Original scientific paper

Examining the Optimal Bucking Method to Maximize Profits in Commercial Thinning Operations in Nasunogahara Area, Tochigi Prefecture, Japan

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Abstract

Optimal bucking methods were applied to two operational sites of the Nasu-machi Forest Owners' Co-operative to maximize profits, with and without taking log size into consideration, and to maximize revenues considering a new subsidy system and higher unit prices of small-sized logs. Corresponding optimum extraction rates and small-sized log prices were examined. Extraction rates from stands using the optimal bucking method to maximize profits considering log sizes were similar to the actual values, unlike the estimations obtained using other methods, e.g. without considering log sizes or maximizing revenues. However, the differences in extracted volumes and economic balances among these estimations were small and can be said to be within the error limits traditionally seen for forests and forestry conditions in the stands. The stands were about 50 years old, with an average diameter at breast height (DBH) of about 20 cm. Differences in extraction rates from stems with a DBH exceeding 20 cm were small. However, extraction rates from stems with a DBH less than 20 cm were significantly different. Therefore, the optimal bucking method to maximize profits considering log sizes could help determine the optimal extraction rates of younger stands with smaller DBHs. Possible effects of the new subsidy system and different unit prices for small-sized logs were also discussed. Both the new subsidy system and the unit prices with feed-in tariff contributed to an increase in extracted volumes of small-sized logs.

Keywords: Optimal bucking, maximum profit, extraction rate, economic balance, small-sized logs, subsidy

1. Introduction

Facilities such as biomass power plants, chip production factories, and pellet plants in Tochigi prefecture require woody biomass resources. These resource requirements are mainly fulfilled by sawmill residues and construction waste woods. However, there are concerns about the future adequacy of supplies of these materials, because of the increased number of entrepreneurs who have set up biomass power plants as a measure against climate change and to improve energy security. Furthermore, the Feed-In Tariff (FIT) scheme was introduced in Japan starting July 1, 2012. In FIT, the purchase price (without tax) of electricity generated with unused materials such as small-sized logs and logging residue, general materials such as sawmill residue, and recycled material such as construction waste wood are 0.32 USD/kWh, 0.24 USD/kWh, and 0.13 USD/kWh, respectively (Agency for Natural Resources and Energy 2012). Power generation with unused materials was incentivized. Therefore, the use of small-sized logs and logging residue must be promoted in the near future.

Tochigi prefecture measures 640 785 ha, of which about 54.5% is covered by forests (Tochigi Prefectural Government 2009). About 45% of these forests are man-made, constituting a volume of 42 255 000 m^3

(62.4%). Given the delay in thinning, which was a serious problem for man-made forests throughout Japan, the Tochigi Prefectural Government introduced a new regulation in April 2008, along with subsidies for thinning operations, aimed at making forests healthy (Tochigi Prefectural Government 2010a). As a result, thinning operations were conducted on 2 663 ha of forest in 2009. However, large amounts of thinned wood were left in the forests, because nearly all the thinning operations conducted were pre-commercial for small-sized trees and affected profitability.

The Nasu-machi Forest Owners' Co-operative extracts smaller diameter logs for pellets or pulp in addition to larger diameter logs for saw timber or laminated 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. 1989a, 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.

The optimum bucking problems can be categorized into three levels: (1) stem-level problems to determine the optimum bucking for each stem in a way that maximizes the total stem value; (2) stand-level problems to determine the best possible bucking results with maximum aggregate production value; and (3) forest-level problems to maximize the global profit considering demand constraints, merchandising restrictions, and forest-estate (Laroze 1999). Network analysis techniques (Sessions 1988) and DP (Nasberg 1985) have been effectively used to solve stem-level optimum bucking problems. At stand-level, optimum bucking problems have been generally formulated as two-level optimization problems utilizing both LP and DP (Sessions et al. 1989b, Laroze and Greber 1997). The optimization procedures involving heuristic techniques such as Tabu Search (Laroze 1999) and Genetic Algorithm (Kivinen 2004) have been used to solve forest-level bucking problems. Uusitalo (2007) developed a Genetic Algorithm based method to integrate transportation cost and product values into forest-level optimum bucking problem.

This study integrated forwarding costs into stem-level optimum bucking problem. Nakahata et al. (2013) investigated commercial thinning operations around Nasunogahara area, where the Nasu-machi Forest Owners' Co-operative is located. 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, we determined the optimal bucking methods to maximize profits and the optimum extraction rates of small-sized logs. Here, we examine optimum extraction rates using different optimal bucking methods and small-sized log prices.

Table 1 Study sites

	A		B
Species	Japanese cedar	Japanese cypress	Japanese cedar
Stand age, year	55	55	52
Area, ha	5.25	1.87	6.70
Slope angle, °	19	16	23
DBH*, cm	32	24	25
Tree height, m	19.9	18.7	22.2
Stem volume, m^3/stem	0.80	0.46	0.62
Stand density, stem/ha	937	1 169	1 054
Stock, m^3/ha	749.60	537.74	653.48
Thinned wood DBH, cm	26	19	20
Thinned wood tree height, m	18.5	17.7	20.1
Thinned wood volume, m^3/stem	0.49	0.27	0.36
Thinning rate of stem, %	27.6	35.4	33.3
Thinning rate of volume, %	17.1	20.5	19.3
Thinned volume, m^3	668.27	207.75	844.23
Extracted volume, m^3	606.97		311.08
Extracted rate, %	69.3		36.9
Road density, m/ha	300.3		229.7
Rate of bunching area, %**	83.0	88.2	43.9
Forwarding distance, m***	120.0	247.6	111.9

* DBH: Diameter at Breast Height

** Rate of bunching area to stand area. Bunching area was assumed to be within 20 m from the roads

*** Forwarding distances were estimated from landing to each stand by the Dijkstra method

2. Optimal bucking method to maximize profits

The optimal bucking method to maximize profits was determined as follows: 1) estimate thinning volumes, 2) determine the taper curve formula, 3) estimate extracted volumes, 4) estimate revenues, 5) estimate expenses, 6) estimate economic balances, and 7) determine the optimal bucking method to maximize profits.

2.1 Study sites

The optimal bucking methods were applied to two commercial thinning operation sites where small-sized logs were extracted, in addition to saw logs and logs for laminated lumber (Table 1, Fig. 1). Forestry operations included chainsaw felling, grapple-loader bunching, processor processing, and forwarder forwarding, with a high-density road network, more than 200 m/ha of relatively steep terrain, around 20° (Fig. 2). Road width was 3.5 m. Before 2008, smaller-sized machines were used, and the road width was 2.0 m. Before 2008, the forestry operation system included chainsaw felling and processing, mini grapple-loader bunching, and mini-forwarder forwarding. Using larger machines after 2008, operational efficiencies improved from 2.3–3.8 m^3/person-day to 3.9–5.3 m^3/person-day, and direct operation costs were reduced from 59–76 USD/m^3 to 37–44 USD/m^3 (Aruga et al. 2013).

Site A included 55-year old Japanese cedar and Japanese cypress stands, with an area of 7.12 ha and a slope angle of 19°. Commercial thinning operations were conducted by the Nasu-machi Forest Owners' Cooperative between January 28 and March 9, 2010. The forest road was 268 m long. The strip road was 3.5 m wide and 1 870 m long. Therefore, the road density was 300.3 m/ha. Grapple-loader bunching operations were conducted within 20 m from the roads, and thinned woods beyond 20 m from the roads were left in the forest (pre-commercial thinning operations were conducted in the forest beyond 20 m from the roads). Therefore, the extraction is assumed to be within 20 m from the roads. The rates of the bunching areas to the study site area were 83.0% for Japanese cedar and 88.2% for Japanese cypress.

Site B was a 52-year old Japanese cedar stand, with an area of 6.70 ha and a slope angle of 23°. Commercial thinning operations were conducted by the Nasu-machi Forest Owners' Co-operative between November 12 and December 10, 2010. The forest road was 587 m long. The strip road was 3.5 m wide and 952 m long. Therefore, road density was 229.7 m/ha. Grapple-loader bunching operations were conducted within 20 m from the strip roads only. Therefore, the rate of the bunching area to the study site area was only 43.9%.

2.2 Results of the study

In order to estimate thinning volumes, the diameter at breast height (DBH) distributions of the thinned woods were estimated to apply the Weibull distribution (Kinashi 1978) to the results of the plot data (Fig. 3). The tree heights H (m) were estimated as follows.

Stand A Japanese cedar:

$$H = 5.342D^{0.382}\ (R^2 = 0.53) \quad (1)$$

Stand A Japanese cypress:

$$H = 8.817D^{0.239}\ (R^2 = 0.56) \quad (2)$$

Stand B Japanese cedar:

$$H = 5.065D^{0.46}\ (R^2 = 0.56) \quad (3)$$

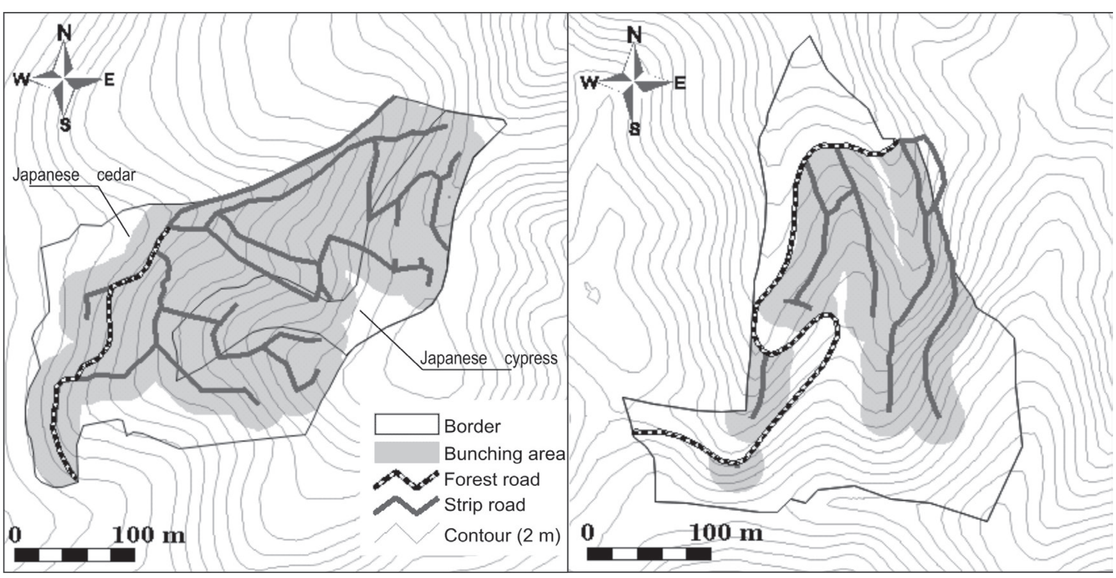

Fig. 1 Study sites (Left: Stand A, Right: Stand B

Fig. 2 Operational system with grapple-loader bunching (A), processor processing (B), and forwarder forwarding (C)

where D denotes DBH (cm). Stem volumes of thinned woods Vn (m^3/stem) were estimated with the two-way volume equation (Forestry Agency of Japan 1970). Thinned volumes in the stands VT (m^3) were estimated as follows.

$$VT = \sum_{j=D_{\min}}^{D_{\max}} VT_{\mathrm{j}} \tag{4}$$

where VT_{j} denotes thinned volumes in the j DBH class (m^3), and $D_{\max}$ and $D_{\min}$ are the maximum and minimum DBH class of thinned woods, respectively. VT_{j} was estimated as follows.

$$VT_{\mathrm{j}} = Vn_{\mathrm{j}} \times N_{\mathrm{j}} \times A \times \frac{RT_{\mathrm{j}}}{100} \tag{5}$$

where Vn_{j} denotes stem volumes of thinned woods in the j DBH class (m^3/stem), N_{j} refers to the number of thinned woods in the j DBH class (stem/ha), A is the stand area (ha), and RT_{j} is the thinning rate of stems in the j DBH class (%).

2.3 Determination of the taper curve formula

Stem diameter d (cm) at the height h (m) above the ground was estimated with the following taper curve formula (Inoue and Kurokawa 2001).

$$d = \frac{\left\{a\left(1.0 - \frac{1.2}{H}\right) - 0.9a + 1.8\right\}\left(1.0 - \frac{h}{H}\right)}{\left\{a\left(1.0 - \frac{h}{H}\right) - 0.9a + 1.8\right\}\left(1.0 - \frac{1.2}{H}\right)} D \tag{6}$$

Coefficient a was estimated as follows.

$$a = \frac{\left(18.0 - \frac{21.6}{H}\right) - 12.6\sqrt{\frac{7}{10f}}}{\left(2.0 - \frac{2.4}{H}\right) - \left(0.7 - \frac{8.4}{H}\right)\sqrt{\frac{7}{10f}}} \tag{7}$$

where f denotes the breast height form factor estimated as follows.

$$f = \frac{4Vn}{\left(\frac{HD^2\pi}{10000}\right)} \tag{8}$$

Average Root Mean Squared Errors (RMSEs) between the measured and estimated stem diameters were 1.1 cm for both Japanese cedar and Japanese cypress. Log diameters were usually rounded by 2 cm. Therefore, these RMSEs were within allowable ranges.

2.4 Estimation of extracted volumes

Extracted logs were classified as saw logs, logs for laminated lumber, and small-sized logs (Table 2). Saw

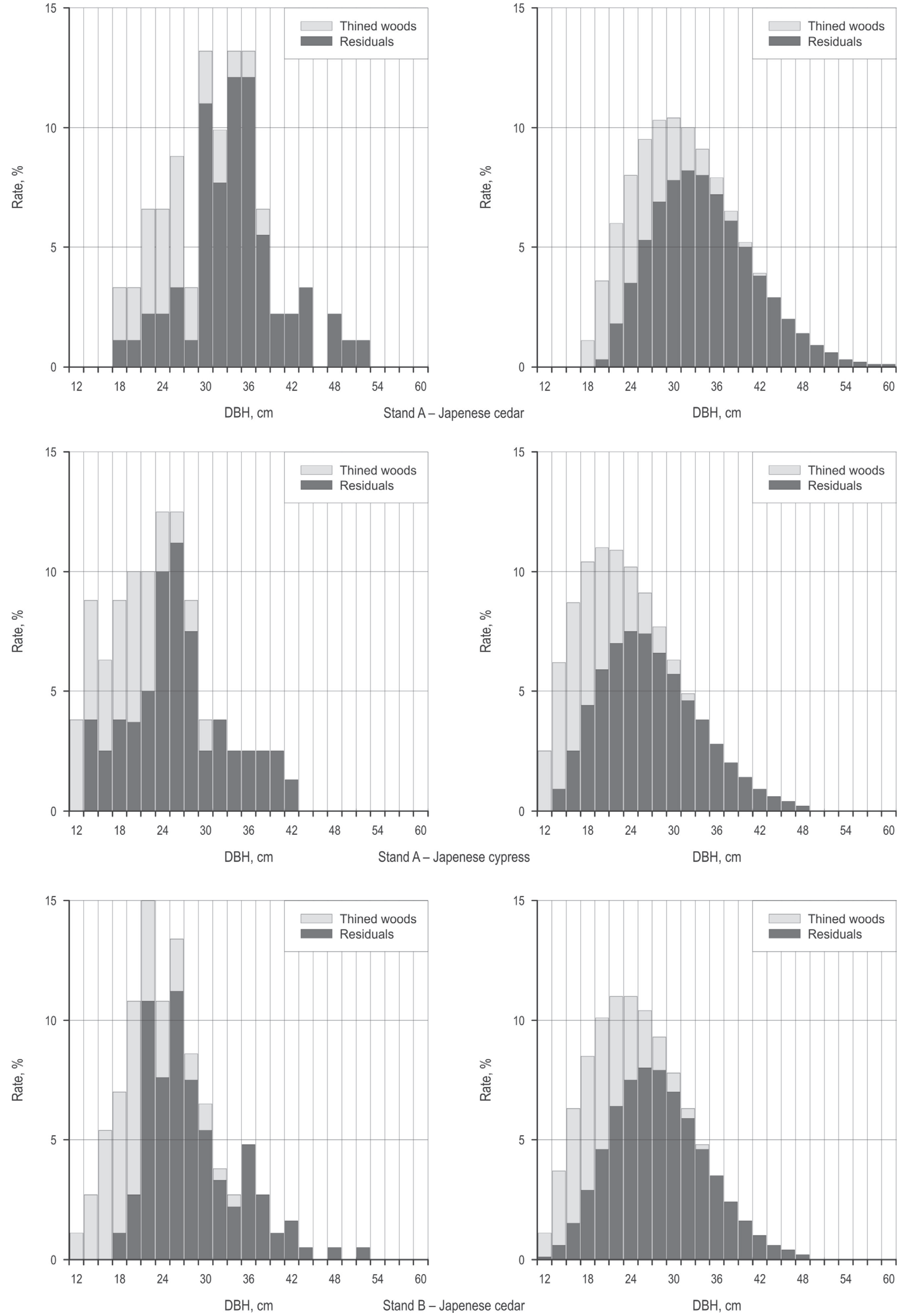

Fig. 3 DBH distributions (Left: Survey results, Right: Weibull distribution)

logs were 3.00–6.00 m long, with the top-end diameter exceeding 10 cm. Logs for laminated lumber were 2.00 m long, with the top-end diameter exceeding 16 cm. Corresponding values for small-sized logs were 2.00 m and over 3 cm. Small-sized logs were sold to a pellet plant or a chip production factory. Log lengths were assumed to be 2.00 m, 3.00 m, 3.65 m, and 4.00 m for Japanese cedar and 2.00 m, 3.00 m, and 4.00 m for Japanese cypress (interview with the Nasu-machi Forest Owners' Co-operative). Cutting height was assumed to be 20 cm above the ground (Iehara and Kurokawa 1990). Possible combinations of log length bucked from a thinned wood were estimated, and log volumes v (m^3/log) were estimated with log length l (m) and top-end diameters of logs using estimated stem diameter d (cm).

$$v = \frac{d^2 l}{10000} \tag{9}$$

Then, extracted volumes Vl (m^3/stem) were estimated as follows.

$$Vl = \sum_{i=1}^{n} v_i \tag{10}$$

where v_i is the i-th log from the butt end (m^3/stem), and n is the number of logs from a thinned wood. Extracted volumes were estimated with possible combinations of log length bucked from a thinned wood.

Extracted volumes in the stands VE (m^3) were estimated as follows.

$$VE = \sum_{j=D_{min}}^{D_{max}} VE_j \tag{11}$$

where VE_j denotes extracted volumes in the j DBH class (m^3). VE_j was estimated as follows.

$$VE_j = Vl_j \times N_j \times A \times \frac{RT_j}{100} \times \frac{RS}{100} \tag{12}$$

where Vl_j refers to extracted volumes of thinned woods in the j DBH class (m^3/stem), and RS is the rate of bunching area to stand area (%).

2.5 Estimation of revenues

Log prices p (m^3/log) were estimated with log volume and unit prices (Table 2). Unit prices of saw logs were sourced from the unit prices in the Ootawara log market, where the Nasu-machi Forest Owners' Co-operative sells saw logs. Unit prices of logs for laminated lumber and small-sized logs were sourced from the unit prices of a laminated lumber factory, the pellet plant, and the chip production factory, where the Nasu-machi Forest Owners' Co-operative sells logs for laminated lumber and small-sized logs. Then, revenue from a thinned wood was estimated with the number of logs per thinned wood and each log price.

Table 2 Log unit prices

	Species	Length	Diameter	Unit prices, USD/m^3	
		m	cm	Stand A	Stand B
Saw logs	Japanese Cedar	3.00	11–14	69.50	92.70
			16–20	116.60	141.00
			22–28	112.20	135.10
		3.65	18–28	127.40	142.90
			>30	127.40	150.40
		4.00	10–14	75.90	120.10
			16–20	107.90	125.70
			22–28	127.50	133.20
			>30	125.90	145.70
	Japanese Cypress	3.00	11–14	66.40	94.40
			16–28	179.80	223.10
			>30	170.00	260.40
		4.00	10–14	94.00	128.40
			16–20	197.30	237.50
			22–28	225.00	257.30
			>30	–	390.50
Logs for laminated lumber	Japanese Cedar	2.00	16–18	50.00	
			>20	55.00	
	Japanese Cypress	2.00	16–18	70.00	
			>20	90.00	
Small-sized logs	Japanese Cedar Japanese Cypress	2.00	>3	30.00	

Revenues in the stands S (USD) were estimated as follows.

$$S = \sum_{j=D_{min}}^{D_{max}} S_j \tag{13}$$

where S_j denotes revenues in the j DBH class (USD). S_j was estimated as follows.

$$S_j = \sum_{i=1}^{n} P_{ij} \quad N_j \quad A \quad \frac{RT_j}{100} \quad \frac{RS}{100} \qquad (14)$$

where $\sum_{i=1}^{n} P_{ij}$ is the log price in the j DBH class (USD/stem).

In addition to revenues from log sales, subsidies were estimated with standard unit costs, areas, assessment coefficients, and the subsidy rate offered by the Tochigi Prefectural Government (2010b). Standard unit costs were determined by age class, thinning rates, and whether extraction occurred (Fig. 4). An extraction rate of at least 50% was required. The assessment coefficient and the subsidy rate were assumed to be 1.7 and 4/10, respectively. In Japan, subsidies for strip road establishment are also provided for stands with subsidized thinning operations. Standard unit costs for strip road establishment were determined using the average slope angle (°) and road width (Table 3). Subsidies were estimated with standard unit costs, length, assessment coefficients, and the subsidy rate offered by the Tochigi Prefectural Government (2011). The assessment coefficient and the subsidy rate were assumed to be 1.7 and 4/10, respectively.

2.6 Estimation of revenues

Costs in the stands C (USD) were estimated as follows.

$$C = \sum_{j=D_{min}}^{D_{max}} OE_j + OC \qquad (15)$$

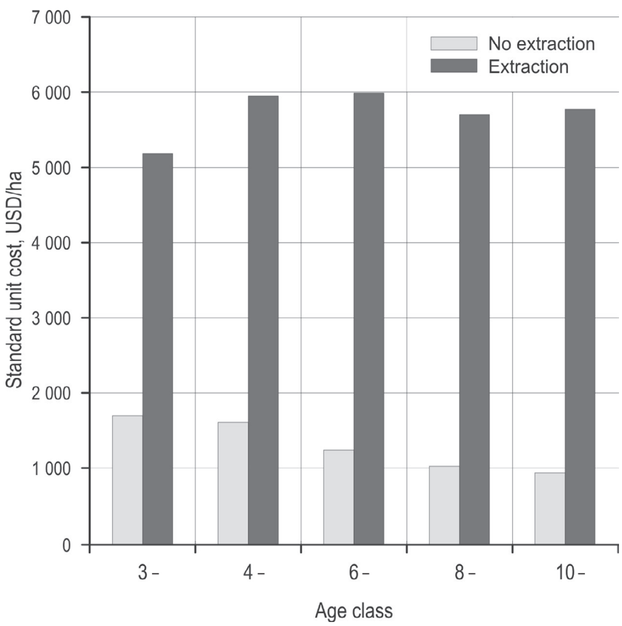

Fig. 4 Standard unit costs for subsidy for 30% stem thinning rate

Table 3 Standard unit costs for strip road construction (3.5 m wide)

Slope angle, °	Standard unit costs, USD/m
35 –	43.97
30 –	12.50
25 –	7.02
20 –	4.06
15 –	3.38
10 –	2.81
5 –	2.34

where OE_j denotes direct expenses in the j DBH class (USD), and OC refers to other expenses (USD). OE_j was estimated as follows.

$$OE_j = \left(OE_F + OE_S \times RS\right)VT_j + \left(OE_P + OE_E\right)VE_j \qquad (16)$$

where OE_F denotes chainsaw felling costs (USD/m^3); OE_S, grapple-loader bunching costs (USD/m^3); OE_P, processing costs (USD/m^3); and OE_E, forwarding costs (USD/m^3).

Costs of chainsaw felling and grapple-loader bunching were estimated using the equations in Nakahata et al. (2011). These equations were developed without considering log sizes, because these operations were conducted with whole trees before processing operations, and the costs were not affected by log sizes (Table 4). Costs of processor processing and forwarder forwarding were estimated using the equations developed in Nakahata et al. (2013), which considered log sizes. RMSEs between measured values and estimations using the equations in Nakahata et al. (2013) that considered log sizes, estimations using the equations in Nakahata et al. (2011) and Ishikawa et al. (2008) that did not consider log sizes, were compared. For processing operations, the RMSE of 1.29 USD/m^3 obtained from the equations in Nakahata et al. (2013) was lower than that obtained from the equations in Nakahata et al. (2011) (2.14 USD/m^3) and Ishikawa et al. (2008) (6.12 USD/m^3) (Fig. 5). For forwarding operations, the RMSE of 0.85 USD/m^3 using the equations in Nakahata et al. (2013) was also lower than that using the equations in Nakahata et al. (2011) (2.31 USD/m^3) (Fig. 6). RMSEs in Nakahata et al. (2013) were the smallest of all estimations.

In addition to these direct expenses, strip road expenses, truck transportation expenses, machine transportation expenses, insurance costs, handling fees of the Forest Owners' Co-operative and the log market,

Table 4 Direct expenses, USD/m^3

		Nakahata et al. (2011)	Nakahata et al. (2013)
Chainsaw felling	Whole tree	$0.91/Vn + 1.12$	$0.91/Vn + 1.12$
Grapple-loader bunching	Whole tree	12.41	12.41
Processor processing	Log	$2.88/Vl + 2.66$	$\{(2.42Vla + 0.22)\ n + 1.90\}/Vla \cdot n$
Forwarder forwarding	Log	$0.0060L_F + 7.08$	$\{(-34.30Vla + 16.77) + 0.012\ L_F\}/(1.74Vla + 1.71)$

Vn – Stem volume, m^3/stem;
Vl – Extracted volume, m^3/stem;
Vla – Average log volume, m^3/log;
n – Number of logs per stem, logs/stem;
L_F – Forwarding distance, m.

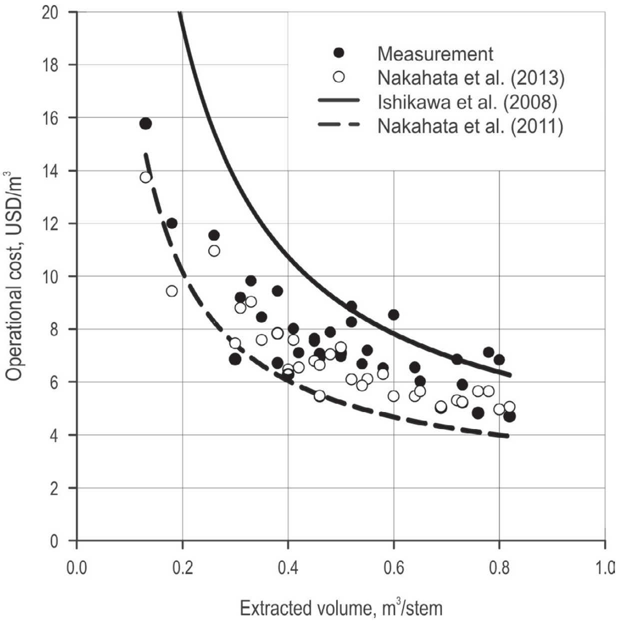

Fig. 5 Extracted volumes, m^3/stem and operational costs, USD/m^3

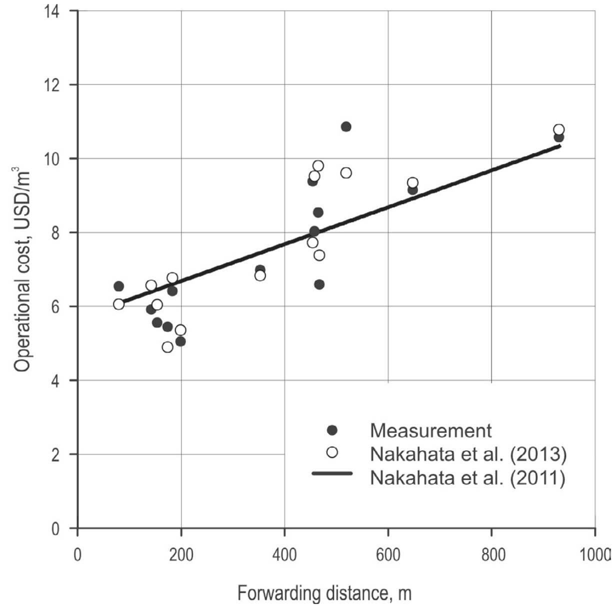

Fig. 6 Forwarding distances, m and operational costs, USD/m^3

and piling fees in the log market were also estimated. Strip road expenses were estimated assuming labor expenses of 25.50 USD/h, backhoe machinery expenses of 46.39 USD/h, and strip road construction times of 117 and 33 hours for Stand A and B, respectively. Truck transportation expenses were estimated to be 13.00 USD/m^3 for saw logs, 0 USD/m^3 for logs for laminated lumber (because of landing sales), and 15.00 USD/m^3 for small-sized logs. Machine transportation expenses were estimated to be 50.00 USD/machine. There were five machines to be transported: a backhoe, a grapple-loader, a processor, and two forwarders. Insurance costs were estimated to be 18.4% of direct expenses. Handling fees of the Forest Owners' Co-operative and the log market were estimated to be 5% and 5%, respectively. Piling fees in the log market were estimated to be 7.00 USD/m^3.

2.7 Estimation of economic balances

Economic balances were estimated with revenues and costs of possible combinations of log length bucked from a thinned wood. Then, bucking method and extraction rate with maximum profits were determined as the optimal bucking method and the optimal extraction rate, respectively. Extraction rate from stems RE_S was estimated as follows.

$$RE_S = \frac{Vl}{Vn} \times 100 \tag{17}$$

Extraction rate on the stands *RE* was estimated as follows.

$$RE = \frac{VE}{VT} \times 100 \tag{18}$$

3. Results and discussion

3.1 Optimal bucking method to maximize profits

By the optimum bucking method to maximize profits, maximum four to five logs were made for Stand A and B, respectively (Tables 5, 6, and 7). The

Table 5 Results of the optimal bucking method to maximize profits in Stand A of Japanese cedar

Thinned trees	DBH	Height	Stem volumes	Extracted volumes	Rate	No. of logs	Revenues	Direct expenses	Economic balance
Stem/ha	cm	m	m^3/stem		%		USD/m^3		
10	18	16	0.210	0.176	83.6	3	91.69	43.80	47.89
31	20	17	0.270	0.218	80.7	3	97.40	39.64	57.77
39	22	17	0.320	0.257	80.3	3	114.49	36.98	77.51
42	24	18	0.400	0.349	87.3	4	107.05	34.37	72.68
39	26	19	0.490	0.426	87.0	4	117.41	32.03	85.38
32	28	19	0.550	0.490	89.0	4	121.33	30.60	90.73
24	30	20	0.660	0.578	87.6	4	121.49	28.92	92.56
17	32	20	0.740	0.652	88.1	4	121.97	27.80	94.17
10	34	21	0.870	0.749	86.1	4	123.82	26.53	97.29
7	36	21	0.960	0.841	87.6	4	122.67	25.53	97.14
4	38	21	1.050	0.962	91.6	4	126.57	24.42	102.15
2	40	22	1.210	1.082	89.4	4	126.67	23.39	103.28
1	42	22	1.330	1.206	90.7	4	125.86	22.48	103.37
259*	25.9	18.5	0.495	0.429	86.6	3.7	116.91	31.22	85.69

*Total value. The other values refer to averages

Table 6 Results of the optimal bucking method to maximize profits in Stand A of Japanese cypress

Thinned trees	DBH	Height	Stem volumes	Extracted volumes	Rate	No. of logs	Revenues	Direct expenses	Economic balance
Stem/ha	cm	m	m^3/stem		%		USD/m^3		
29	12	16	0.100	0.000	0.0	0	–	–	–
62	14	16	0.130	0.000	0.0	0	–	–	–
72	16	17	0.180	0.127	70.4	2	93.38	48.27	45.11
70	18	17	0.220	0.160	72.7	2	159.81	43.09	116.73
60	20	18	0.290	0.232	79.9	3	154.66	35.59	116.08
46	22	18	0.340	0.295	86.8	3	179.67	35.20	144.47
32	24	19	0.430	0.350	81.3	3	180.35	32.84	147.51
20	26	19	0.490	0.448	91.5	4	193.73	31.57	162.16
13	28	19	0.560	0.523	93.4	4	198.89	30.00	168.89
7	30	20	0.670	0.574	85.6	4	200.30	28.97	171.33
4	32	20	0.770	0.677	87.9	4	212.11	27.45	184.66
414*	18.8	17.5	0.266	0.195	73.3	2.1	168.04	36.67	131.37

*Total value. The other values refer to averages

Table 7 Results of the optimal bucking method to maximize profits in Stand B of Japanese cedar

Thinned trees	DBH	Height	Stem volumes	Extracted volumes	Rate	No. of logs	Revenues	Direct expenses	Economic balance
Stem/ha	cm	m	m^3/stem		%		USD/m^3		
29	12	16	0.100	0.000	0.0	0	–	–	–
62	14	17	0.140	0.098	69.7	2	120.49	55.62	64.87
72	16	18	0.190	0.136	71.6	2	120.00	46.63	73.37
70	18	19	0.250	0.204	81.4	3	127.55	40.85	86.70
60	20	20	0.320	0.263	82.1	3	136.56	36.72	99.84
46	22	21	0.410	0.373	91.0	4	134.32	33.65	100.67
32	24	22	0.500	0.453	90.5	4	139.97	31.45	108.53
20	26	23	0.610	0.568	93.1	5	140.02	30.25	109.76
13	28	23	0.690	0.685	99.3	5	140.71	28.61	112.10
7	30	24	0.820	0.772	94.2	5	141.16	27.50	113.66
4	32	25	0.940	0.885	94.2	5	141.31	26.35	114.96
4	34	26	1.090	1.019	93.5	5	142.57	25.19	117.38
417*	19.0	19.5	0.312	0.262	83.9	2.9	134.35	35.58	98.77

*Total value. The other values refer to averages

average number of logs was 3.7 and 2.1 for the Japanese cedar and the Japanese cypress of Stand A, and 2.9 for Stand B. The number of logs increased according to the DBH. However, thinned trees with DBH values between 12 and 14 cm for Stand A and of 12 cm for Stand B were not bucked into logs (i.e., they were left in the forests), because these thinned trees with small DBH were not profitable with the optimum bucking method for maximizing profits. The average extraction rates from stems were 86.6% and 73.3% for Japanese cedar and Japanese cypress of Stand A, and 83.9% for Stand B. The average extraction rates from stems also increased according to the DBH (Fig. 7).

Revenues increased and direct expenses decreased according to the DBH (Tables 5, 6, and 7 and Fig. 8). Therefore, economic balances increased according to the DBH. Despite smaller log volumes and lower extraction rates, the average revenues for the Japanese cypress of Stand A were higher than those for the Japanese cedar of Stands A and B, because of the former's higher unit prices. The average direct expenses for the Japanese cypress of Stand A were a little higher than those for the Japanese cedar of Stands A and B, but almost same. Therefore, the average economic balances for the Japanese cypress of Stand A were higher than those for the Japanese cedar of Stands A and B.

Optimal extraction rates were 70.3% and 37.9% for Stand A and B, respectively. Extracted volumes with these rates were 86.48 m^3/ha and 47.77 m^3/ha, respectively (Fig. 9). Conversely, actual extraction rates and volumes were 69.3% and 36.9%, or 85.25 m^3/ha and 46.43 m^3/ha for Stand A and B, respectively. Estimated optimal extraction rates and volumes were similar to the actual values. However, small-sized log volumes differed. The actual values were 1.79 m^3/ha and 1.76 m^3/ha, although no small-sized logs were estimated with the optimal extraction rate, because the profitability of extracting small-sized logs was low. However, the Nasu-machi Forest Owners' Co-operative had an annual contract with a pellet production factory to transport a certain log volume. Furthermore, estimated and actual log volumes for laminated lumber also differed. The actual values were larger than the estimations, because the Nasu-machi Forest Owners' Co-operative also had an annual contract with a laminated lumber production factory at log prices, which were more stable than those in log markets.

Fig. 10 shows revenues, costs, and economic balances for Stands A and B. Estimated revenues were larger than actual values, because estimated volumes of saw logs, which were relatively higher priced, were larger than the actual values, and log quality

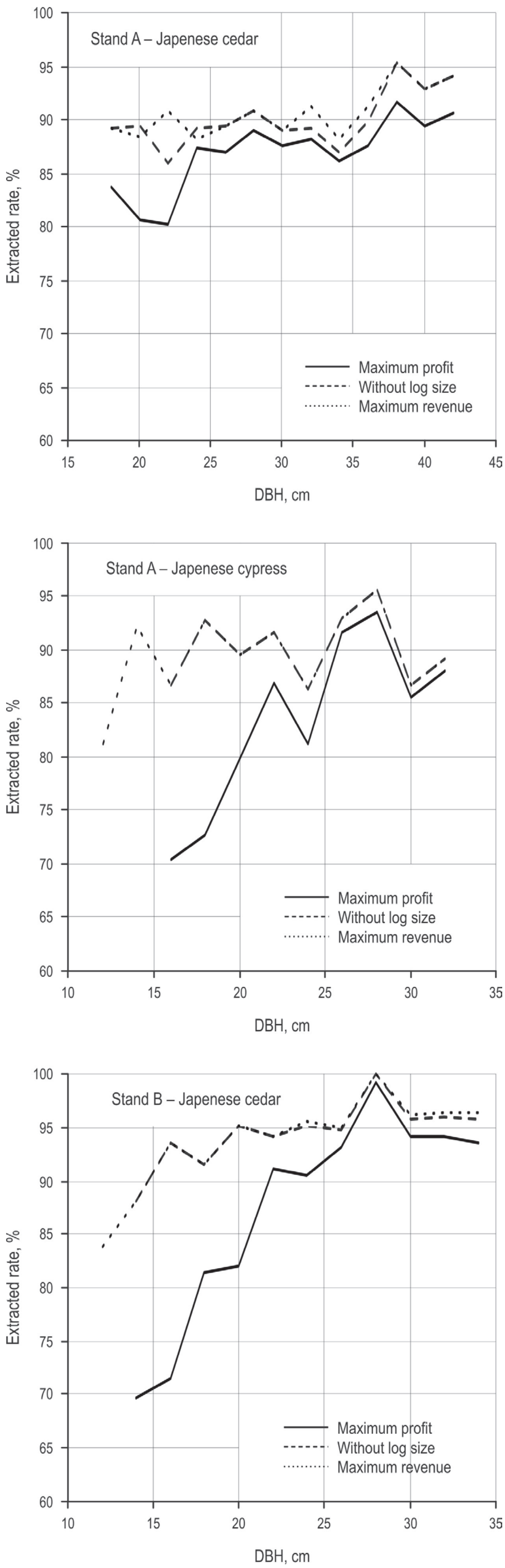

Fig. 7 DBH, cm and extraction rates from stems, %

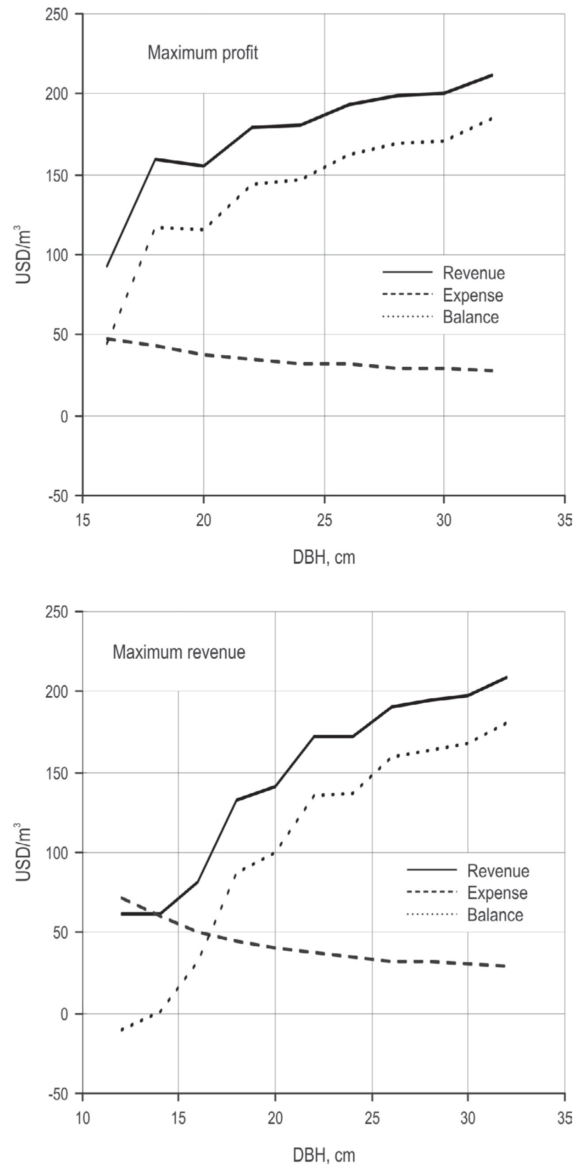

Fig. 8 DBH, cm; and revenues, direct expenses, and economic balances, USD/m^3 in Stand A of Japanese cypress

was not considered in this estimation. Estimated costs were smaller than actual costs, because actual loss times would be larger than 1/4 of productive time as assumed in the study (Kamiiizaka and Kanzaki 1990, Nakahata et al. 2013). Therefore, estimated economic balances were larger than actual values.

3.2 Comparison with the optimal bucking method without considering log sizes

In the previous section, the optimal bucking method to maximize profits was determined using equations developed in Nakahata et al. (2013), which con-

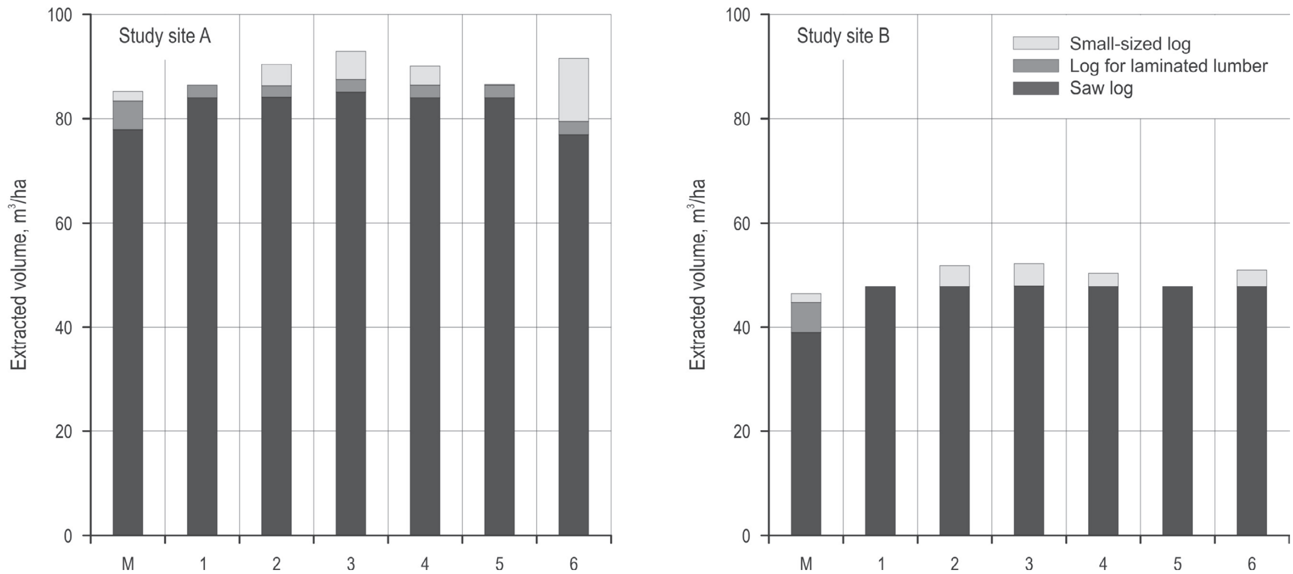

Fig. 9 Extracted volumes (M: Measurement, 1: The optimum bucking method, 2: Without considering log sizes, 3: With maximum revenues, 4: With the new subsidy, 5: Unit prices of small-sized logs, 40.80 USD/m^3, 6: Unit prices of small-sized logs, 68.00 USD/m^3)

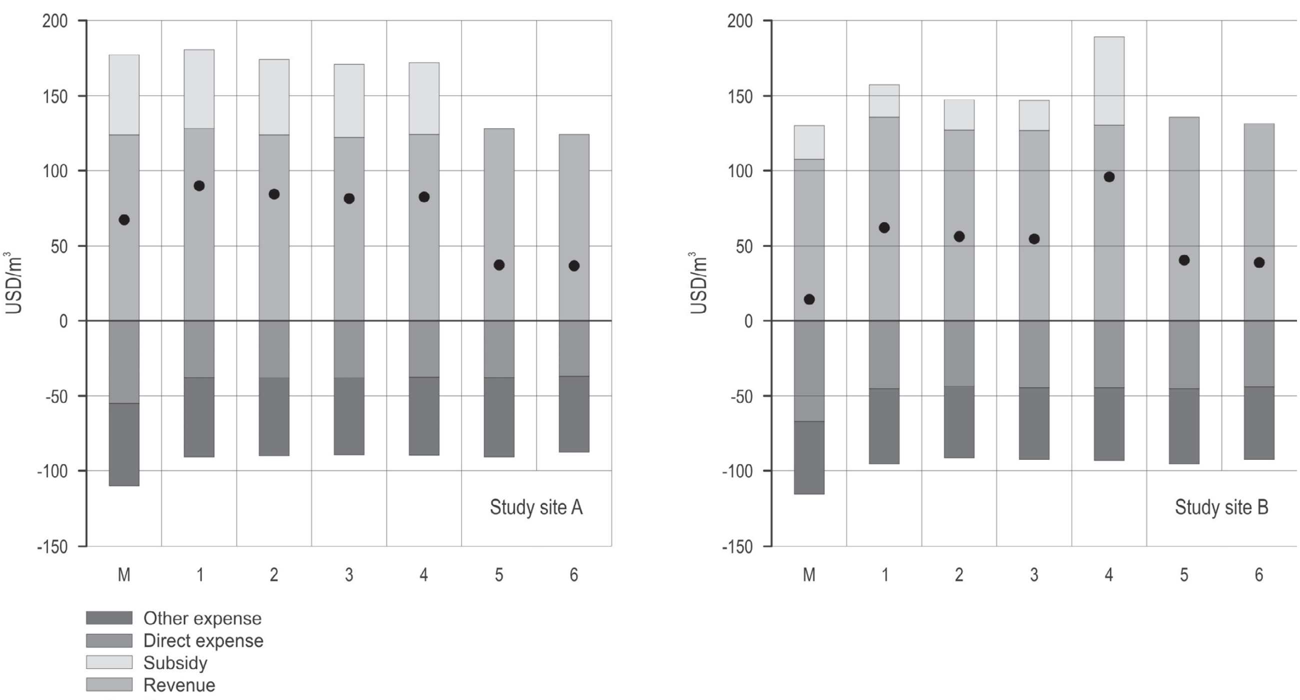

Fig. 10 Revenues, costs, and economic balances per extracted volume (M: Measurement, 1: The optimum bucking method, 2: Without considering log sizes, 3: With maximum revenues, 4: With the new subsidy, 5: Unit prices of small-sized logs, 40.80 USD/m^3, 6: Unit prices of small-sized logs, 68.00 USD/m^3)

sidered log sizes. This section determines the optimal bucking method to maximize profits without considering log sizes using equations developed in Nakahata et al. (2011) and compares the two optimal bucking methods. The average extraction rates from stems without considering log sizes were 89.3% and 81.2% for the Japanese cedar and the Japanese cypress of Stand A, and 92.2% for Stand B. The average extraction

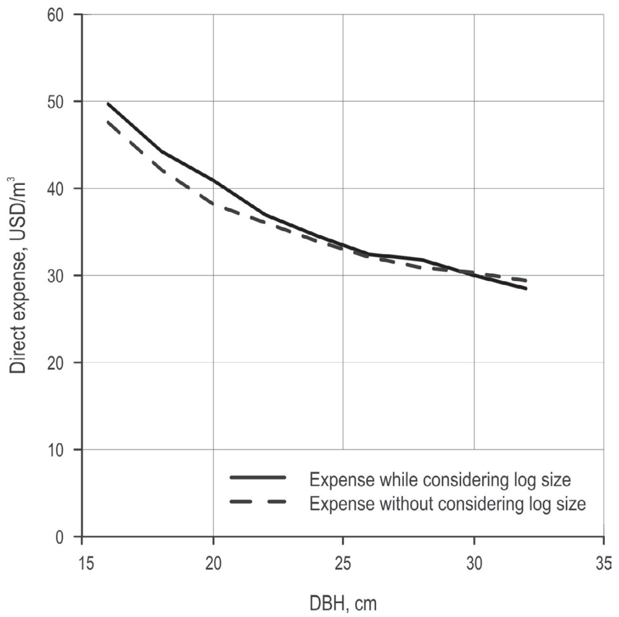

Fig. 11 DBH, cm and direct expenses, USD/m^3 in Stand A of Japanese cypress

rates from stems without considering log sizes were higher. Notably, the differences became larger with smaller DBHs (Fig. 7), because direct expenses of small-sized logs did not increase when log sizes were not considered; subsequently, small-sized logs tended to be extracted although the differences in direct expenses were small between the two cases (Fig. 11). For example, only five logs could be bucked maximally from the thinned woods in the optimal bucking method considering log sizes. On the other hand, maximum seven logs were bucked from the thinned woods by the bucking method that did not consider log sizes.

Optimal extraction rates without taking log size into consideration were 73.5% and 41.1% for Stand A and B, respectively (Fig. 9). The corresponding extracted volumes with optimal extraction rates were 90.44 m^3/ha and 51.83 m^3/ha. Small-sized log volumes were 4.03 m^3/ha and 4.04 m^3/ha for Stand A and B, respectively. These were larger than the actual values and estimations made by the optimal bucking method considering log sizes. However, revenues per m^3 decreased, and subsequently, economic balances per m^3 also decreased (Fig. 10).

3.3 Comparison with the optimal bucking method to maximize revenues

The optimal bucking method usually maximizes revenues and is used to estimate revenues (Iehara and Kurokawa 1990). Here, the optimal bucking method to maximize revenues is determined and compared. The average extraction rates from stems with maximum revenues were 90.0% and 90.0% for the Japanese cedar and the Japanese cypress of Stand A, respectively, and 94.2% for Stand B. The average extraction rates from stems with maximum revenues increased compared to those from stems with maximum profits. Notably, the differences became larger for smaller DBHs (Fig. 7), because revenues increased according to extracted volumes. Furthermore, thinned trees with a DBH between 12 and 14 cm for Stand A, and of 12 cm for Stand B, were extracted with the optimal bucking method to maximize revenues. As with the optimum bucking method to maximize profits, these were not bucked into logs (i.e., they were left in the forests), because these thinned trees with small DBH were not profitable. Therefore, for the optimal bucking method to maximize revenues, direct expenses exceeded revenues, and economic balances suffered a deficit with small DBHs (Fig. 8).

Extraction rates with maximum revenues were estimated to be 76.0% and 41.4% for Stand A and B, respectively (Fig. 9). Corresponding values for extracted volumes with maximum revenues were 93.50 m^3/ha and 52.22 m^3/ha. Small-sized log volumes were 6.14 m^3/ha and 4.26 m^3/ha for Stand A and B, respectively. These were larger than the actual values and estimations with maximum profits. Therefore, revenues per ha increased according to extracted volumes. However, costs per ha also increased according to extracted volumes. Subsequently, the estimated economic balances decreased. On the other hand, revenues per m^3 decreased and subsequently, economic balances per m^3 also decreased (Fig. 10).

3.4 Comparison with the optimal bucking method considering the new subsidy system

The subsidy system was changed in 2011. Until 2010, standard unit costs (Tochigi Prefectural Government 2010b) were determined by age class, thinning rates, and extraction, if any (Fig. 4). An extraction rate of at least 50% was required. In the new subsidy system, standard unit costs (Tochigi Prefectural Government 2011) were determined by operation system, thinning rate, and extracted volumes (Fig. 12). Operation systems were classified into two types: ground-based and skyline system. The sites in this study use the ground-based operation system and have a thinning rate of 30%. In the new subsidy system, the subsidy was increased according to extracted volumes.

The average extraction rates from stems with the new subsidy system were 89.3% and 79.1% for the

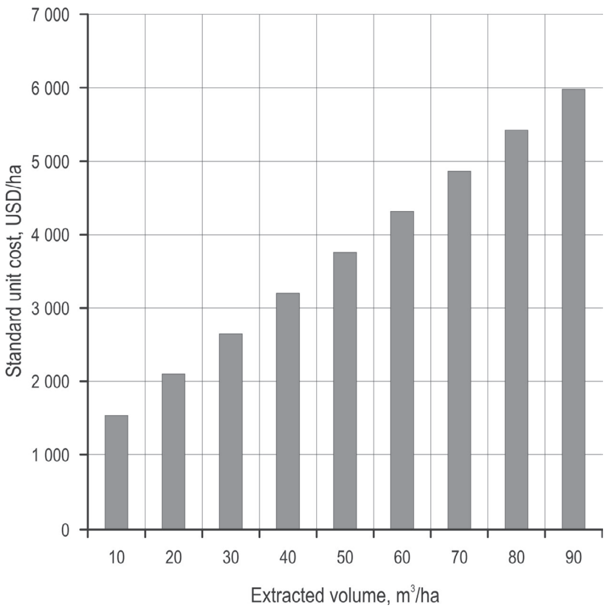

Fig. 12 Standard unit costs for the new subsidy with a ground-based system

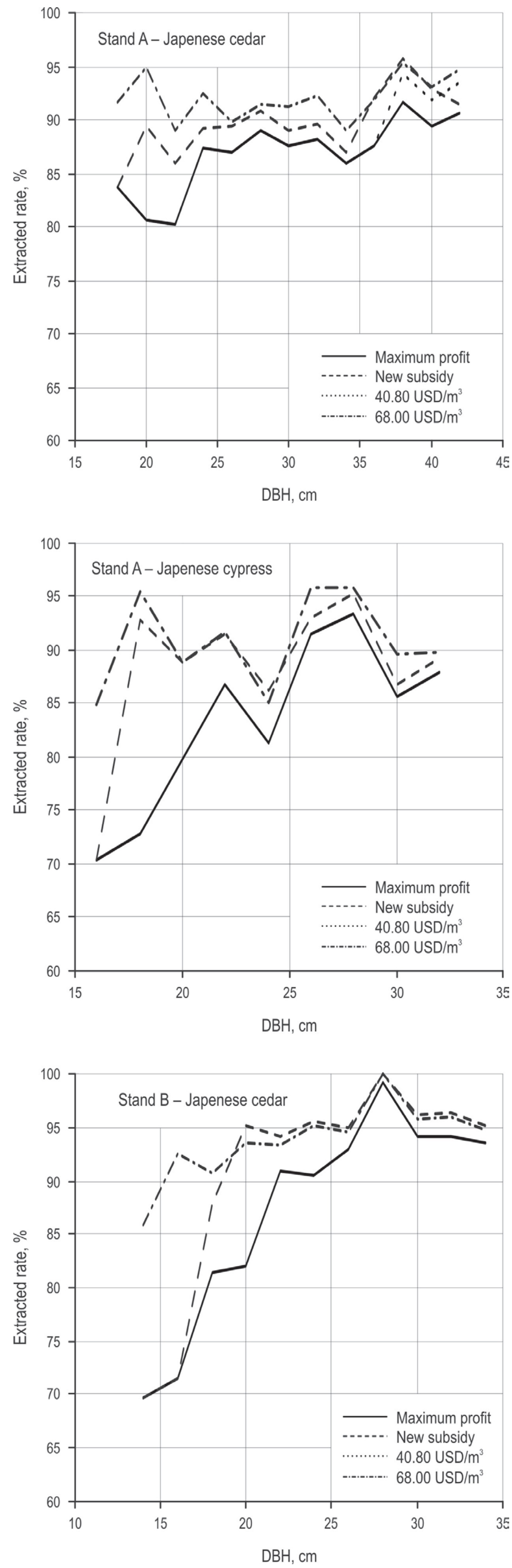

Fig. 13 DBH, cm and extraction rates from stems, % with the new subsidy and higher unit prices

Japanese cedar and the Japanese cypress of Stand A, and 88.3 % for Stand B. These rates were higher compared to those for the previous subsidy system, because the subsidy increased according to extracted volumes (Fig. 13). Extraction rates from stands with the new subsidy system in place were estimated to be 73.3% and 39.9% for Stand A and B, respectively (Fig. 9). Corresponding extracted volumes were 90.12 m^3/ha and 50.29 m^3/ha. Small-sized log volumes were 3.63 m^3/ha and 2.51 m^3/ha for Stand A and B, respectively. Small-sized log volumes with the new subsidy system increased compared to those in the previous subsidy system. Consequently, the economic balances increased with the increase in extracted volumes, especially in Stand B (Fig. 10).

3.5 Comparison of optimal bucking methods with higher unit prices for small-sized logs

In addition to the unit prices for small-sized logs: 30.00 USD/m^3, the following unit prices were examined assuming no subsidy for thinning operations and strip road establishments: 40.80 USD/m^3 and 68.00 USD/m^3. These prices would be converted using a bulk density of 0.68 ton/m^3 (Mikamo Forest Owners' Co-operative and Sumitomo Osaka Cement Company 2008) from 60.00 USD/ton with additional subsidies to small-sized log prices (Japanese Forestry Investigation Committee 2011b) and 100.00 USD/ton if FITs were introduced in Japan (Japanese Forestry Investigation Committee 2011a).

The average extraction rates from stems with the unit price 40.80 USD/m^3 were 86.7% and 73.3% for the Japanese cedar and the Japanese cypress of Stand A, and 83.9% for Stand B. The average extraction rates from stems with the unit price 40.80 USD/m^3 were almost the same as those from stems with the unit price 30.00 USD/m^3 excluding DBH higher than 38 cm for the Japanese cedar of Stand A (Fig. 13). Extraction rates from stands with the unit price 40.80 USD/m^3 were estimated to be 70.4% and 37.9%, and corresponding extracted volumes were 86.60 m^3/ha and 47.77 m^3/ha. Small-sized log volumes were 0.12 m^3/ha and 0.00 m^3/ha for Stand A and B, respectively (Fig. 9). Small-sized log volumes increased marginally to 0.12 m^3/ha with 40.80 USD/m^3 for Stand A; subsequently, extraction rates from stands and extracted volumes also increased at almost the same rate. Revenues of 40.80 USD/m^3 were relatively higher. However, economic balances decreased in the absence of a subsidy (Fig. 10).

The average extraction rates from stems with the unit price 68.00 USD/m^3 were 91.4% and 81.5% for the Japanese cedar and the Japanese cypress of Stand A, and 91.5% for Stand B. These rates are higher compared to those from stems with the unit price 30.00 USD/m^3. Notably, the differences became larger for smaller DBHs (Fig. 13). Extraction rates from stands with the unit price 68.00 USD/m^3 were estimated to be 74.5% and 40.4% for Stand A and B, respectively, and corresponding extracted volumes were 91.60 m^3/ha and 50.95 m^3/ha. Small-sized log volumes were 12.14 m^3/ha and 3.17 m^3/ha for Stand A and B, respectively (Fig. 9). These increased in line with unit price increases for small-sized logs. Notably, small-sized log volumes in Stand A were the largest of all estimations. However, economic balances decreased in the absence of a subsidy (Fig. 10).

4. Conclusions

Optimal bucking methods to maximize profits were applied to two operational sites of the Nasu-machi Forest Owners' Co-operative, and optimum extraction rates were examined with different optimal bucking methods and small-sized log unit prices. Extraction rates from stands with maximum profits were similar to the actual values, compared with the optimal bucking method that does not consider log sizes and the optimal bucking method to maximize revenues. However, differences in extracted volumes and economic balances among these estimations were small and are likely to fall within the error limits traditionally seen for forests and forestry conditions in the stands. Stand in this study were about 50 years old, with an average DBH of about 20 cm. Among the estimations, differences of extraction rates from stems with DBH exceeding 20 cm were small. However, extraction rates from stems with a DBH less than 20 cm were significantly different. Therefore, it is likely that the optimal bucking method to maximize profits while considering log sizes can help determine the optimal extraction rates of younger stands with smaller DBH. Additional studies for different forests and forestry conditions would be useful.

Small-sized log volumes with the optimal bucking method were smaller than the actual values, because this model did not consider contracts with factories concerning annual supply obligations and stable prices. Furthermore, this model did not consider log quality, and bucking operations should be conducted also taking log quality into consideration. Low-quality logs were sold to chip or pellet factories rather than to log markets. Therefore, future studies should consider supply obligations and log quality, although the latter can be difficult to predict.

Effects of the new subsidy system and higher unit prices for small-sized logs were also discussed. The new subsidy system and unit prices with FITs both contributed to increased extracted volumes of small-sized logs. However, it is likely that subsidies will be reduced in the future, due to the government's budget constraints. Therefore, a low-cost harvesting system should be developed to establish forest road networks and improve forestry operation systems.

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