

## Analyses on Strip Road Networks and Profitability of Final Felling Operations Considering Regeneration Expenses at Nasu in Tochigi Prefecture, Japan

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### Abstract

In this study, strip road networks of final felling operations were investigated, and then, effects of areas and road network densities on operational costs were analyzed. Finally, total revenues and costs during a 55-year rotation were estimated and profitability of forest management during that rotation was examined. It was found that road network densities of final felling operations were significantly greater than those of thinning operations because of avoiding residual tree damage in thinning operations and efficient bunching operations in final felling. Minimum operational expenses of final felling operations were less than those of thinning operations. Similar to the thinning operations, lower volumes and greater road network densities increased operational expenses; however, differences among minimum operational expenses of final felling operations with various volumes and road network densities were smaller than those of thinning operations. Site areas with minimum operational expenses of final felling operations were smaller than those of thinning operations. Final felling operations on smaller site areas would be environmentally friendly. Total revenues and costs during the 55-year rotation were USD 77,591.60/ha and USD 73,030.24/ha, respectively. Therefore, economic balance during the rotation was USD 4,561.36/ha. Because subsidies during the rotation were USD 27,542.89/ha, economic balance during the rotation with subsidies were USD 32,104.25/ha. However, economic balances reduced according to the reduced site index. This highlights the current situation in Japanese forestry, in which many forest owners are unwilling to conduct regeneration operations after final felling operations.

**Keywords:** Economic balance, Final felling operation, Thinning operation, Site area, Road network density

### 1. Introduction

Japan's forest resources are mature enough for final felling operations. The share of planted forest area exceeding 50 years in age was 35% in 2007 and it is expected to exceed 60% by 2017. However, profit of final felling operations, USD 11,700.00/ha, did not cover reforestation expenses for the next decade (USD 15,600.00/ha) (Forestry Agency of Japan, 2013). Therefore, many forest owners are not willing to conduct final felling operations and extending cutting age expected to increase revenues, owing to improvement of log prices, or unwilling to conduct regeneration operations even on unsuitable natural regeneration sites after final felling operations.

On the other hand, the Nasu-machi Forest Owners' Cooperative in Tochigi Prefecture of Japan is willing to perform final felling operations because of less demand for large-diameter logs more than 40 cm in this area (Yano, 2013). In previous studies, the profitability of final felling operations have been examined (Mizuniwa et al., 2014; 2015; 2016); however, profitability of final

felling operations including regeneration expenses has not been analyzed. Murakami et al. (2011) and Aruga et al. (2013b) developed a method for extracting production forests based on economic balance by considering regeneration expenses using a Geographic Information System (GIS). However, they did not analyze strip road networks, although they considered forest roads between public roads and operation sites.

Strip road networks were crucial for efficient forestry operations. Aruga et al. (2013a) analyzed effects of aggregating forests, establishing forest road networks, and mechanization on operational efficiency and costs of commercial thinning operations. In the present study, it was aimed to investigate strip road networks of final felling operations of the Nasu-machi Forest Owners' Cooperative using a method similar to Aruga et al. (2013a). Then, effects of areas and road network densities on operational costs were examined. Finally, total revenues and costs during a 55-year rotation were estimated, and profitability of forest management during that rotation was studied.

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## 2. Materials and Methods

### 2.1 Study site and road network analysis

Investigations were made at seven thinning operation sites (Aruga et al., 2013a) and nine final felling operation sites (Figure 1). The operational system of final felling was the same as that of thinning operations with mechanized systems using chainsaw for felling, grapple loader for bunching, processor for bucking and delimiting, and forwarder for

forwarding (Aruga et al., 2013a) (Figure 2, Table 1). Strip road networks, established at a width of 3.5 m, were analyzed by considering density, average bunching distance, ratio of average bunching distance to its theoretical average, and average forwarding distance (Table 2). Theoretical bunching distances were estimated using a rectangular model (i.e. theoretical average bunching distance =  $2,500/\text{road density}$ ).

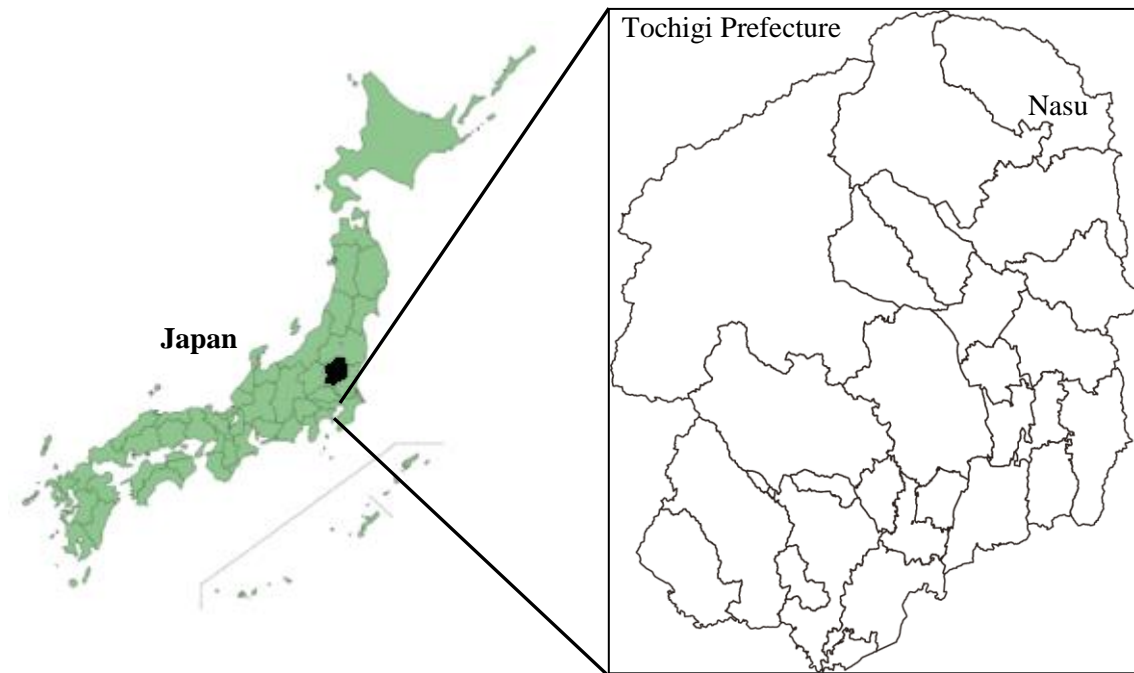


Figure 1. Nasu in Tochigi Prefecture



Figure 2. The stages of mechanized logging operation

Table 1. Study sites

	A	B	C	D	E	F	G	H	I
Species	Japanese cedar	Japanese cedar	Japanese cedar	Japanese cedar Japanese cypress	Japanese cedar	Japanese cedar	Japanese cedar	Japanese cedar Japanese cypress	Japanese cedar Japanese cypress
Stand age (years)	49-55	41-70	43-61	44-59	59	67	50	47	34-103
Area (ha)	1.84	4.55	2.03	1.78	0.96	1.49	1.69	1.30	4.26
Slope angle (°)	22.47	24.40	9.78	21.55	19.77	29.85	15.48	24.32	22.07
Stand density (stem/ha)	1,050	1,240	1,400	900	509	786	692	1,180	898
Production volume (m <sup>3</sup> /stem)	0.54	0.26	0.44	0.41	1.00	0.60	0.74	0.37	0.74
Production volume (m <sup>3</sup> /ha)	565	328	611	371	507	471	515	440	453
Revenue (USD/m <sup>3</sup> )	79.84	85.07	86.46	95.03	105.74	105.91	107.79	103.13	114.73

Table 2. Strip road network analysis

	A	B	C	D	E	F	G	H	I
Length (m)	595	1,627	790	630	395	438	807	558	1,785
Density (m/ha)	323.30	357.62	389.01	354.20	410.97	294.44	477.47	429.23	419.48
Bunching distance (m)	10.86	8.06	11.44	8.91	9.57	12.42	7.40	6.80	8.18
Ratio of bunching distance*	1.40	1.15	1.78	1.26	1.57	1.46	1.41	1.17	1.37
Forwarding distance (m)	80.82	225.13	152.51	155.15	200.35	169.90	241.67	123.39	314.62

\*Ratio of average bunching distance to theoretical average bunching distance estimated using a rectangular model (theoretical average bunching distance = 2,500/road density)

## 2.2 Operational expenses

Direct operational expenses were estimated with equations established by Mizuniwa et al. (2016) for final felling operations (Table 3), consisting of labor and machinery expenses (i.e. maintenance, management, depreciation, fuel, and oil). Direct operational expenses of strip road establishment  $C_R$  (USD) were estimated using strip road length  $L$  (m), consisting of areas and road network density.

$$C_{RF} = 3.16L \text{ (i.e. for final felling operation)} \quad (1)$$

Table 3. Equations for direct operational expenses

Machine	Operation	Direct expense (USD/m <sup>3</sup> )
Chainsaw	Felling	$0.45/Vn + 0.51$
Grapple loader	Bunching	6.40
Processor	Processing	$2.32/Vl + 2.50$
Forwarder	Forwarding	$0.0045L_F + 4.79$

$Vn$ : Harvested stem volume (m<sup>3</sup>/stem),  $Vl$ : Production volume from stem (m<sup>3</sup>/stem),  $L_F$ : Forwarding distance (m)

Overhead costs, log transportation expenses, machine transportation expenses, handling fees associated with the forest owners' cooperative and log markets, and piling fees at those markets were considered indirect operational expenses (Zenkoku Ringyo Kairyo Fukyu Kyokai, 2001). Overhead costs were estimated at 18.4% of direct operational expenses. Logs were sold at four locations, a log market, sawmill, laminated lumber factory, and chip factory. Log transportation expenses were USD 13.00/m<sup>3</sup> for the log market and USD 15.00/m<sup>3</sup> for the chip factory. Logs for the sawmill and the laminated lumber factory were sold at a landing and no transportation costs were incurred. Machine transportation expenses were estimated at unit costs of USD 50.00/machine multiplied by the number of machines, which was five, including two forwarders for the mechanized operation

system. Handling fees associated with the forest owners' cooperative were 5% of revenues and those associated with the log market were 5% of timber prices at the market. Piling fees at the log market were USD 7.00/m<sup>3</sup>.

## 2.3 Total revenues and costs during the 55-year rotation

For estimating total revenues and costs during the 55-year rotation, silvicultural prescriptions were established based on interviews with officials of the cooperative, and production volumes were estimated with a local yield table construction system (LYCS) (Table 4). Direct operational expenses for thinning operations were estimated with equations established by Nakahata et al. (2011) similarly to the previous study (Aruga et al., 2013a).

For estimating total revenues and costs during the 55-year rotation, strip roads were assumed established upon first commercial thinning operations, at 35 years old (Table 4). Then, 10% of direct operational expenses of strip road establishment were included in expenses for second commercial thinning operations at 45 years old and final felling operations at 55 years old, as maintenance expenses based on the aforementioned interviews with officials.

In addition to the timber extraction expenses, regeneration expenses included site preparation, planting, weeding, pruning, and cleaning. These expenses were estimated at USD 27,308.80/ha on the basis of interviews with forest owners' cooperative officials, similar to USD 25,123.76/ha for Japanese cedar and USD 28,923.65/ha for Japanese cypress (Okawabata, 2003) in the previous study (Aruga et al., 2013b). In the present study, about 3,000 seedlings/ha were assumed to be planted, and weeding operations

were assumed to be conducted once per year for 7 years after planting. Then, pruning and cleaning were assumed to be performed at 15 years after planting.

Within total revenue and cost estimation during the 55-year rotation, revenues were estimated with prices and rates of logs for the log market, laminated lumber factory, and chip production factory. Prices and rates were set on the basis of interviews with forest owners' cooperative officials. Prices of logs for the log market, laminated lumber factory, and chip production factory were USD 120.00/m<sup>3</sup>, USD 80.00/m<sup>3</sup>, and USD 40.00/m<sup>3</sup>, respectively. Corresponding rates of logs were 50%, 30%, and 20% for thinning operations, and 70%, 20%, and 10% for final felling operations.

Subsidies, introduced for thinning operations in Japan, were estimated with standard unit costs multiplied by area, assessment coefficient (1.7), and subsidy rate (0.4) of the Tochigi Prefectural Government (2011) (Table 5). To promote the extraction of thinned woods, subsidies were increased

according to extracted volumes. For subsidized thinning operations in Japan, subsidies for strip road establishment were also received. Standard unit costs for strip road establishment were determined using the average slope angle (degree) and road width. Then, subsidies (Table 6) were estimated using standard unit costs multiplied by length, assessment coefficient (1.7), and subsidy rate (0.4) of the prefectural government (2011).

The subsidy for regeneration was estimated similar to thinning operations, by considering the standard unit cost, area, assessment coefficient, and subsidy rate (Tochigi Prefectural Government, 2011). The subsidies were estimated at USD 17,124.08/ha greater than USD 12,274.00/ha for Japanese cedar and USD 12,192.40/ha for Japanese cypress (Aruga et al., 2013b). This was because the Nasu-machi Forest Owners' Cooperative planted fewer pollen seedlings to measure pollen allergies, which were a serious problem in Japan, and to increase the subsidy. Therefore, the regeneration expenses excluding subsidies were USD 10,184.72/ha.

Table 4. Production volumes estimated with a local yield table construction system

Site index	Age	Stand density	Stem volume	Stand volume	Cutting rate of stem	Harvested tree	Harvested stem volume	Harvested volume	Production rate	Production volume from stem	Production volume
	year	stem/ha	m <sup>3</sup> /stem	m <sup>3</sup> /ha	%	stem/ha	m <sup>3</sup> /stem	m <sup>3</sup> /ha	%	m <sup>3</sup> /stem	m <sup>3</sup> /ha
	1	3,000									
1	25	2,548	0.20	515	25	637	0.13	81	0		
	35	1,773	0.42	737	30	532	0.29	153	50	0.14	76.50
	45	1,189	0.55	656	35	416	0.50	208	50	0.25	104.00
	55	758	0.97	733	100	758	0.97	733	80	0.77	586.40
2	25	2,701	0.12	337	25	675	0.08	53	0		
	35	1,917	0.26	501	30	575	0.18	101	50	0.09	50.50
	45	1,300	0.43	559	35	455	0.30	138	50	0.15	69.00
	55	833	0.66	552	100	833	0.66	552	80	0.53	441.60
3	25	2,885	0.07	209	25	721	0.05	35	0		
	35	2,086	0.15	320	30	626	0.11	68	50	0.05	34.00
	45	1,429	0.25	362	35	500	0.19	94	50	0.09	47.00
	55	920	0.39	358	100	920	0.39	358	80	0.31	286.40

Table 5 Subsidies for thinning operations (USD/ha)

Thinning ratio	Extracted volume (m <sup>3</sup> /ha)									
	10-	20-	30-	40-	50-	60-	70-	80-	90-	
20%-	1,120.40	1,589.63	2,058.66	2,537.67	3,006.90	3,476.12	3,954.93	4,424.16	4,893.39	
30%-	1,321.50	1,800.31	2,269.54	2,738.76	3,217.57	3,686.80	4,156.03	4,634.83	5,104.06	

Table 6. Subsidies for strip road establishment (USD/m)

Average slope angle	Width 3.5 m
Gradual (-15 degrees)	1.53
Medium (15-30 degrees)	3.58
Steep (30- degrees)	12.62

### 3. Results and Discussion

#### 3.1 Strip road network analysis

In terms of the relationship between road network density  $d$  (m/ha) and average slope angle  $\theta$  ( $^{\circ}$ ), the road network density of both thinning and final felling operations declined according to the increased average slope angle  $\theta$ , because it is more difficult to establish forest road networks on steeper terrain (Figure 3). Road network densities of final felling operations were significantly greater than those of thinning operations, because of the avoidance of residual tree damage in the latter operations. Furthermore, all harvested woods of final felling operations were bunched by a grapple-loader for extraction. Therefore, road network densities were subject to increase and average bunching distances decreased (Figure 4). The latter distances of final felling operations were 6.80–12.42 m, whereas those of thinning operations were 12.82–27.74 m. Grapple-loader bunching operations were conducted within 20 m of roads.

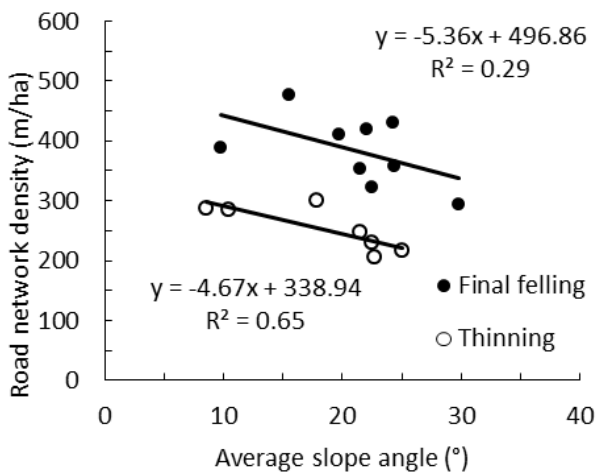


Figure 3. Average slope angle and road network density

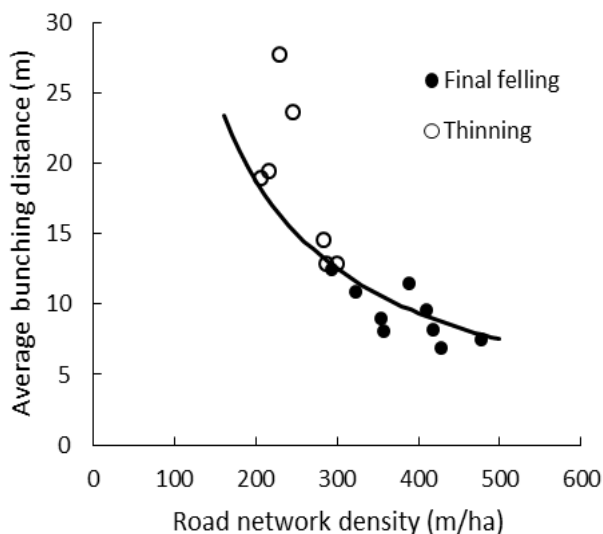


Figure 4. Road network density and average bunching distance (Line was indicated as ratio of average bunching distance to theoretical average bunching distance, 1.5)

Thus, all harvested woods of final felling operations could be bunched, whereas thinned woods beyond 20 m from roads were left in the forest (pre-commercial thinning operations were done in those areas). High road network densities could also be useful for regeneration operations to do site preparation and transport seedlings for planting operations.

The average forwarding distance  $L_F$  (m) increased according to increased operation site area  $A$  (ha) (Aruga et al., 2013a).

$$L_{FT} = 13.29A + 63.43 \text{ (i.e. for thinning operation)} \quad (2)$$

$$L_{FF} = 32.94A + 112.04 \text{ (i.e. final felling operation)} \quad (3)$$

Road network densities were significantly different between thinning and final felling operations. Therefore, road lengths estimated with areas and road network densities were used to estimate average forwarding distances (Figure 5) although the forwarding distances were simply estimated with  $0.5 \times \text{road density (m/ha)} \times \text{site area (ha)}$  in other studies (Ishikawa et al., 2008; Nakahata et al., 2011).

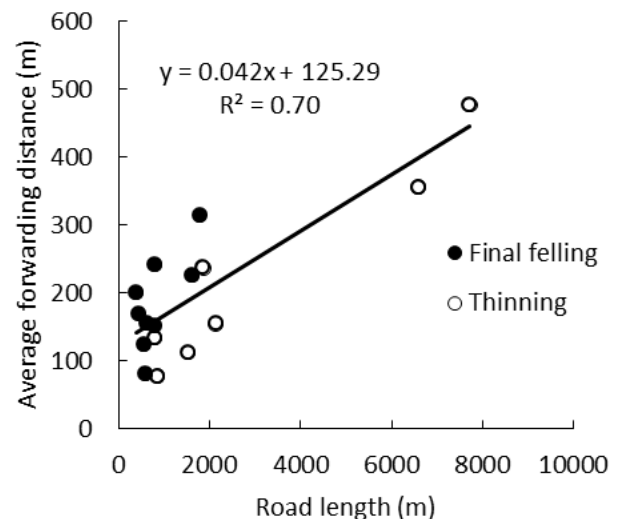


Figure 5. Road length and average forwarding distance

#### 3.2 Operational expenses

Operational expenses were estimated with different average production volumes from stems, according to site areas based on stand conditions of Site A (Figure 6). Minimum operational expenses of final felling operations were USD 49.45/m<sup>3</sup> for 0.20 m<sup>3</sup>/stem on 4.00 ha, USD 39.92/m<sup>3</sup> for 0.35 m<sup>3</sup>/stem on 3.00 ha, USD 36.10/m<sup>3</sup> for 0.50 m<sup>3</sup>/stem on 2.50 ha, and USD 34.03/m<sup>3</sup> for 0.65 m<sup>3</sup>/stem on 2.25 ha. Minimum operational expenses of thinning operations were USD 108.79/m<sup>3</sup> for 0.20 m<sup>3</sup>/stem on 8.00 ha, USD 90.35/m<sup>3</sup> for 0.35 m<sup>3</sup>/stem on 6.00 ha, and USD 82.95/m<sup>3</sup> for 0.50 m<sup>3</sup>/stem on 5.00 ha with the conventional system (Aruga et al. 2013a). For the mechanized system, corresponding expenses were USD 113.14/m<sup>3</sup> for 0.20 m<sup>3</sup>/stem on 7.00 ha, USD 86.30/m<sup>3</sup> for 0.35 m<sup>3</sup>/stem

on 5.25 ha, and USD 75.59/m<sup>3</sup> for 0.50 m<sup>3</sup>/stem on 4.50 ha (Aruga et al. 2013a). Minimum operational expenses of final felling operations were less than those of thinning operations. Similar to the thinning operations, smaller volumes caused higher operational expenses and areas with minimum operational expenses were reduced according to increased volumes (Aruga et al. 2013a; Ishikawa et al. 2008). However, site areas with minimum operational expenses of final felling operations were smaller than those of thinning operations. In fact, the cooperative conducted final felling operations on smaller site areas, 0.96–4.55 ha (Table 1), whereas those of thinning operation sites were 3.03–27.12 ha (Aruga et al. 2013a). Final felling operations on smaller site areas would be environmentally friendly.

Operational expenses were estimated with different road network densities according to site areas based on

stand conditions of Site A (Figure 7). Minimum operational expenses of final felling operations were USD 34.93/m<sup>3</sup> for 250 m/ha on 2.75 ha, USD 35.29/m<sup>3</sup> for 300 m/ha on 2.50 ha, USD 35.65/m<sup>3</sup> for 350 m/ha on 2.50 ha, and USD 36.01/m<sup>3</sup> for 400 m/ha on 2.25 ha. Minimum operational expenses of thinning operations were USD 81.01/m<sup>3</sup> for 200 m/ha, USD 83.94/m<sup>3</sup> for 250 m/ha, and USD 86.87/m<sup>3</sup> for 300 m/ha on 6.00 ha with the mechanized system (Aruga et al. 2013a). Higher road network densities increased operational expenses because of greater direct operational expenses of strip road establishment. However, differences among minimum operational expenses of final felling operations with varying road network densities were less than those of thinning operations. Thus, final felling operations with higher road network densities were not costly for efficient bunching operations.

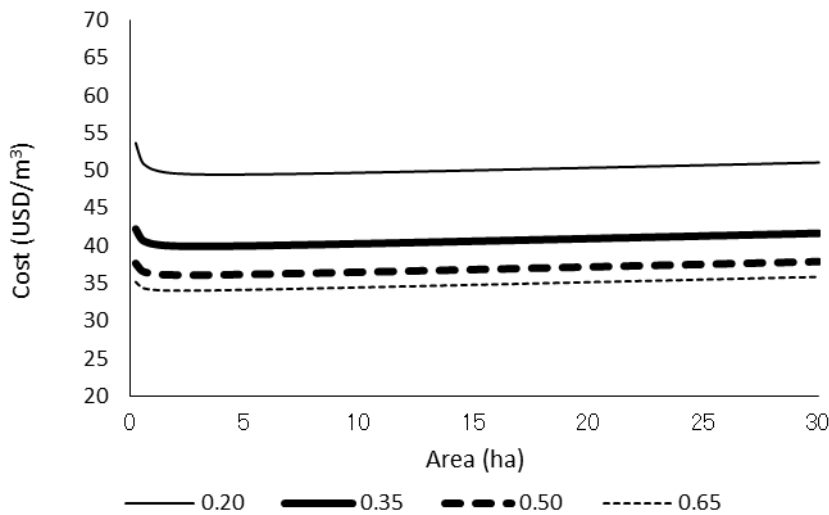


Figure 6. Estimated operational expenses (USD/m<sup>3</sup>) with different average production volumes from stems (m<sup>3</sup>/stem) based on stand conditions of Site A

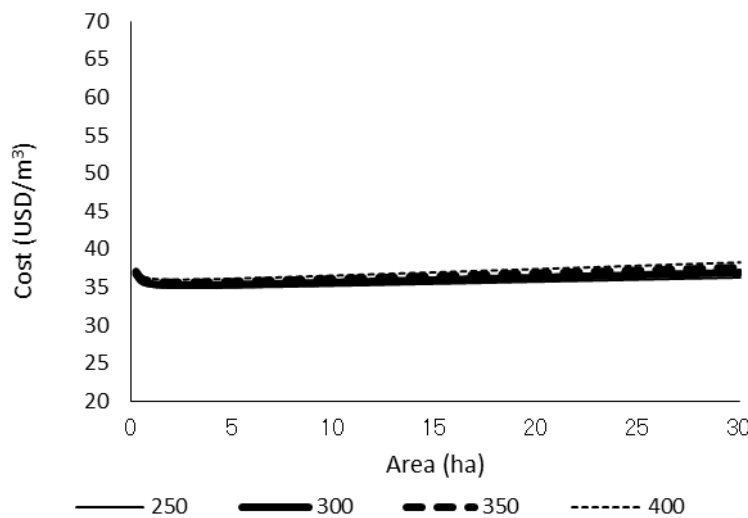


Figure 7. Estimated operational expenses (USD/m<sup>3</sup>) with different road network densities (m/ha) based on stand conditions of Site A

### 3.3 Total revenues and costs during the 55-year rotation

Total revenues and costs during the 55-year rotation were estimated based on stand conditions of Site A with Site index 1 and road network density, 323 m/ha (Figure 8). Revenues and costs of final felling operations were USD 60,985.60/ha and USD 28,543.12/ha, respectively. Therefore, the net profit of final felling operations was USD 32,442.48/ha. Regeneration costs were USD 27,308.80/ha and the cumulative economic balance from final felling to regeneration operations was USD 5,133.68/ha. Because subsidies for regeneration were USD 17,124.08/ha, the cumulative economic balance from final felling to regeneration operations with subsidies was USD 22,257.76/ha. Revenues of commercial thinning operations at 35 and 45 years old were USD 7,038.00/ha and USD 9,568.00/ha, respectively. Costs of thinning operations at 25, 35, and 45 years old were USD 797.92/ha, USD 7,977.73/ha, and USD 8,402.67/ha, respectively. Total revenues and costs of thinning operations were USD 16,606.00/ha and USD 17,094.19/ha, respectively. Therefore, the economic balance of thinning operations was USD -572.33/ha and that from final felling to thinning operations was USD 4,561.36/ha. Because subsidies for thinning operations were USD 10,418.81/ha, the cumulative economic balance from final felling to thinning operations with subsidies were USD 32,104.25/ha.

According to the reduced site index, production volumes were reduced, as were subsequent revenues. Costs were also reduced according to the reduced production volumes. However, reductions of costs were smaller than those of revenues. Economic balances were reduced according to the reduced site index. Without subsidies, economic balances of site index 2 and 3 were negative, USD -8,108.18/ha and USD

-20,626.56/ha, respectively. According to the increased road network density, costs increased but revenues remained constant. Therefore, economic balances were reduced according to the increased road network density. However, reduction was slight and bunching costs could be decreased with the increased road network density and reduced average bunching distance, although bunching costs were assumed constant in this study. Thus, appropriate forest road networks should be established as 200–300 m/ha for thinning to avoid residual stand damage, and 300–400 m/ha for final felling operations for efficient bunching.

### 4. Conclusions

In this study, it was aimed to investigate forest road networks of final felling and then, effects of areas and road network densities on operational costs were analyzed. Finally, total revenues and costs during the 55-year rotation were estimated, and profitability of forest management during the rotation was examined. It was found that road network densities of final felling operations were significantly greater than those of thinning operations, because of the avoidance of residual tree damage in thinning operations and efficient bunching in final felling operations.

Minimum operational expenses of final felling operations were smaller than those of thinning operations. Similar to the thinning operations, smaller volumes and greater road network densities increased operational expenses. However, differences among minimum operational expenses of final felling operations with varying volumes and road network densities were smaller than those of thinning operations. Site areas with minimum operational expenses of final felling operations were smaller than those of thinning operations. Final felling operations on smaller site areas would be environmentally friendly.

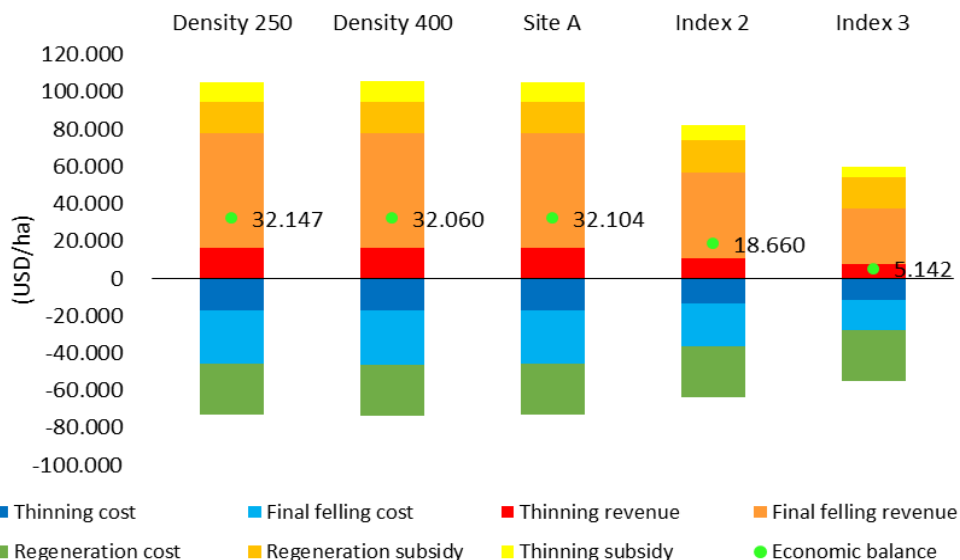


Figure 8. Estimated total revenues and costs (USD/ha) during the 55-year rotation based on stand conditions of Site A

Total revenues and costs during the 55-year rotation were USD 77,591.60/ha and USD 73,030.24/ha, respectively. Therefore, the net profit during the 55-year rotation was USD 4,561.36/ha. Because subsidies during the rotation were USD 27,542.89/ha, the net profit during the rotation with subsidy was USD 32,104.25/ha. However, economic balances were reduced according to the reduced site index. Without subsidies, economic balances of site indexes 2 and 3 were negative. The Japan Forest Agency has implemented measures for long-term rotation management, because revenues from final felling operations cannot cover regeneration costs under current conditions as in the present study for site indexes 2 and 3. Extending cutting age is expected to increase revenues, owing to improvement of log prices. However, effects of changing log prices were not considered in this study, but the rate of log quality was. Log quality and production rates varied by site. Therefore, future studies will address different rotation management and log prices along with log quality.

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