Research Article
https://doi.org/10.33904/ejfe.508056

Eur J Forest Eng 2019, 5(1): 1-10

EJFE

Numerical Examination of the Optimal Bucking Method to Maximize Profits Applied in Nasu Town, Tochigi Prefecture, Japan

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Abstract

In this study, the optimal bucking methods were numerically applied to Nasu town, and the factors of effects on profitability of commercial thinning operations and feasibility of extracting small sized logs were discussed. As a result, commercial thinning operations could be conducted on 18% (818 ha) and 54% (2427 ha) of 35 and 45 years old forests, respectively. On the other hand, pre-commercial thinning operation would be conducted on 81% (3666 ha) and 46% (2089 ha) of 35 and 45 years old forests. This shows current situation of Japanese forestry where nearly all the thinning operations conducted were pre-commercial. Stands with extracting small sized logs accounted for approximately ten percent of the total forest area. Extracted small sized logs from 35 years old forests were more than those from 45 years old forests although saw logs from 35 years old forest were less than those from 45 years old forests. The areas of stands with extracting small sized logs were increased according to the more gentle slope and shorter forwarding distances. Thus, it was clear that the reduction of forwarding distances by establishing forest road networks were effective in order to increase stands with extracting small sized logs.

Keywords: Extraction rate, Extracting thinned woods, Economic value, Optimal bucking, Small sized log

1. Introduction

Forestry Agency of Japan established the forest and forestry basic plan in May 2016 (Forestry Agency of Japan, 2016). In the plan, timber supply and demand are 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 projected to increase from 31% in 2014 to 50% in 2025. In order to accomplish the plan, Forestry Agency of Japan implemented a measure on "coordination and consolidation of forestry practices." This measure will ensure coordination among a number of small forest owners and expand forestry operation sites while merging small forests. Forest road networks will be established and mechanization will be promoted in order to conduct forestry operations efficiently on a large scale and reduce costs. To promote this measure, the subsidy was paid for thinning in operation areas larger than 5 ha and with extracted volumes exceeding 10 m^3/ha. Furthermore, subsidies were increased in line with the extracted volumes in order to increase timber supply.

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 8.3% in 2016 (ANRE, 2017). 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. In the Feed-In Tariff (FIT) scheme introduced in Japan starting 1 July, 2012, incentives have promoted the use of power generated from unused materials such as small sized logs and logging residue (0.32 USD/kWh) compared to general materials such as sawmill residue (0.24 USD/kWh) and recycled material such as construction waste wood (0.13 USD/kWh), respectively (ANRE, 2017). Usage of unused materials are also expected to increase from 2 million m^3 in 2014 to 8 million m^3 in 2025 based on the forest and forestry basic plan of Japan (Forestry Agency of Japan, 2016).

Numerous studies have examined the availability of woody biomass resources such as small sized logs and logging residues using GIS in Japan (Yoshioka and Sakai, 2005; Kamimura et al., 2009, 2012; Kinoshita et al. 2009, 2010; Aruga et al., 2011, 2014; Yamaguchi et al., 2014; Uemura et al., 2015; Yamamoto et al., 2019) as well as in other countries (Nord-Larsen and Talbot, 2004; Ranta, 2005; Möller and Nielsen, 2007; Panichelli and Gnansounou, 2008; Rørstad et al., 2010; Viana et al., 2010). However, these studies have not considered the optimal bucking methods although those have been

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Received 4 January 2018; Accepted 7 April 2018

conducted in Japan (Nagumo et al., 1981; Yoshida and Imada, 1989; Nakajima et al., 2008, 2009) as well as in other countries (Sessions et al., 1989; Olsen et al., 1991; Haynes and Visser, 2004; Akay, 2009, 2017; Wang et al., 2009; Akay et al., 2010, 2015; Serin et al., 2010; Pak and Gulci, 2017). In this study, the optimal bucking methods integrating forwarding costs to maximize profits (Nakahata et al., 2014) were numerically applied to Nasu town, and the factors of effects on profitability of commercial thinning operations and feasibility of the extraction of small sized logs were discussed.

2. Material and Methods

2.1. Study Site and Data

The study sites were Nasu town in Tochigi Prefecture, Japan (Figure 1). The gross area of Nasu town is 37231 ha, and the forest area is 23654 ha (64% of the gross area). In this study, major plantation species such as Japanese cedar and Japanese cypress in private and communal forests were analyzed. Private and communal forests were consisted of 10 404 sub-compartments of Japanese cedar comprising 4468 ha, and 4331 sub-compartments of Japanese cypress comprising 143 ha (Figure 2, Table 1). In this study, forestry operations were assumed to be conducted in a unit of sub-compartment which were usual operation unit in Japan. Therefore, the average operation unit assumed in this study was only 0.44 ha, very small. These forests are mainly 45–55 years old. The site index, which ranks the order of the productivity of the stands, was relatively high (Figure 3). 67% of forest area were the highest site index among three ranks of site index. The average slope angle is 13 degrees. Forestry operations included chainsaw felling, grapple-loader bunching, processor processing, and forwarder forwarding (Nakahata et al., 2014). Forest-registration data (stand ages, tree species, and site indices) and GIS data (information on roads and sub-compartment layers) from the Tochigi Prefectural Government were used in the study, as were 10-m-grid digital elevation models (DEMs) from the Geographical Survey Institute. Because of GIS data problem, only 10 829 sub-compartments comprising 4523 ha were analyzed in this study (Table 1).

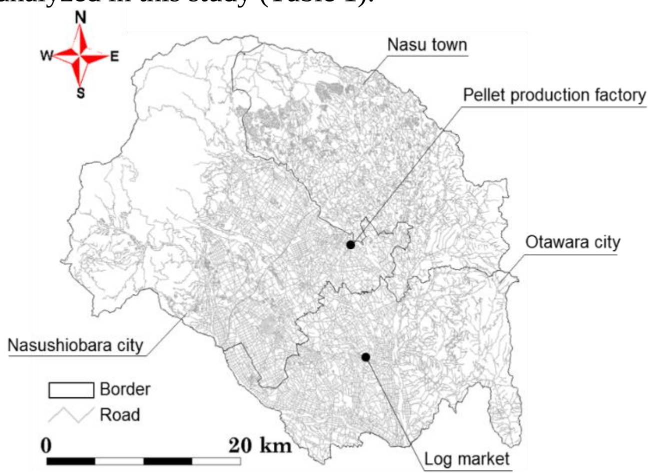

Figure 1. Study site

Table 1. The number and area of sub-compartments

Species	Forest registration		GIS	
	No.	Area, ha	No.	Area, ha
Japanese cedar	10404	4468	8039	3185
Japanese cypress	4331	2143	2790	1338
Total	14735	6612	10829	4523

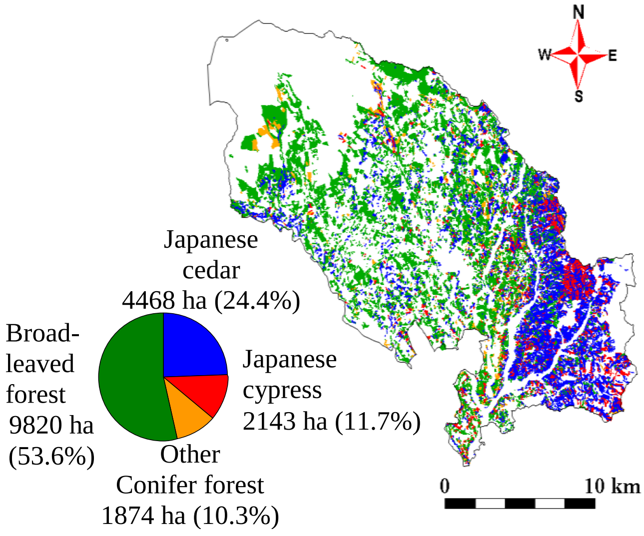

Figure 2. Stand species

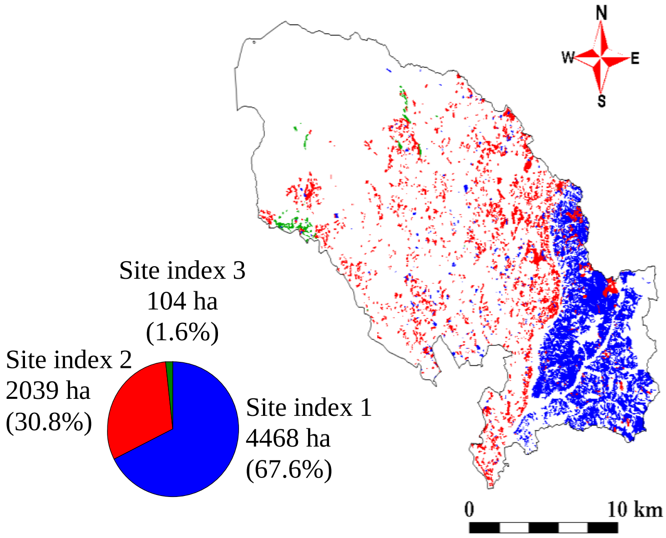

Figure 3. Site index

2.2. Methods

The optimal bucking method to maximize profits was determined as follows: 1) estimate thinning volumes, 2) estimate extracted volumes, 3) estimate revenues, 4) estimate expenses, 5) estimate economic values, and 6) determine the optimal bucking method to maximize profits. A simple version of Methods will be described below. Full technical details will be found in an earlier paper (Nakahata et al., 2014).

2.2.1 Estimation of Thinning Volumes

To estimate thinning volumes, the system yield table, LYCS (Shiraishi, 1985; Nakajima et al., 2010) is applied to the forest register. Silvicultural prescription were assumed that 3,000 seedlings/ha were planted and three thinning operations were conducted before final felling operations at 55 years old on the basis of interviews with forest owners' co-operative officials. First thinning operations were assumed to be pre-commercial thinning operations with 20% thinning rate of stem at 25 years old. Second and third thinning operations were assumed to be commercial thinning operations with 30% thinning rate of stem with 35 and 45 years old, respectively (Figure 4, 5). In Figures 4 and 5, “Rate” means the rate of the number of trees in each diameters of breast height DBH class to the total number of trees of which “Thinned woods” were removed and “Residuals” were left. Tree height H (m) were estimated in the following equations according to DBH (Shiraishi, 1981):

$$H = H_{ave}(D/D_{ave})^{0.5594-0.00178t} \tag{1}$$

where D was DBH (cm), H_{ave} and D_{ave} were the average tree height (m) and DBH (cm) of sub-compartment estimated with LYCS, t was forest age (years). In this study, forest ages were set to be 35 and 45 years old in order to analyze profitability of commercial thinning operations. Stem volumes of thinned woods Vn (m^3/stem) were estimated with the volume equation (Forestry Agency of Japan 1970).

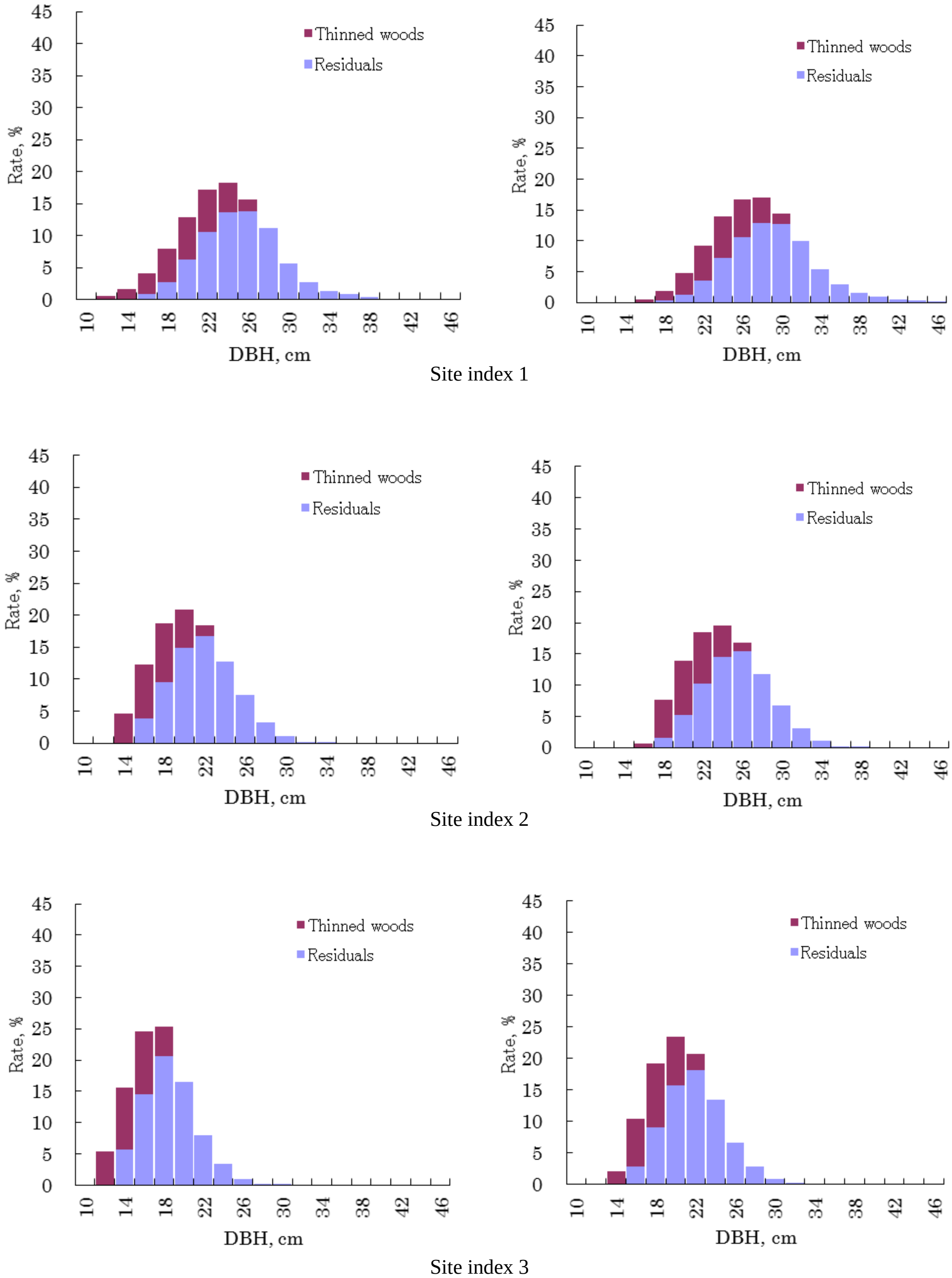

Figure 4. DBH distributions of Japanese cedar (Left: 35 years old, Right: 45 years old)

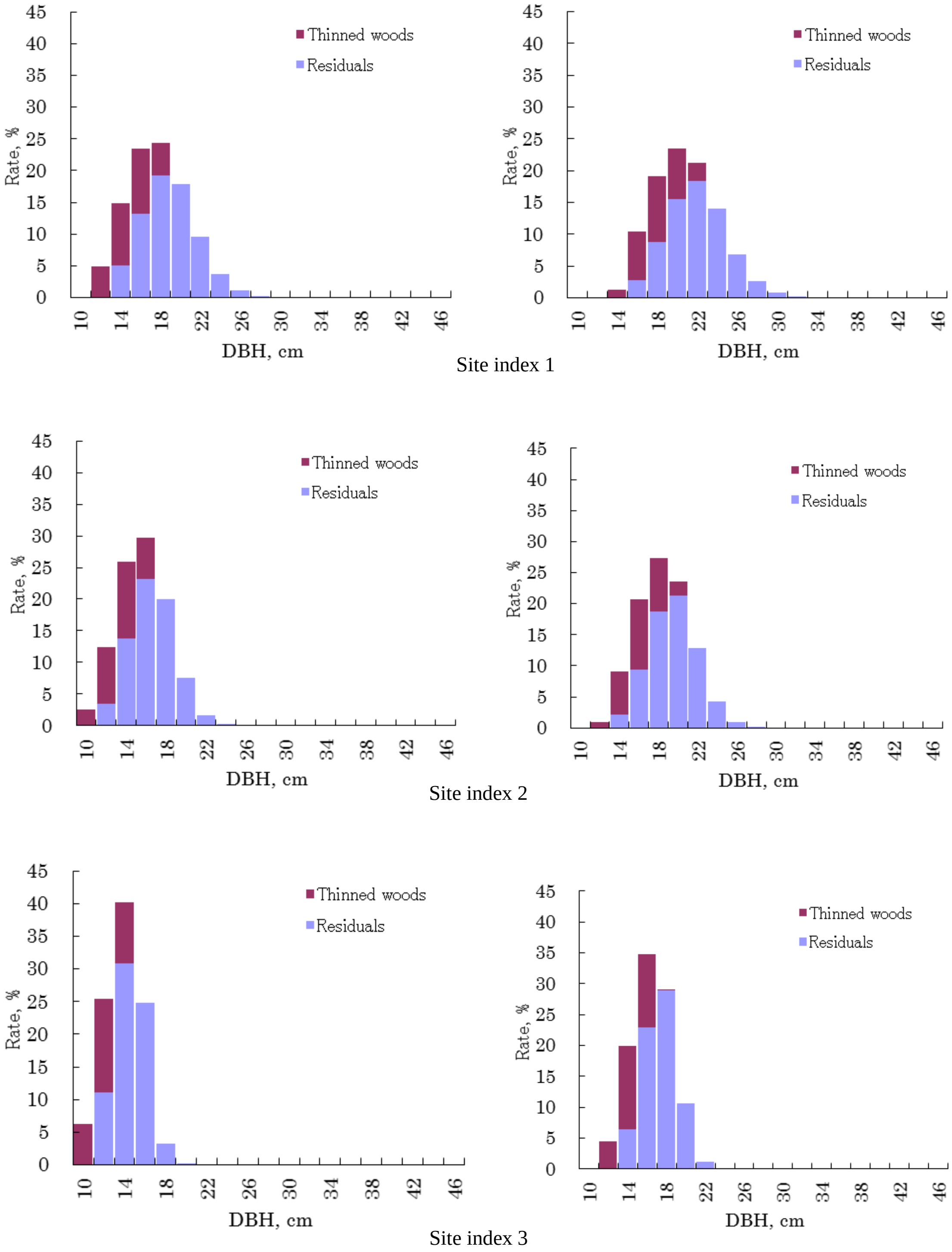

Figure 5. DBH distributions of Japanese cypress (Left: 35 years old, Right: 45 years old)

2.2.2 Estimation of Extracted Volumes

Extracted logs were classified as saw logs, lamina logs, and small sized logs (Table 2). Saw logs were 3.00-4.00 m long, with the top-end diameter exceeding 10 cm. Lamina logs 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. 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). Possible combinations of log length bucked from a thinned wood were estimated, and log volumes were estimated with log length and top-end diameters of logs using estimated stem diameter (Nakahata et al., 2014).

2.2.3 Estimation of Revenues

Log prices *p* (USD/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 lamina logs and

Table 2. Log unit prices

	Species	Length, m	Diameter, cm	Unit prices, USD/m^3
Saw log at sawmill	Japanese Cedar	3.00	11-14	81.70
			16-20	130.00
			22-28	123.90
		3.65	18-28	131.80
			30-	138.05
		4.00	10-14	101.22
			16-20	117.94
			22-28	126.89
			30-	137.65
	Japanese Cypress	3.00	11-14	81.80
			16-28	201.20
			30-	243.50
		4.00	10-14	116.60
			16-20	218.00
			22-28	251.90
			30-	402.30
Lamina log at landing	Japanese Cedar	2.00	16-18	50.00
			20-	55.00
	Japanese Cypress	2.00	16-18	70.00
			20-	90.00
Small sized log at factory	Japanese Cedar Japanese Cypress	2.00	3-	30.00

small sized logs were sourced from the unit prices of a laminated lumber factory and a pellet production factory, where the Nasu-machi Forest Owners' Co-operative sells lamina logs and small sized logs. Then, revenue from a thinned wood was estimated with the number of logs per thinned wood and each log price.

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 (2011). Subsidies were paid for the thinning operations with more than 5-ha operation site areas and more than 10-m^3/ha extracted volumes. Therefore, small sub-compartments were aggregated until more than 5-ha.

2.2.4 Estimation of Costs

Direct and other costs in the stands C (USD) were estimated (Nakahata et al. 2014). Forwarding costs were estimated using forwarding distances L_E (m) (Aruga et al. 2013).

$$L_E = 13{,}3A + 63{,}4 \quad (2)$$

where A was the stand area (ha). Strip-road expenses OC_R (USD/m) were estimated as follows (Sawaguchi 1996).

$$OC_R = 2{,}20e^{0{,}117\theta} \quad (3)$$

where θ was slope angle of sub-compartment (degree). If sub-compartments were not along public roads, strip roads were planned from nearest public road to sub-compartments with the shortest path algorithm, the Dijkstra method (Dijkstra, 1959). Planned road gradients were limited to 60% larger than those for existing roads, around 40% because of the 10-m grid-based program. In the forest, the route could be selected more precisely than that by the 10-m grid-based program. The actual road length tended to be 1,5 to 2,0 times longer than the straight distance of the road plan on the steep terrain in Japan. Therefore, the planned road gradient of 60% made actual road gradient of around 40% with the winding. However, 264 sub-compartments comprising 92 ha could not be reached. In these sub-compartments, pre-commercial thinning operations were assumed to be conducted even at 35 and 45 years old forests.

Truck transportation expenses OC_T (USD/m^3) of saw logs for log market and small sized logs for a pellet production factory were estimated as the following equations (Sawaguchi 1996).

$$OC_T = 0{,}31L_T + 7{,}78 \quad (4)$$

where L_T was transportation distance (m). Truck transportation expenses OC_T (USD/m^3) of lamina logs was 0 USD/m^3 because of landing sale.

2.2.5 Estimation of Economic Values

Economic values were estimated with revenues and costs of possible combinations of log length bucked from a thinned wood. Then, bucking method with maximum profits were determined as the optimal bucking method. If economic values of sub-compartments were deficit, costs without extraction (pre-commercial thinning operations) were estimated and compared with economic values of commercial thinning operations. Then, pre-commercial or commercial thinning operations with smaller loss were planned for the sub-compartments. Costs without extraction was estimated with felling operations and its insurance costs.

3. Results and Discussion

Commercial thinning operations could be conducted on 18% and 54% of 35 and 45 years old forests, respectively (Figure 6). On the other hand, those without subsidy could be conducted on only 8% and 48% of 35 and 45 years old forests, respectively. Even with subsidy, pre-commercial thinning operation would be conducted on 81% and 46% of 35 and 45 years old forests. This shows current situation of Japanese forestry where nearly all the thinning operations conducted were pre-commercial. Small sized logs could be extracted only on 8% and 10% of 35 and 45 years old forest, respectively.

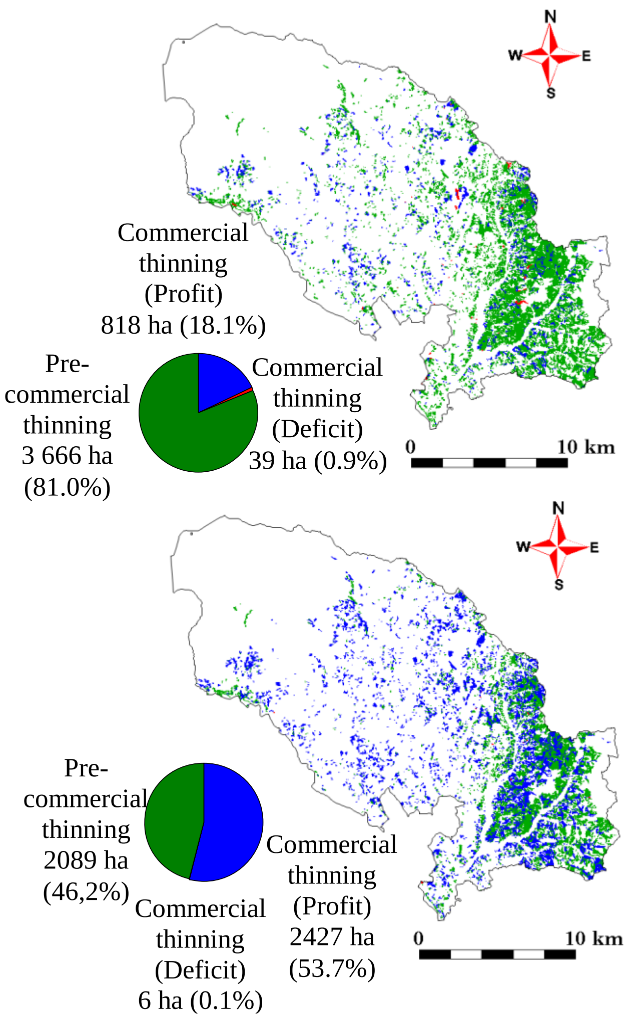

Figure 6. Results (Above: 35 years old, Bottom: 45 years old)

The average extracted volumes from 35 years old Japanese cedar forests with Site index 1 and 2 were 129.24 m^3/ha and 79.81 m^3/ha, respectively while those from 35 years old Japanese cypress forests with Site index 1 and 2 were 35.00 m^3/ha and 9.29 m^3/ha, respectively (Figure 7). On the other hand, the average extracted volumes from 45 years old Japanese cedar forests with Site index 1 and 2 were increased to 190.29 m^3/ha and 127.68 m^3/ha, respectively while those from 45 years old Japanese cypress forests with Site index 1 and 2 were increased to 75.65 m^3/ha and 44.55 m^3/ha, respectively. Furthermore, 71.28 m^3/ha would be extracted from 45 years old Japanese cedar forests with Site index 3.

Moreover, small sized logs could be extracted with subsidy while no small sized logs could be extracted without subsidy. The average extracted small sized log volumes from 35 years old Japanese cedar forests with Site index 1 and 2 were 3.64 m^3/ha and 6.45 m^3/ha, respectively while those from 35 years old Japanese cypress forests with only Site index 1 were 3.09 m^3/ha. On the other hand, the average extracted small sized log volumes from 45 years old Japanese cedar forests with Site index 1, 2, and 3 were 1.21 m^3/ha, 1.19 m^3/ha and 0.39 m^3/ha, respectively while those from 45 years old Japanese cypress forests with Site index 1 and 2 were increased to 2.04 m^3/ha and 2.51 m^3/ha, respectively. Extracted small sized logs from 35 years old forests were more than those from 45 years old forests although saw logs from 35 years old forest were less than those from 45 years old forests.

Economic values of commercial thinning operations were increased according to the site index and forest age (Figure 8). Profitability of commercial thinning operations would be decreased according to slope angles, forwarding distances, and transportation distances of small sized logs (Table 3). Larger areas expected to increase profitability of commercial thinning operations because access strip roads establishment costs and machine transportation costs per ha were decreased. However, forests with larger areas were located relatively steep terrain. Thus, larger areas did not increase profitability of commercial thinning operations. Shorter transportation distances of saw logs also expected to increase profitability of commercial thinning operations. However, forests with distances less than 10 km and between 20 and 25 km had relatively low productivity because forest areas near log market were small less than 1 ha and forests with transportation distance between 20 and 25 km had relatively steep terrain.

Areas with extracting small sized logs were reduced according to the increased slope angles, forwarding distances and transportation distances of small sized logs (Table 3). No small sized logs could be extracted more than 30°-slope angles and more than 300-m forwarding distances in this study. Since volumes of small sized logs extractions were 4.89 m^3/ha and 1.37 m^3/ha of 35 and 45 years old forests, volumes of small sized logs extractions were 4000 m^3 and 3 325 m^3 from profitable commercial thinning operations, 818 ha and 2 427 ha of 35 and 45 years old forests during 55-years rotation. Therefore, annual volumes of small diameter logs extractions were estimated at only 73 m^3/year and 60 m^3/year of 35 and 45 years old forests, respectively.

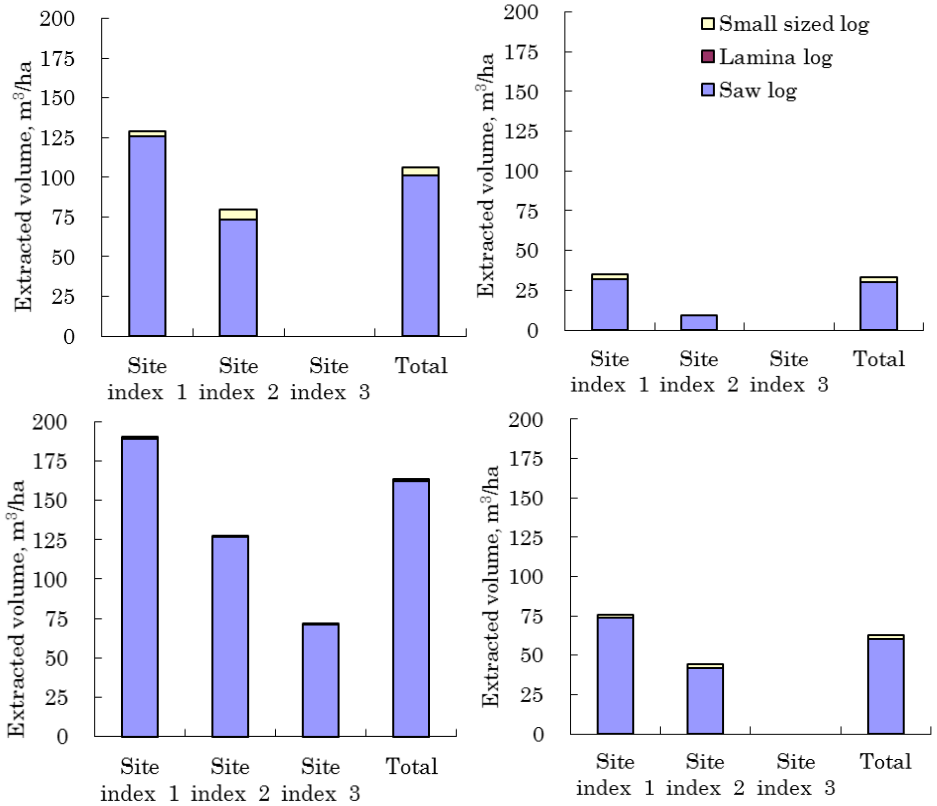

Figure 7. Extracted volumes (Above: 35 years old, Bottom: 45 years old, Left: Japanese cedar, Right: Japanese cypress)

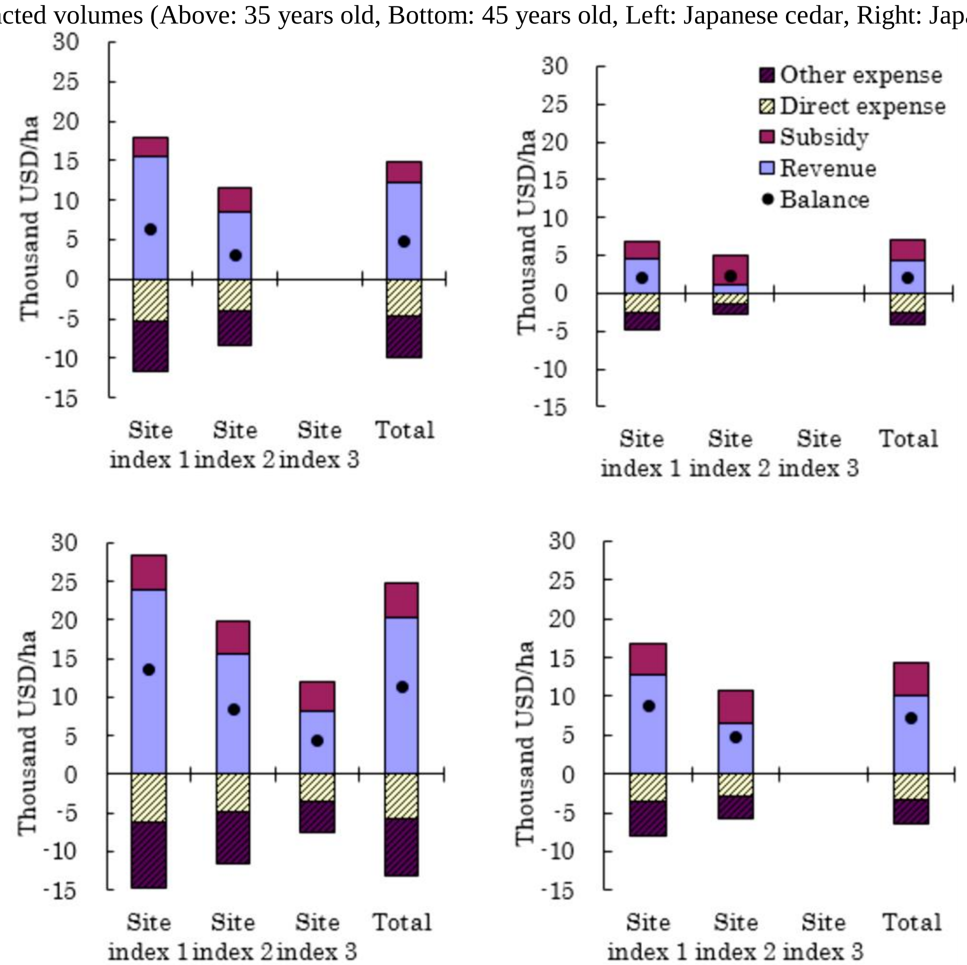

Figure 8. Economic values (Above: 35 years old, Bottom: 45 years old, Left: Japanese cedar, Right: Japanese cypress)

Table 3. Effect of site condition

	35 years old							45 years old						
Slope angle, degree	-5	-10	-15	-20	-25	-30	30-	-5	-10	-15	-20	-25	-30	30-
1, %	17	18	14	22	2	0	0	81	67	52	52	42	8	0
2, %	1	1	1	1	1	0	0	0	0	0	0	0	0	0
3, %	47	60	77	69	96	100	100	9	14	30	36	51	90	100
4, %	36	20	7	8	1	0	0	10	19	18	13	7	2	0
Forwarding distance, m	-100	-150	-200	-250	-300	300-		-100	-150	-200	-250	-300	300-	
1, %	15	10	5	3	1	0		58	48	41	29	17	6	
2, %	1	1	0	0	0	0		0	0	0	0	0	0	
3, %	70	82	88	93	98	100		28	42	53	66	82	94	
4, %	13	6	7	3	1	0		15	10	6	5	1	0	
Transportation distance of small sized logs, km	-10	-15	-20	20-				-10	-15	-20	20-			
1, %	13	9	10	2				65	51	34	38			
2, %	1	1	0	0				0	0	0	0			
3, %	63	80	85	94				17	39	57	57			
4, %	23	9	4	4				18	9	9	5			
Subcompartment area, ha	-0.5	-1.0	-1.5	-2.0	-2.5	-3.0	3.0-	-0.5	-1.0	-1.5	-2.0	-2.5	-3.0	3.0-
1, %	10	11	10	7	14	6	11	40	43	40	54	58	41	50
2, %	1	0	1	1	2	3	1	0	0	0	0	0	0	0
3, %	84	78	81	76	72	90	83	51	46	49	36	35	48	41
4, %	6	11	8	16	13	1	6	9	11	11	11	7	11	9
Transportation distance of saw logs, km	-10	-15	-20	-25	25-			-10	-15	-20	-25	25-		
1, %	2	12	8	10	15			1	46	45	41	64		
2, %	0	1	1	1	0			0	0	0	0	0		
3, %	98	78	83	82	64			60	34	47	50	25		
4, %	0	8	7	7	21			39	20	8	9	11		

1: Commercial thinning (Profit) and extracted small sized logs
2: Commercial thinning (Profit)
3: Commercial thinning (Deficit)
4: Pre-commercial thinning

4. Conclusion

Numerous studies have examined the availability of woody biomass resources such as small sized logs and logging residues using GIS with the average log price and cost. Therefore, these studies have not examined the feasibility of the small sized log extraction. In this study, the optimal bucking methods were numerically applied to Nasu town, and the factors of effects on profitability of commercial thinning operations and feasibility of the extraction of small sized logs were discussed. As a result, stands with extracting small sized logs accounted for approximately ten percent of the total forest area. The areas of stands with extracting small sized logs were increased according to the more gentle slope and shorter forwarding distances. Thus, it was clear that the reduction of forwarding distances by establishing forest road networks were effective in order to increase stands with extracting small sized logs.

Small sized log volumes with the optimal bucking method were smaller than the actual values 11 m^3/ha (Akaguma et al., 2017) because the method did not consider log quality. However, bucking operations should be conducted considering log quality also. Low quality logs were sold as pellet and fuel logs instead of saw and lamina logs. Therefore, future studies should consider log quality, although this can be difficult to predict. Furthermore, stem diameter at the height above the ground was estimated with the taper curve formula in this study. Detailed description of stem shape such as bending, sweep, and lean were not considered. Terrestrial LiDAR has been used to measure detailed description of stem shape (Aruga et al., 2016; 2017). The future study will apply terrestrial LiDAR to optimal bucking algorithm to consider detailed description of stem shape.

Acknowledgements

We are grateful to the Nasu-machi Forest Owners' Co-operative for their cooperation during the course of this research. This study was supported by JSPS KAKENHI Grand Number 15H04508 and 16KK0168.

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