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Economic Balance of a Clearcutting Operation Using Terrestrial LiDAR

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Abstract

The present study verified terrestrial LiDAR data measured at a clearcutting operation site of the Funyu Experimental Forest, Utsunomiya University, Japan. The economic balance of the operation was analyzed with time studies. Finally, the economic balances estimated using terrestrial LiDAR data and an optimal bucking algorithm were compared. The root mean squared errors (RMSEs) between top end diameters of logs that were obtained below 10 m and measured using manual and terrestrial LiDAR were within 2 cm. Log diameters were normally rounded to 2 cm; therefore, the RMSEs were within allowable ranges. However, RMSEs were increased according to an increase in top end heights because of branches. Furthermore, the understory vegetation also disrupted laser scanning. The economic balance considering sweep from terrestrial LiDAR was estimated. As a result, the profit was estimated to be USD 96,797/ha, which was close to that estimated by manually measured data, at USD 90,235/ha. Without considering sweep, profit was overestimated as USD 116,306/ha. The use of an optimal bucking algorithm improved the profit to USD 126,536/ha.

Keywords: Economic balance, Optimal bucking algorithm, Sweep, Terrestrial LiDAR, Top end diameter of log

1. Introduction

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 logging residue (at USD 0.32/kWh), (b) general materials such as sawmill residue (at USD 0.24/kWh), and (c) recycled materials such as construction waste wood (at USD 0.13/kWh) (ANRE 2012). Incentives have promoted the use of power generated from unused materials, and they are expected to promote the use of logging residue in the near future.

The price of USD 0.32/kWh for unused materials was determined based on a model plant featuring 5 MW of direct combustion with initial cost USD 4,100.00/kW, annual operating cost USD 270.00/kW, and Internal Rate of Return 8%. Annual consumption of fuel wood chips was 60,000 ton/year collected within 50 km with a price of USD 120.00/ton consisting of 34% (USD 40.80/ton) was extraction, 25% (USD 30.00/ton) was transportation, 16% (USD 19.20/ton) was chipping, and 25% (USD 30.00/ton) was chip transportation. However, forest ownership in Japan is characterized by a large number of small, fragmented, and scattered forest owners (Forestry Agency of Japan, 2009). Therefore, it is difficult to supply the amount of 60,000 ton/year stably from such small, fragmented, and scattered forests.

To promote the use of thinned wood and logging residue from these forests, the price of USD 0.40/kWh for unused materials with less than 2 MW of direct combustion was set, starting from April 2015. The price of USD 0.40/kWh was determined based on a model plant featuring 1.5 MW of direct combustion with initial cost USD 6,200.00/kW, annual operating cost 640.00/kW, and Internal Rate of Return 8%. Annual consumption of fuel wood chips was 20,000 ton/year collected within 30 km with a price of USD 90.00/ton excluding chip transportation because a small-scale power generation plant could chip small amount volumes necessary for its own plant on its own place.

The Nasu-machi Forest Owners' Co-operative in Tochigi prefecture, Japan extracts smaller diameter logs for a small-scale power generation plant in addition to larger diameter logs for saw timber or laminated

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lumber. However, the extraction of smaller diameter logs would increase revenue, but also increase costs, and subsequently, decrease profitability. Numerous studies have examined optimal bucking for increasing revenues (Akay et al., 2010; Haynes and Visser, 2004; Nagumo et al., 1981; Nakajima et al., 2008; Nakajima et al., 2009; Olsen et al., 1991; Sessions et al., 1989; Wang et al., 2009; Yoshida and Imada, 1989). However, the bucking methods affected the efficiencies of the bucking and extracting operations, thereby increasing costs and lowering profitability. Therefore, it is essential to conduct optimal bucking with a consideration of costs and profitability as well as revenues.

Nakahata et al. (2014) integrated forwarding costs into stem-level optimum bucking problem. They investigated commercial thinning operations around Nasunogahara area, where the Nasu-machi Forest Owners' Co-operative is located. Then, they analyzed the relationships between log sizes and operational costs of processing as well as forwarding, and developed equations to estimate operational costs according to log sizes. The operation costs estimated with the equations were increased according to the extraction of smaller diameter logs. Thus, they determined the optimal bucking methods to maximize profits and the optimum extraction rates of small-sized logs. However, log volumes for a small-scale power generation plant with the optimal bucking method were smaller than the actual values consisted of sweep and defect logs as well as small-sized logs, because this model classified only small-sized logs for a power generation plant. This model only considered the taper curve formula, but did not consider detailed descriptions of stem shape such as sweep and lean. However, bucking operations should be conducted considering detailed descriptions of stem shape and log quality.

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 and volumes (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 present study verified terrestrial LiDAR data measured at a clearcutting operation site of the Funyu Experimental Forest, Utsunomiya University, Japan. Then, the economic balance of the operation was analyzed with time studies. Finally, the economic balances estimated using terrestrial LiDAR data and an optimal bucking algorithm were compared.

2. Materials and Methods

Study sites included 32- and 62-year-old Japanese cypress (*Chamaecyparis obtusa*) and Japanese cedar (*Cryptomeria japonica*), which are major plantation species in Japan (Figure 1). Areas measured by terrestrial LiDAR (Figure 2, Figure 3) were 0.71 ha and 0.37 ha, and contained 1,138 and 441 trees in 32- and 62-year-old forests, respectively. Therefore, stand densities were 1,603 stems/ha and 1,192 stems/ha. Average DBH, height, and branch height were 18.79 cm, 16.08 m, and 5.8 m in the 32-year-old forest and 26.08 cm, 22.69 m, and 13.5 m in the 62-year-old forest. DBH, height, and diameters at 4- and 6-m heights were measured and compared with terrestrial LiDAR data obtained for 63 trees and 58 trees from 32- and 62-year-old forests, respectively (Table 1 and 2).

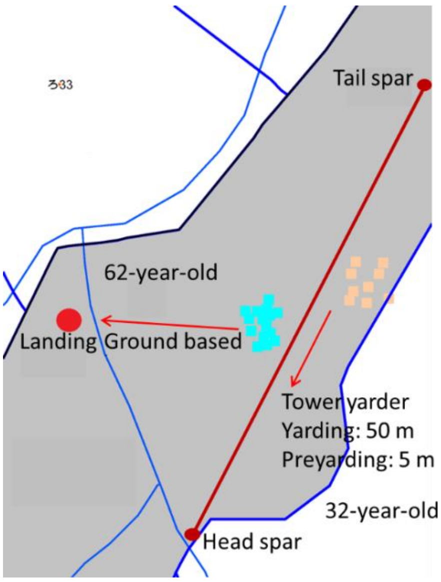

Figure 1. Study sites


Figure 2. Terrestrial LiDAR

Figure 3. Study sites (Left: 32-year-old, Right: 62-year-old)

Table 1. DBH and Height

	No.		Average		Error		RMSE	
	DBH	Height	DBH (cm)	Height (m)	DBH (cm)	Height (m)	DBH (cm)	Height (m)
32-year-old	63	63	18.79	16.08	-0.34	0.41	1.33	2.29
62-year-old	58	58	26.08	22.69	0.47	0.68	1.35	1.41
Total	121	121	22.28	19.25	0.05	0.54	1.34	1.92

Table 2. Diameters at 4- and 6-m heights

	No.		Average		Error		RMSE	
	4 m	6 m	4 m (cm)	6 m (cm)	4 m (cm)	6 m (cm)	4 m (cm)	6 m (cm)
32-year-old	60	55	16.17	14.76	-0.61	-1.08	1.28	1.97
62-year-old	55	51	23.39	22.59	-0.03	0.05	1.11	1.20
Total	115	106	19.59	18.52	-0.33	-0.53	1.20	1.65

Time studies of a clearcutting operation were conducted in the 62-year-old forest. In total, 114 logs from 15 stems were extracted by a ground based system, which included the use of chainsaw felling, processor processing, and grapple loader piling. Additionally, 62 logs were extracted from 10 stems by a tower yarder (Table 3, Figure 4). The average yarding and preyarding distances were 50 m and 5 m, respectively. Productivity and costs were estimated based on results obtained from the time studies. Revenues were estimated using a price list that included length, sweep class, and diameter at a log auction market (Table 4). Sweep classes were classified by the ratio of sweep to top end diameters, including less than 12% for A (saw log), 12–20% for B (lamina log), and more than 20% for C (chip log).

The optimum bucking method for maximizing profits was determined using the following process: 1) estimate the possible combinations of log lengths bucked from felled wood, 2) estimate the values for log volume v (m^3/log) using those for log length l (m) and top-end diameter of log d (cm) with terrestrial LiDAR data, 3) estimate revenues, 4) estimate expenses, 5) estimate economic balances, and 6) determine the optimum bucking method for maximizing profits.

The productivities, P (m^3/h) were estimated with cycle times, CT (s/cycle) and volumes, V (m^3/cycle):

$$P = \frac{3{,}600 \times V}{CT} \tag{1}$$

The direct operational expenses, OE (USD/m^3) were estimated using productivities and hourly operational expenses consisting of labour expenses, OL (USD/h) and machinery expenses, OM (USD/h).

$$OE = \frac{OL + OM}{P} \tag{2}$$

Labour expenses were set at USD 26.09/h. Machinery expenses consisted of maintenance, management, depreciation, and fuel and oil expenses, USD 4.02/h for a chainsaw, USD 27.59/h for a tower yarder, USD 40.54/h for a processor and USD 23.59/h for a grapple loader. In addition, truck transportation expenses were estimated as USD 13.00/m^3. Handling fees for a Forest Owners' Co-operative were estimated as 3% of revenues. In the log auction market, handling fees were estimated as 5% of revenues and piling fees were estimated as USD 7.00/m^3.

Table 3. Study sites in a clearcutting operation

	No. Stem	No. Log	Log volume (m^3/log)
Ground based	15	114	0.082
Tower yarder	10	62	0.099
Total	25	176	0.088

Figure 4. Forestry machines (Left: tower yarder, middle: processor, right: grapple loader)

Table 4. Price list

Japanese cypress				Japanese cedar			
Length (m)	Sweep class	Diameter (cm)	Price (USD/m^3)	Length (m)	Sweep class	Diameter (cm)	Price (USD/m^3)
2	A	6–14	30.00	2	A	6–14	28.00
		16–28	148.90			16–	69.80
		30–	330.00		B	6–14	28.00
	B	6–14	30.00			16–	68.90
		16–	68.90		C	6–	28.00
	C	6–	28.00	3	A	11–14	118.60
3	A	11–14	112.40			16–20	147.80
		16–	205.83			22–28	133.00
	B	6–14	28.00		B	6–28	28.00
		16–28	177.60			30–	50.00
	C	6–	28.00		C	6–	28.00
4	A	10–14	170.90	3.65	A	22–28	122.00
		16–20	190.00			30–	138.20
		22–	258.00	4	A	22–28	154.80
						30–	146.60

3. Results and Discussion

3.1 Verifications

Average errors (manual–LiDAR) of DBH and height were -0.34 cm and 0.42 m in the 32-year-old forest, and 0.47 cm and 0.68 m in the 62-year-old forest, respectively (Figure 5). Root mean square errors (RMSEs) of 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. Log diameters were normally rounded to 2 cm; therefore, RMSEs of DBH were within allowable ranges. The RMSE of height in the 32-year-old forest was higher than that in the 62-year-old forest because of higher stand density.

Diameters of 63 and 58 trees at 4- and 6-m heights in the 32- and 62-year-old forests were measured manually. However, terrestrial LiDAR only detected diameters of 60 and 55 trees at 4- and 6-m heights in the 32-year-old forest, and 55 and 51 trees at 4- and 6-m heights in the 62-year-old forest due to the presence of branches, especially at 6 m (Figure 6). Average errors of diameters at heights of 4 and 6 m were -0.61 cm and -1.08 cm in the 32-year-old forest, and -0.03 cm and -0.05 cm in the 62-year-old forest. RMSEs of diameters at 4 and 6 m were 1.28 cm and 1.97 cm in the 32-year-old forest, and 1.11 cm and 1.20 cm in the 62-year-old forest. RMSEs of measurements from the 32-year-old forest were higher than those from the 62-year-old forest. However, both RMSEs were still within allowable ranges.

The top end diameters, sweep, and ratio of sweep to the top end diameter of 176 logs were measured manually. However, terrestrial LiDAR only detected 150 logs (Table 5). The average error of top end diameters was -1.85 cm and RMSEs were 3.33 cm. RMSEs were beyond allowable ranges.

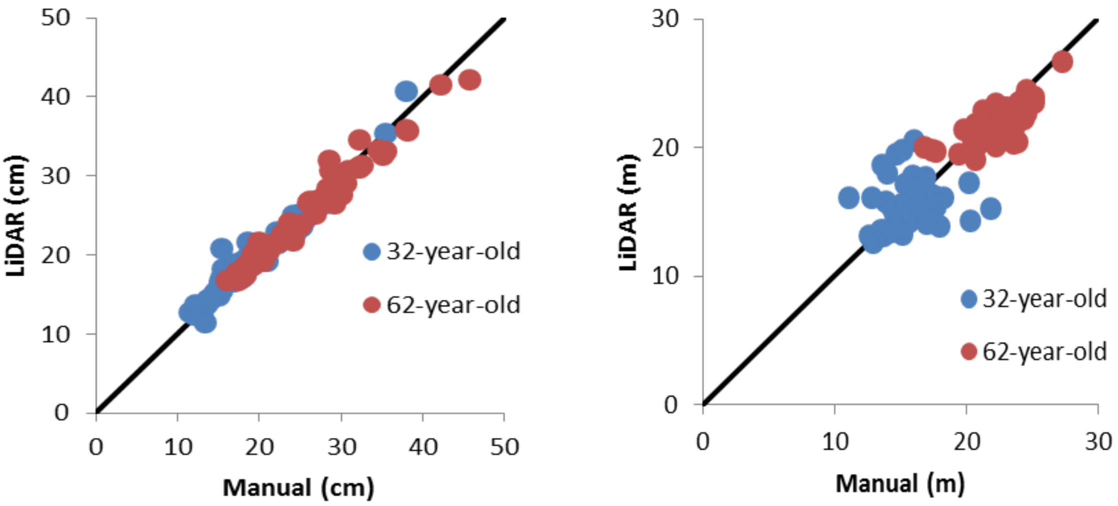

Figure 5. Results of DBH (left) and height (right)

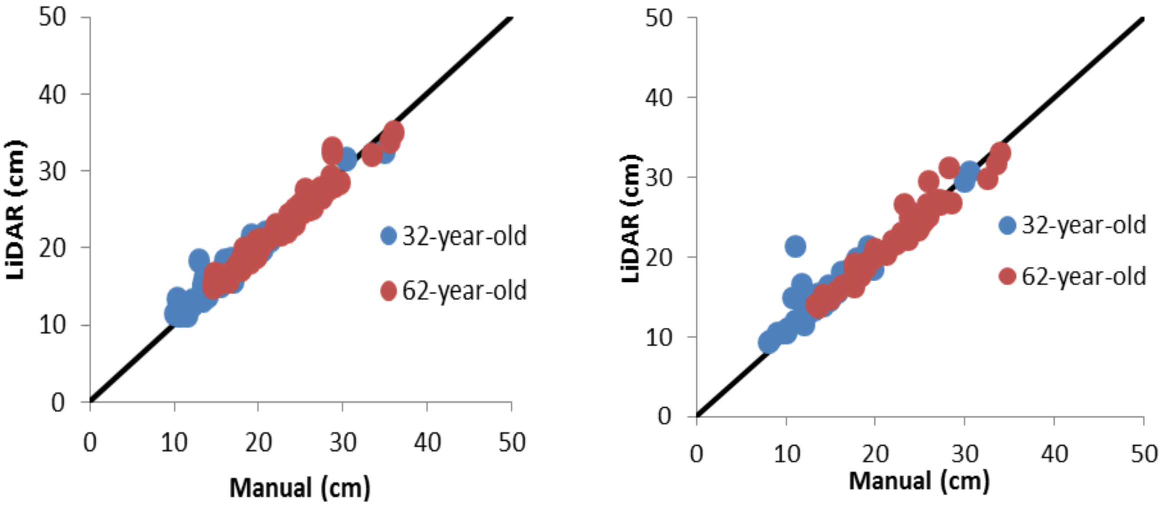

Figure 6. Results of diameters at 4- (left) and 6-m (right) heights

Table 5. Results of top end diameter, sweep, and ratio according to heights

	Manual	LiDAR	Top end diameter (cm)			Sweep (cm)			Ratio (%)		
Height	Logs	Logs	Average	Error	RMSE	Average	Error	RMSE	Average	Error	RMSE
- 5 m	32	32	22.83	-0.37	1.55	2.50	0.15	1.39	11.40	1.15	6.80
- 10 m	40	40	20.38	-0.75	1.43	1.04	-0.46	0.78	5.29	-1.85	3.71
- 15 m	38	33	16.63	-2.37	3.80	1.14	-1.50	2.60	7.03	-6.62	12.06
- 20 m	53	40	12.51	-3.44	4.46	1.38	-2.31	3.34	12.00	-11.38	17.52
20 m -	13	5	8.16	-4.02	6.88	1.68	-2.65	3.55	21.74	-12.43	15.17
Total	176	150	16.74	-1.85	3.33	1.48	-1.12	2.34	10.01	-5.15	11.62

Errors and RMSEs increased with increasing top end heights because of branches (Figure 7). Furthermore, understory vegetation also disrupted laser scanning. Therefore, RMSEs below 5-m top end heights were higher than those between 5 and 10-m top end heights, especially sweep because of swelling near the base (Figure 8).

Logs were bucked into 14 4-m logs, 74 3-m logs, and 88 2-m logs (Figure 9). However, terrestrial LiDAR detected 14 4-m logs, 72 3-m logs, and 64 2-m logs. Terrestrial LiDAR could not detect two 3-m logs and 24 2-m logs. The 2-m logs were bucked from the bottom and top of trees for which laser scanning was disrupted by the understory and branches (Figure 10).

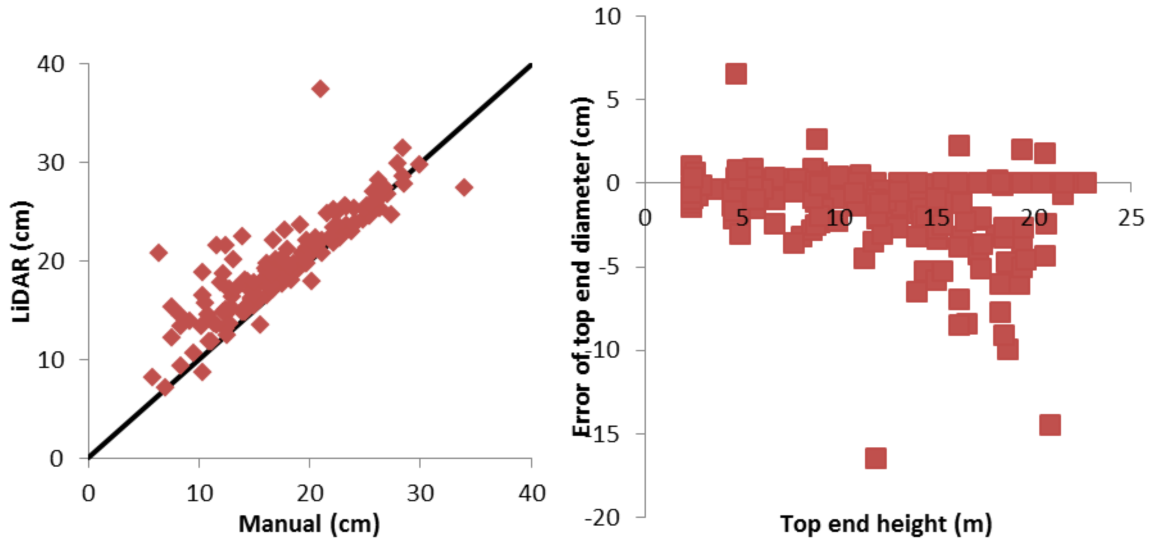

Figure 7. Results (left) and errors (right) of top end diameters

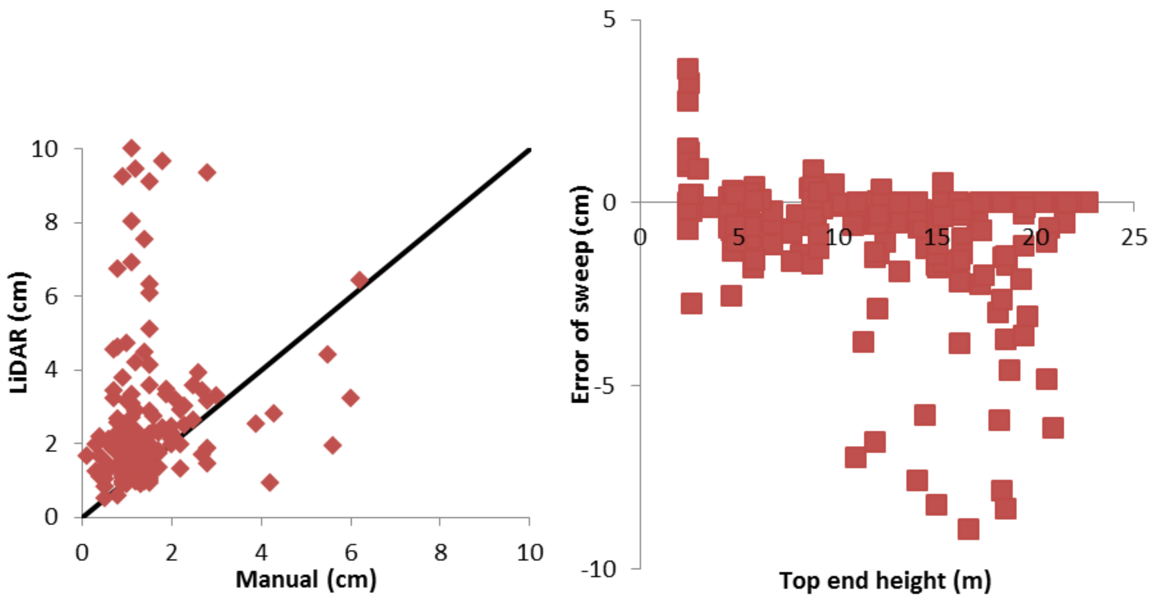

Figure 8. Results (left) and errors (right) of sweep

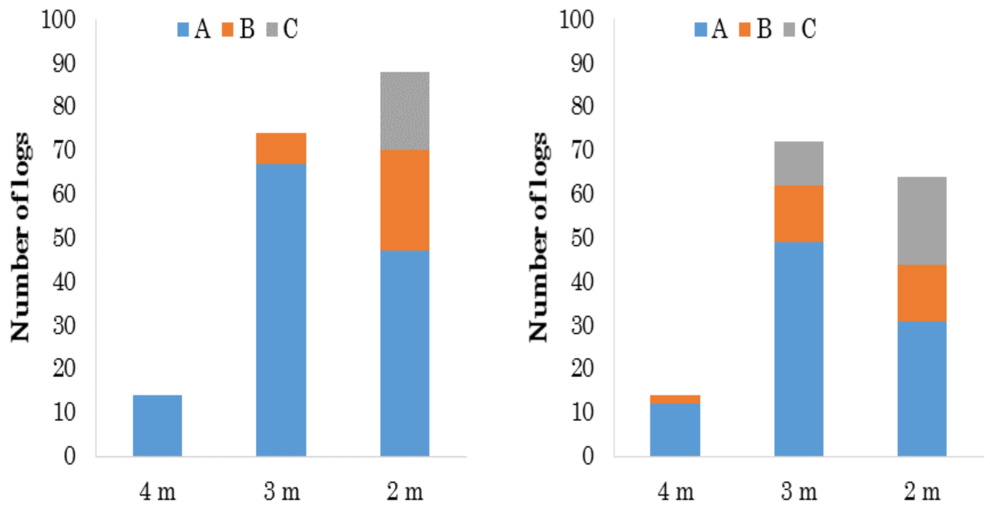

Figure 9. Sweep class distribution (left: manually measured, right: terrestrial LiDAR)

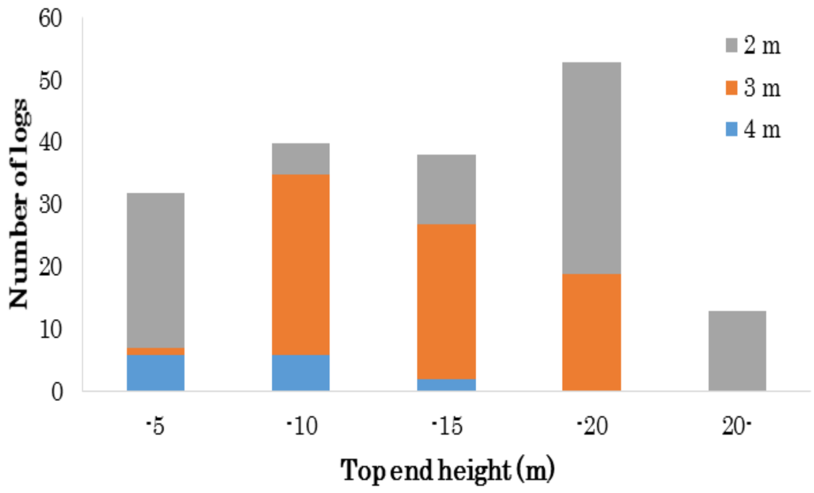

Figure 10. Log length distribution according to small end heights

3.2 Time Study

The values of felling cycle time CT_C (s/stem) were related to those of stem volume Vn (m^3/stem) using regression analysis (Figure 11).

$$CT_C = 59Vn + 35 \text{ (s/stem)} \tag{3}$$

Thereafter, equations for estimating the productivities (Eq. 4) and costs (Eq. 5) of felling operations were established.

$$P_C = \frac{3{,}600Vn}{59Vn+35} \text{ (m}^3\text{/h)} \tag{4}$$

$$OE_C = \frac{1.05}{Vn} + 1.78 \text{ (USD/m}^3\text{)} \tag{5}$$

The average velocities with in and out hauling and preyarding for tower yarder were 1.03, 2.44, and 0.44 m/s, respectively. The average loading and unloading time was 127 s/stem. The values of yarding cycle time CT_Y (s/stem) were expressed with yarding and preyarding distances as x and y (m/cycle).

$$CT_Y = 1.4x + 4.5y + 127 \text{ (s/stem)} \tag{6}$$

Thereafter, equations for estimating the productivities (Eq. 7) and costs (Eq. 8) of yarding operations were established.

$$P_Y = \frac{3{,}600Vn}{1.4x+4.5y+127} \text{ (m}^3\text{/h)} \tag{7}$$

$$OE_Y = \frac{0.03x+0.10y+2.81}{Vn} \text{ (USD/m}^3\text{)} \tag{8}$$

Costs of processor processing were estimated considering log sizes (Nakahata et al., 2013) because the operation costs were increased according to the extraction of smaller diameter logs. Thus, the optimal bucking methods to maximize profits were determined. The values of average delimbing and cross-cutting time tpp (s/log) were related to those of average log volume Vla (m^3/log) using regression analysis (Eq. 9) as shown in Figure 12.

$$tpp = 94Vla + 9 \text{ (s/log)} \tag{9}$$

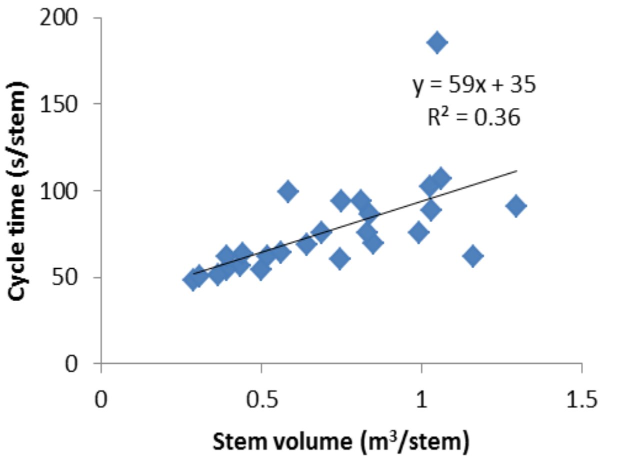

Figure 11. Stem volume and cycle time for chainsaw felling

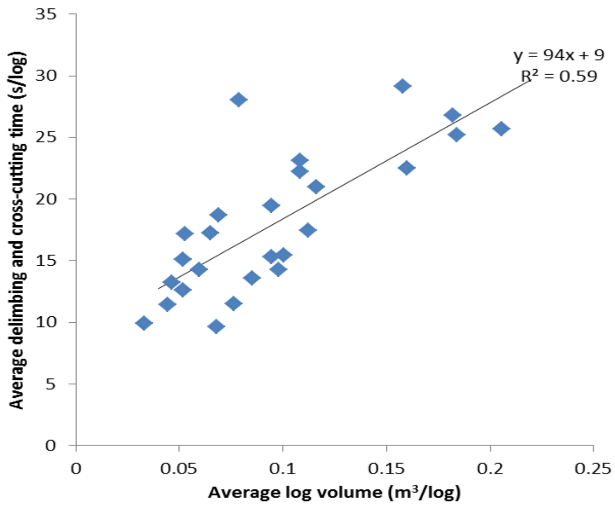

Figure 12. Average log volume and average delimbing and cross-cutting time for processor

The tree grabbing and tops processing times of processing operations were 39 and 21 s, respectively. Therefore, the values of processing cycle time CT_P (s/stem) can be expressed using the number of logs n (logs/stem).

$$CT_P = (94Vla + 9)n + 60 \text{ (s/stem)} \tag{10}$$

Thereafter, equations for estimating the productivities (Eq. 11) and costs (Eq. 12) of processing operations were established.

$$P_P = \frac{3{,}600Vla\times n}{(94Vla+9)n+60} \text{ (m}^3\text{/h)} \tag{11}$$

$$OE_P = \frac{(2.42Vla+0.23)n+1.56}{Vla\times n} \text{ (USD/m}^3\text{)} \tag{12}$$

The values of piling cycle time CT_G (s/stem) were related to those of extracted volume $Vla \times n$ (m^3/stem) using regression analysis (Figure 13).

$$CT_G = 89Vla \times n + 176 \text{ (s/stem)} \tag{13}$$

Thereafter, equations for estimating the productivities (Eq. 14) and costs (Eq. 15) of piling operations were established.

$$P_G = \frac{3{,}600Vla\times n}{89Vla\times n+176} \text{ (m}^3\text{/h)} \tag{14}$$

$$OE_G = \frac{2.42}{Vla\times n} + 1.23 \text{ (USD/m}^3\text{)} \tag{15}$$

3.3 Economic Balance

Next, economic balances were estimated considering sweep from terrestrial LiDAR. As a result, the profit was estimated as USD 96,797/ha, which was close to that estimated by manually measured data, at USD 90,235/ha (Figures 14 and 15). Although terrestrial LiDAR detected only 150 out of 176 logs, the revenues estimated by the LiDAR data were overestimated because top end diameter, subsequently volumes were also overestimated.

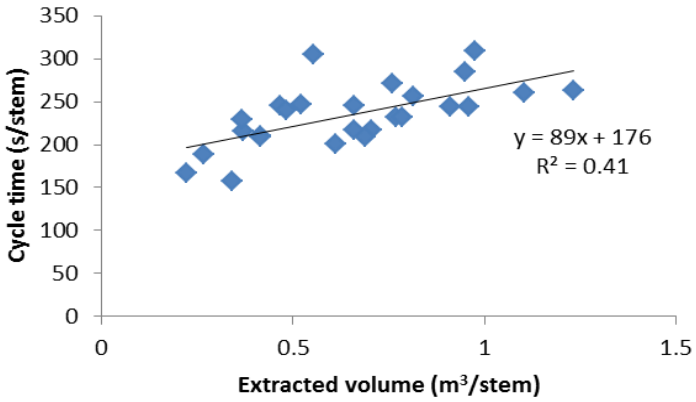

Figure 13. Extracted volume and cycle time for grapple loader piling

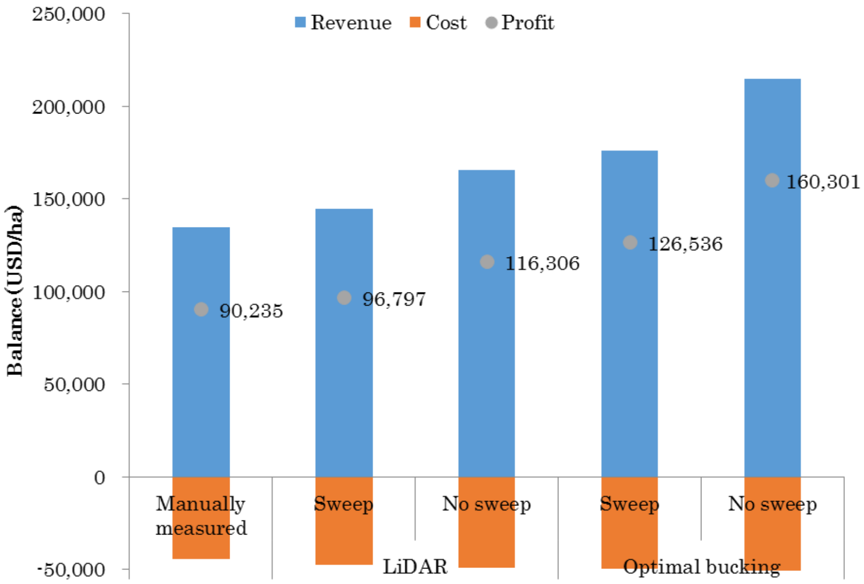

Figure 14. Economic balance

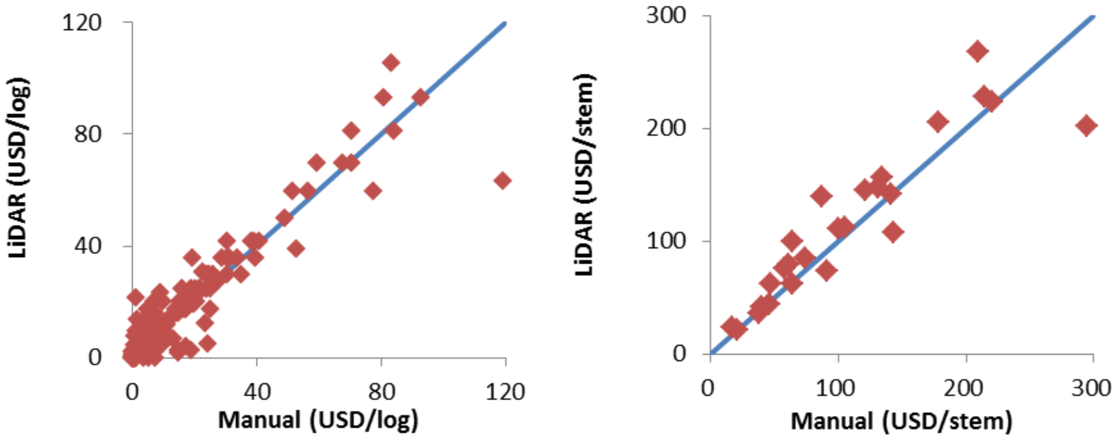

Figure 15. Revenue from logs (Left) and stems (Right)

In this study, terrestrial LiDAR was used to obtain detailed descriptions of stem shape such as taper, sweep and lean. If terrestrial LiDAR was not used, sweep class was not classified. If all logs were classified as A for sweep class, the profit was overestimated at USD 116,306/ha. Therefore, terrestrial LiDAR was effective in obtaining a detailed description of stem shape and in estimating revenues considering sweep class. The use of an optimal bucking algorithm increased the profit to USD 126,536/ha.

3.4. Discussion

Kato et al. (2014a) measured 510 stems in Broad-leaved and conifer forests. As a result, RMSEs of DBH were between 1 and 4 cm according to distances from portable terrestrial laser and RMSEs of height were between 0.2 and 1.2 m. Omasa et al. (2002) measured 24 stems in Japanese larch (*Larix leptolepis*) plantation forest. As a result, RMSE of DBH was 0.73 cm. Urano and Omasa (2002) measured 40 stems in Japanese cedar (*Cryptomeria japonica*) plantation forests. As a result, RMSE of DBH was 0.61 cm. Yoshimi et al. (2004) measured 20 stems in mixed forest. As a result, RMSE of height was 0.18 m. As Kato et al. (2014a) used low cost portable terrestrial laser with range error of 6 mm at 10 m while this study used terrestrial LiDAR with range error of 2 mm at 10 m, RMSEs of DBH on Kato et al. (2014a) were higher than those of this study, but RMSEs of height were lower. RMSEs of DBH and height in Omasa et al. (2002), Urano and Omasa (2002) and Yoshimi et al. (2004) were much lower than those of this study.

RMSEs of top end diameters increased with increasing top end heights because of branches. Furthermore, understory vegetation also disrupted laser scanning. These trends were similar to results of Murphy et al. (2010). Acuna et al. (2009) measured 42 stems in Radiata pine plantation forest. As a result, extracted volumes measured manually and with terrestrial LiDAR were 1.81 and 1.76 m^3/stem, respectively. Difference was 0.05 m^3/stem (3%). Then, value difference was 7%. In this study, average extracted volumes measured manually and with terrestrial LiDAR were 0.62 and 0.70 m^3/stem. Difference was -0.08 m^3/stem (13%). Acuna et al. (2009) underestimated extracted volumes whereas this study overestimated them because of overestimated top end diameters. Therefore, value difference was also overestimated as -8% in this study.

4. Conclusions

In this study, the use of terrestrial LiDAR could provide a detailed description of stem shape. If terrestrial LiDAR was not used, sweep class was not classified. If all logs were classified as grade A for sweep class, the profit was overestimated. Therefore, terrestrial LiDAR was effective in obtaining a detailed description of stem shape and in estimating revenues taking into account sweep class.

The use of an optimal bucking algorithm successfully improved the profit in this study. However, the optimal bucking algorithm should be applied in the fields. Therefore, to conduct real time optimal bucking, a harvester or other forestry vehicle-mounted LiDAR systems should be developed.

Tops and branches are dominant logging residues. However, terrestrial LiDAR could not accurately measure the tops and branches. Combining airborne and terrestrial LiDAR would allow the tops and branches to be measured more accurately.

Acknowledgement

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