved forest using portable TLS were higher than those of coniferous plantation forests. However, DBHs were normally rounded to 2 cm; therefore, RMSEs of DBH were within allowable ranges.

RMSEs of height of the broad-leaved forest using portable TLS were higher than those of the 62-year-old coniferous plantation forest. However, these were lower than the 32-year-old coniferous plantation forest, which was dense before thinning, even though secondary broad-leaved forests have complex structures and were measured using portable TLS.

Figure 2 shows *Quercus serrate* and *Castanea crenata* had undulating surfaces, whereas *Magnolia obovata* have a smoother surface than the others. Furthermore, *Cerasus jamasakura* had a curved stem. Therefore, point clouds of *Cerasus jamasakura* at the breast height were dispersed. However, species did not affect accuracy of DBH mensuration.

RMSEs outside the plot were expected to be lower than those in the plot because the trees outside the plot were measured from every 2-3 locations of the portable TLS at a closer distance than those in the plot. However, the RMSE of height outside the plot was higher than that in the plot. Distances from portable TLS to trees were too short to measure tree heights.

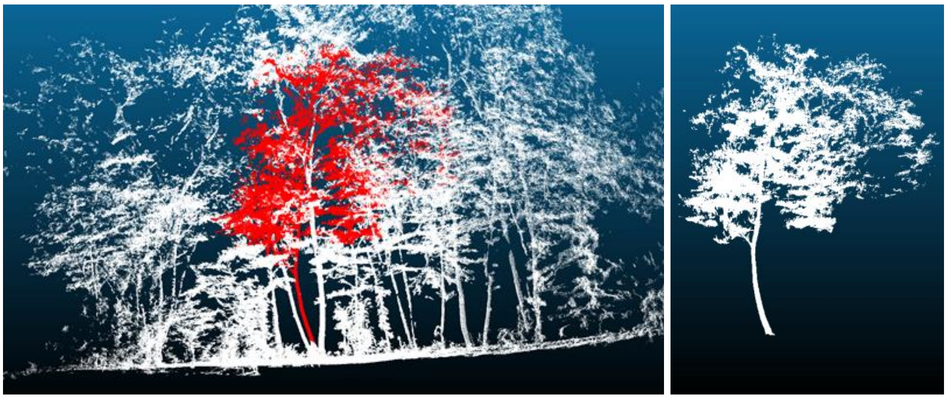

Figure 5. Extraction of the measured tree colored in Red (Left) and the extracted tree (Right)

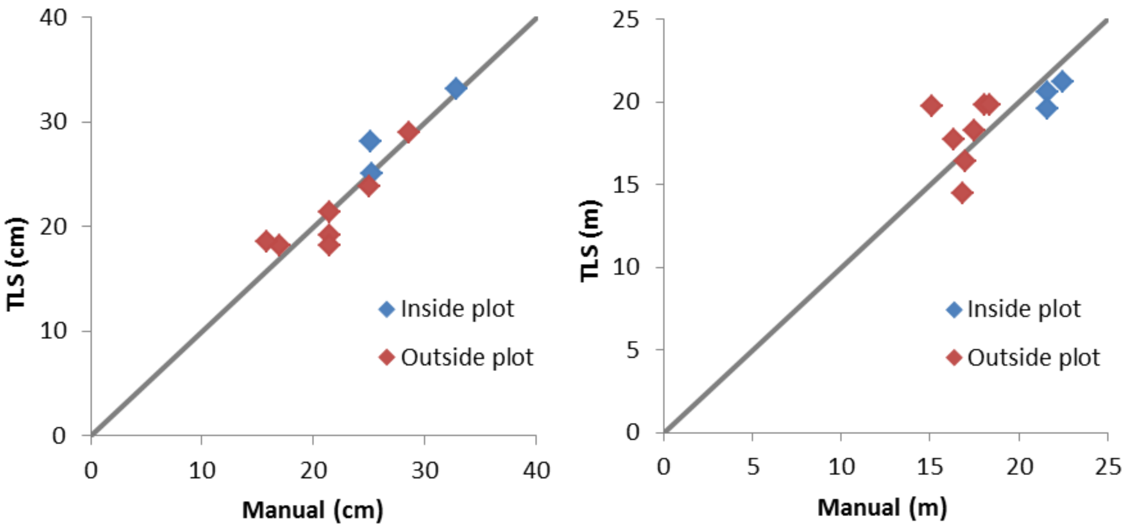

Figure 6. Results of DBH (left) and height (right)

3.2. Top End Diameters and Sweep

The top end diameters and sweeps of 77 logs were measured manually. However, portable TLS only detected 61 logs (Table 2). The rate of lost logs increased with increasing top end heights because of leaves and branches.

The average error and RMSEs of top end diameters were -0.65 cm and 2.19 cm, respectively (Table 2, Figure 7). RMSEs were beyond allowable ranges. Errors and RMSEs slightly increased with increasing top end heights, especially at a top end height of 13.2 m. The average error and RMSEs of top end diameters in coniferous plantation forests were -1.85 cm and 3.33 cm, respectively (Aruga et al., 2016). Furthermore, RMSEs clearly increased with increasing top end heights. Since the broad-leaved trees were extracted manually in the present study, leaves and branches were almost removed from stems. On the other hand, coniferous trees were extracted automatically, and some point clouds of leaves and branches were left in the point clouds of stems. Therefore, top end diameters of stems were overestimated.

Figure 8 shows errors of top end diameters according to the number of points, and Figure 9 shows the number of points according to the top end heights. Errors of top end diameters tended to be larger with a smaller number of points, and the number of points decreased with increasing top end heights. Therefore, errors of top end diameters tended to increase with increasing top end heights.

According to sweep, *Magnolia obovata* was relatively straight (Figure 2, Table 2), similar to coniferous plantation trees (Aruga et al., 2016). However, others were not straight, especially as sweep increased with increasing top end diameters (Table 2). Errors of sweep were overestimated and increased with increasing top end heights (Figure 10) because sweep was estimated using the center and diameter of each 10-cm slice; errors of top end diameters tended to increase with increasing top end heights.

Table 2. Results of top end diameter and sweep

Height	Manual Logs	LiDAR Logs	Top end diameter (cm) Average	Error	RMSE	Sweep (cm) Average	Error	RMSE
1.2 m	10	10	23.40	-0.06	1.91	1.00	-4.15	6.08
3.2 m	10	10	20.75	-1.04	1.44	3.55	-1.43	3.48
5.2 m	10	10	19.31	-0.61	2.44	3.30	-4.45	5.85
7.2 m	10	10	17.40	0.40	2.18	5.22	-3.45	4.14
9.2 m	10	9	15.52	-1.04	2.28	3.94	-6.64	7.28
11.2 m	10	6	12.74	-0.65	1.22	5.05	-11.91	13.77
13.2 m	10	4	10.42	-2.53	4.03	5.89	-11.98	12.88
15.2 m	4	2	9.63	-1.47	1.82	2.50	-9.97	10.22
17.2 m	3	0	8.30			7.67		
Inside	27	20	18.34	-1.51	2.59	3.79	-6.44	7.51
Outside	50	41	15.27	-0.22	1.96	4.28	-5.00	7.59
Quercus serrate	9	5	21.18	0.24	1.70	5.68	-6.35	6.75
Magnolia obovata	24	23	16.15	-0.88	2.38	1.35	-6.71	8.02
Castanea crenata	23	17	15.00	-0.73	2.56	5.27	-4.72	6.32
Cerasus jamasakura	21	16	15.98	-0.50	1.50	5.37	-4.23	8.31
Total	77	61	16.35	-0.65	2.19	4.11	-5.47	7.56

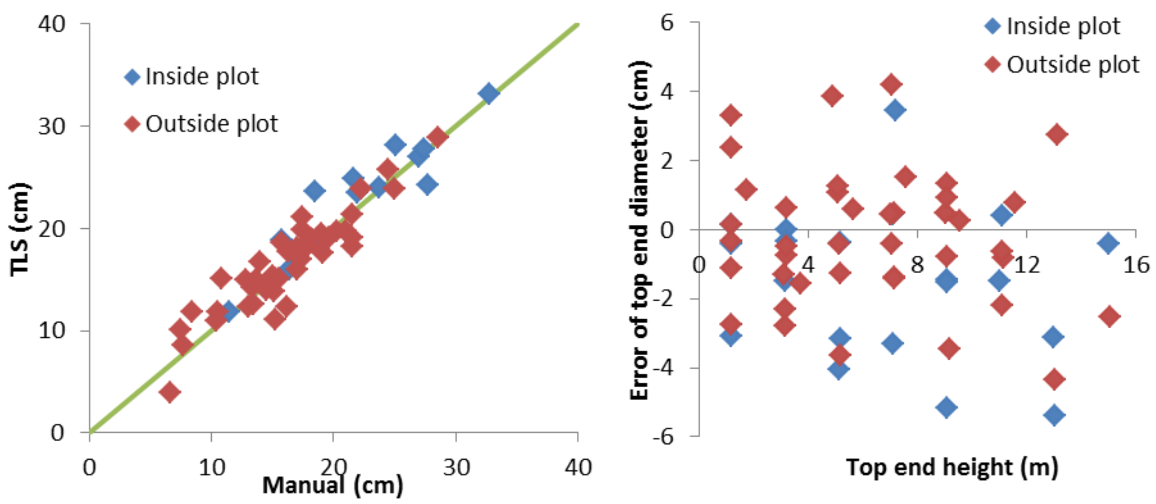

Figure 7. Results (left) and errors (right) of top end diameters

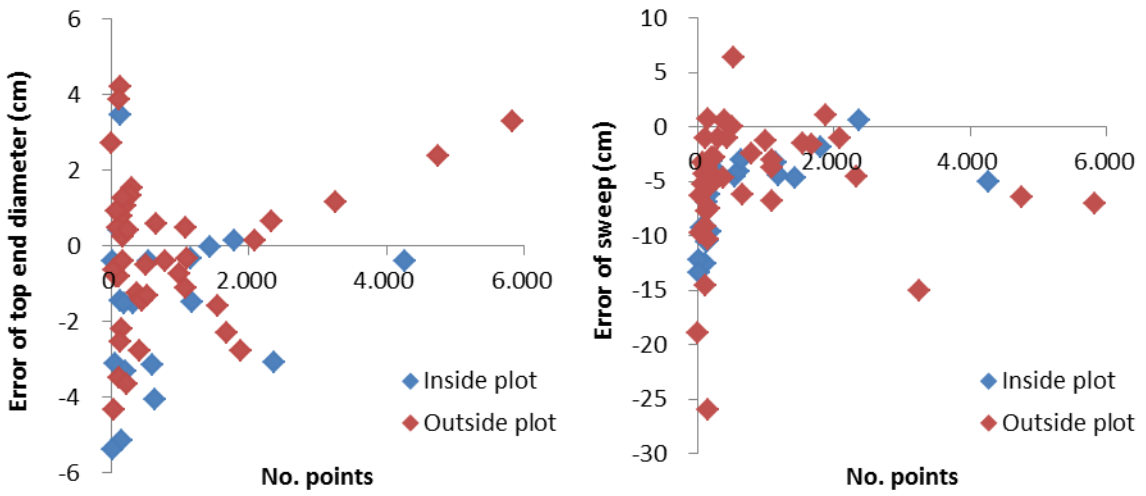

Figure 8. Errors of top end diameters (left) and sweep (right) according to the number of points

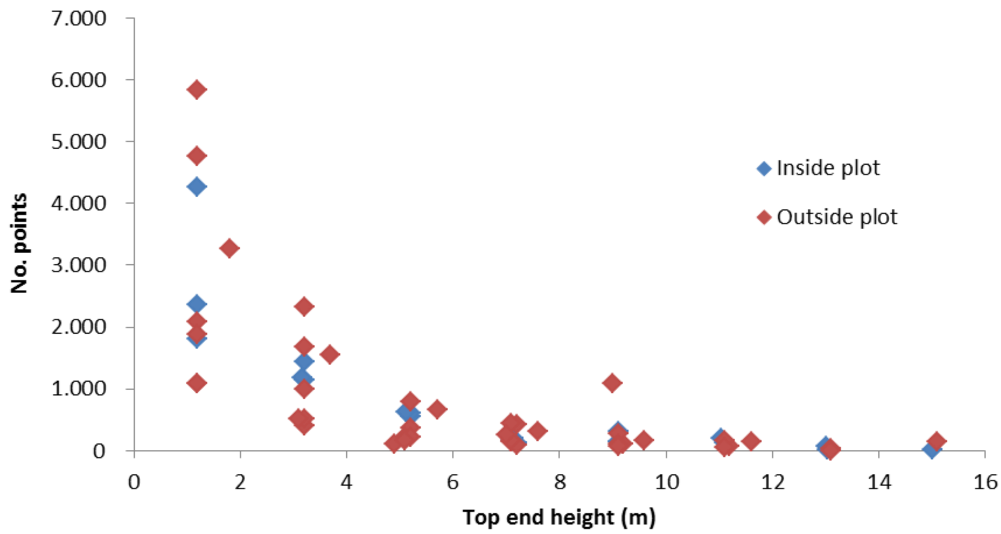

Figure 9. The number of points according to the top end heights

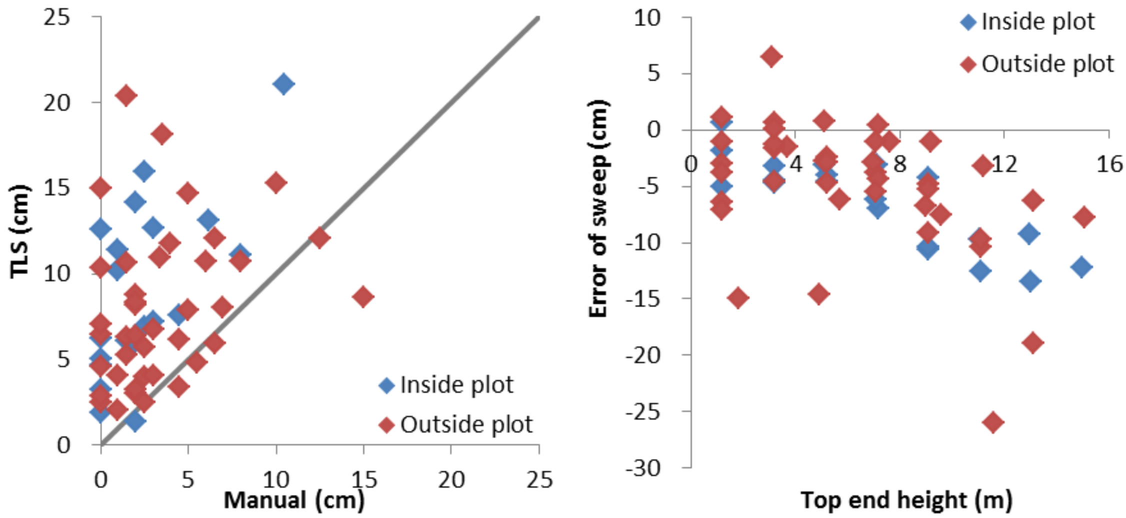

Figure 10. Results (left) and errors (right) of sweep

3.3. Tree Volumes

Average stem volume was 0.431 m^3 (Table 1, Figure 11). The average error and RMSE of stem volumes were -0.011 m^3 and 0.061 m^3, respectively. Average stem volume from the portable TLS was slightly overestimated. Average stem volumes using allometric equations with DBH and height (Forestry Agency of Japan, 1970) measured by manual and portable TLS were similar, 0.395 m^3 and 0.398 m^3, because of similar DBH and height values between the manual and portable TLS (Table 1). The average stem volumes using allometric equations were underestimated. RMSEs of stem volumes using allometric equations were 0.059 m^3 by manual measurement and 0.055 m^3 by portable TLS.

Average and RMSEs of extracted volumes from stems in the coniferous plantation forest were 0.620 m^3 and 0.162 m^3 (Aruga et al., 2016). Therefore, the RMSE was 26.1% of the average extracted volumes. On the other hand, the RMSE of stem volumes in the present study was 14.3%, which was lower than that of the coniferous plantation forest, despite the low-cost portable TLS, because of lower RMSEs of top end diameters and shorter distances from portable TLS.

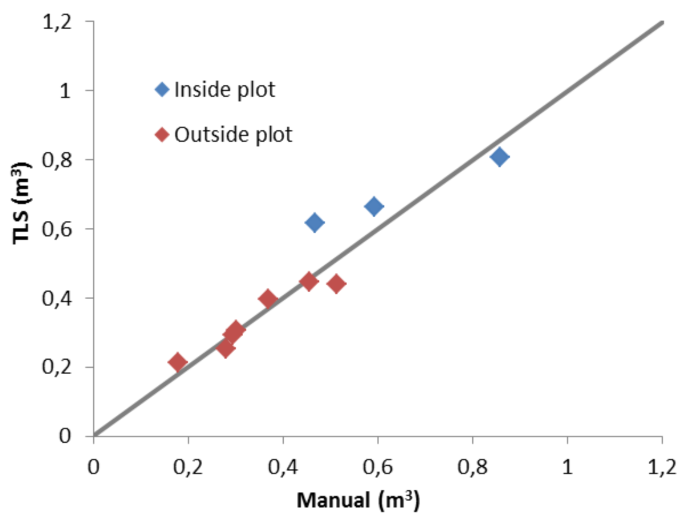

Figure 11. Stem volumes

4. Discussion

Kato et al. (2014a) measured 510 stems in broad-leaved and coniferous forests. As a result, RMSEs of DBH were between 1 and 4 cm, according to distances from portable TLS. In order to understand the limitation of portable TLS, Kato et al. (2015) measured a tropical forest with portable TLS and a higher-grade sensor. As a result, RMSE of DBH was 2.77 cm with the portable TLS but 1.14 cm with the higher-grade sensor. Similar to the present study, RMSE of DBH with portable TLS was around 2 cm, which was the allowable range, although it was higher than that measured with a higher-grade sensor.

Kelbe et al. (2012) have also shown that it is possible to produce a highly portable instrument by mounting a low-cost (<USD20,000) and lightweight (<5 kg) time-of-flight scanner on a simple rotary table and produce estimates of stem diameter and form. The portable laser has limited coverage compared to a high-grade sensor. Therefore, a field sampling scheme, such as the optimum sensor location and the optimum number of scans, should be developed to make the portable TLS useful in a practical field survey (Kato et al., 2015).

While DBH estimates can be retrieved from airborne laser scanning using allometric and statistical relationships, terrestrial LiDAR systems provide a more straightforward means for directly retrieving DBH values, usually by fitting circles, cylinders, or free-form curves to scattering points (Yang et al., 2013). The present study used points between 1.15-m and 1.25-m heights to estimate DBH and each 10-cm slice to estimate top end diameters, similar to Kato et al. (2011).

Tansey et al. (2009) and Calders et al. (2015) calculated the DBH on a 0.06 m thick cross-section between 1.27 and 1.33 m above the lowest point. Calders et al. (2015) used a least squares circle fitting algorithm to account for potential occlusion in the LiDAR data, because Tansey et al. (2009) compared least squares circle fitting, least squares cylinder fitting, and circular Hough transformation for estimating DBH and found that least squares circle fitting was the most accurate, even though cylinder fitting performed better in the case of leaning stems.

In order to assess the effects of the circle fit algorithm on the extracted stem diameters and volumes, Pueschel et al. (2013) tested one geometric algorithm and two algebraic algorithms. As a result, the geometric algorithm showed the best overall performance for the single scan DBH extraction (RMSE range 1.39-1.65 cm compared to 1.49-2.43 cm).

Furthermore, Pueschel et al. (2013) determined DBH using both the single value for the diameter fitted at the nominal breast height and using a linear fit of the stem diameter vertical profile. The latter is intended to reduce the influence of outliers and errors in the ground level determination. As a result, the linear fit based approach proved to be more robust for the single scan DBH extraction (RMSE range 1.39-1.74 cm compared to 1.47-2.43 cm).

DBH and top end diameters tended to be overestimated. Kato et al. (2011) used only the points at the inner side for the stem measurement because outliers represented unwanted data (i.e., scanner returns from branches and leaves).

In order to improve the accuracy of DBH and top end diameter, the geometric algorithm for circle fit, as well as cylinder fit for leaning stems and free-form curves for undulating surfaces in a broad-leaved forest, should be examined in a future study. Furthermore, using a linear fit of the stem diameter vertical profile or using only the points at the inner side would be another option to improve the accuracy of DBH and top end diameters.

5. Conclusion

In the present study, a secondary broad-leaved forest was measured using a low-cost portable TLS. Then, DBH, height, top end diameter, sweep, and stem volume were analyzed and compared with results of coniferous plantation forests using terrestrial LiDAR. RMSE of DBH was 1.91 cm, which was higher than that of coniferous plantation forests. However, DBHs were normally rounded to 2 cm; therefore, RMSEs of DBH were within the allowable range. Furthermore, *Quercus serrate* and *Castanea crenata* had undulating surfaces and *Cerasus jamasakura* had a curved stem. However, species did not affect the accuracy of DBH mensuration.

RMSE of height was 2.26 m, which was similar to 2.29 m of the 32-year-old coniferous plantation forest with high stand density. RMSE of height outside the plot was higher than that inside the plot because distances from the portable TLS to trees were too short to measure the heights of trees.

The top end diameters and sweeps of 77 logs were measured manually, whereas the portable TLS only detected 61 logs. The log detection rate was 79.22% in the present study, whereas it was 85.23% in the coniferous plantation forest (Aruga et al., 2016).

RMSE of top end diameters in the present study were lower than the coniferous plantation forest because the broad-leaved trees were extracted manually in the present study, whereas coniferous trees were extracted automatically. Errors in top end diameters tended to increase with increasing top end heights because the number of points decreased with increasing top end heights.

Errors of sweep were overestimated and increased with increasing top end heights because sweep was estimated using the center and diameter each 10-cm slice. RMSE of sweep in the present study was much higher than that of coniferous plantation trees.

RMSE of stem volumes in the present study was 14.3%, which was lower than that of coniferous plantation forest, despite the low-cost portable TLS, because of lower RMSEs of top end diameters and shorter distances from the portable TLS.

In the present study, only stems were extracted and measured manually from the portable TLS. However, the vertical distribution of above-ground biomass is important for many applications, such as fire hazard and biodiversity assessment (Calders et al., 2015). In order to analyze above-ground structure, methods to automatically extract and measure stems, branches, and foliage should be developed.

Acknowledgements

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