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ORIGINAL PAPER

A model to estimate available timber and forest biomass and reforestation expenses in a mountainous region in Japan

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Abstract: We developed a model to estimate supply potentials and available amounts of timber and forest biomass resources from profitable sub-compartments of thinning and final felling operations. Economic balances were estimated while considering not only harvesting expenses but also reforestation expenses after final felling, which should be considered for sustainable forest management. Harvesting expenses were estimated based on two types of timber harvesting systems and three types of forest biomass harvesting systems in each sub-compartment. Then, the model was applied to Nasushiobara city of Tochigi prefecture, Japan. Reforestation expenses had large negative impacts on the financial balances of final felling operations. Few sub-compartments were profitable after considering reforestation expenses. Most profitable sub-compartments were those with mechanized operation systems and landing sales. These accounted for 17.19% of all sub-compartments, while only 5.75% of the sub-compartments were profitable based on their current operation systems and landing sales. Although the overall supply potentials of timber and forest biomass resources were 380,000 m^3 and 210,000 Mg, respectively, and 15 times the planned harvest of coniferous tree volume of 25,000 $m^3 \cdot year^{-1}$ and 50 times the annual demand for the woody gasification power generation of 4,000 $Mg \cdot year^{-1}$ in Nasushiobara, available amounts of timber and forest biomass resources were only 49,429 m^3 and 33,333 Mg, which were 13.0% and 15.7% of supply potentials for landing sales with mechanized operation systems.

Keywords: forest biomass resources; supply potentials; available amounts; economic balance; GIS

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Introduction

Forests play important roles in realizing a low-carbon society in which forests sequester carbon from the atmosphere and produce wood, one renewable resource that stores sequestered carbon. Therefore, forests need to be continuously and properly managed and the wood should be utilized at all levels from building materials, furniture, board and paper to chemical products and fuel. Woody biomass can be categorized into forest biomass resources, sawmill residues and construction waste. Although the use of wood-fired boilers and generators and the production of wood pellets has been steadily increasing in recent years in Japan, large amounts of woody biomass, especially forest biomass resources, remain unused (Forestry Agency 2009). To utilize forest biomass as an energy resource in a region where forestry is the major source of income, it is crucial to understand the relationship between supply potentials and harvesting costs (logging and transport) and to estimate available amounts of forest biomass resources.

Numerous studies examined the availability of woody biomass resources. Iuchi (2004) and Kamimura et al. (2009) developed techniques for estimating the supply potential of woody biomass, including logging residues, sawmill residues and construction waste woods in terms of regional energy in units of cities and towns. In addition to supply potentials, Yoshioka et al. (2005) and Kinoshita et al. (2009) devised techniques for estimating the regional harvesting volumes and costs of logging residues in units of sub-compartments corresponding to conventional forest management units in Japan, whereas Yagi et al. (2007) and Yamamoto et al. (2010) developed techniques for expressing them in units of kilometer-scale grids or cities and towns. Aruga et al.

(2006a) established a technique for estimating regional harvesting volumes and costs of timber and logging residues in units of sub-compartments. Aruga et al. (2006b) developed a technique for estimating forest biomass resource allocation to multiple regional plants in units of sub-compartments, whereas Ranta (2005) and Möller et al. (2007) devised a technique for expressing this at a national level.

In addition to these methods for estimating volumes and costs, Yamaguchi et al. (2010) developed a technique for estimating the available amount of logging residues in consideration of the economic balances estimated from regional revenues and costs of both timber and logging residues in units of sub-compartments. Kinoshita et al. (2010) established a technique to express logging residues amounts for cities and towns. These studies did not, however, consider reforestation expenses, which are important for conducting sustainable forest management. Reforestation expenses include site preparation, planting, weeding, vine cutting, pruning, and forest inventory. We assumed about 2,500 seedlings·ha^{-1} are planted and weeding operations are conducted once a year for ten years after planting. We assumed vine cutting operations are conducted 10 and 12 years after planting, and pruning operations are conducted 15 and 25 years after planting.

In contrast, a previous study (Murakami et al. 2011) developed a method for planning production forests where revenues expected from clear cutting exceeded costs, including harvesting and reforestation expenses. We estimated revenues and costs from forest registration and geographic information system (GIS) data. We considered thinning operations as expenses of reforestation: revenues from thinning were not considered because almost all thinning conducted in Japan at the time was pre-commercial and large amounts of thinned trees were left in the forests.

Therefore, this study developed a method for extracting production forests considering forest biomass harvesting in order to use unused materials such as logging residues in addition to our previous study (Murakami et al. 2011). Then, we discuss the effects of harvesting methods on available amounts of timber and forest biomass.

Materials and methods

Study site and data

The study site was at Nasushiobara city in Tochigi prefecture, Japan (Fig. 1). An agrarian organization in the Nasunogahara area, in cooperation with a Forest Owners' Cooperative in Nasushiobara city, wished to conduct thinning operations to obtain raw materials for the woody biomass power generation plant (Fig. 2) and to maintain forests for soil and water conservation. The gross area was 59,280 ha, the forest area was 38,689 ha (65% of the gross area). The areas of national forests and of privately held and local government forests were 24,981 ha and 13,708 ha, respectively. We analyzed major plantation species such as Japanese cedar and Japanese cypress owned by privates and local governments (Fig. 2).

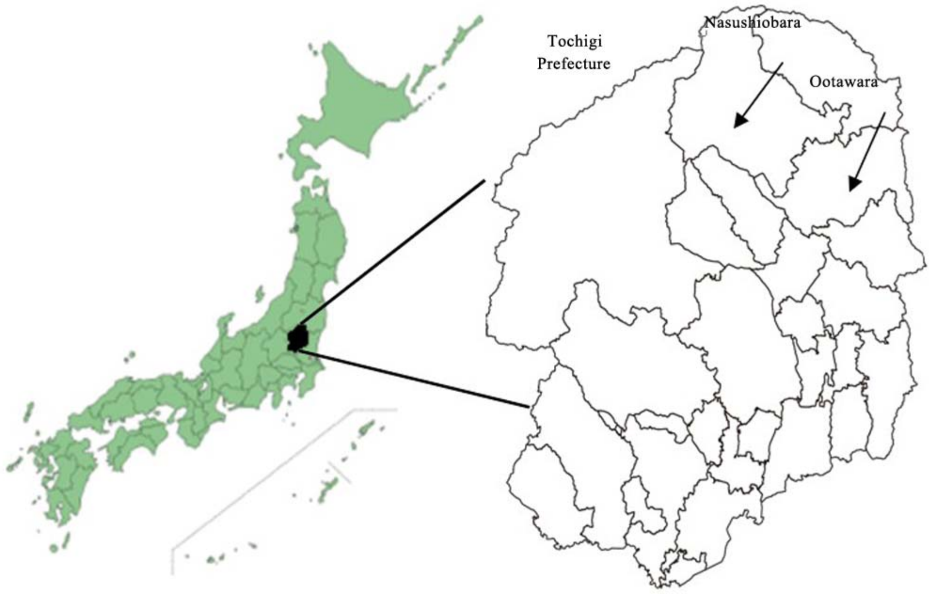


Fig. 1 Study site

These forests were mainly between 45 and 55 years old (Fig. 3). The northern parts of Nasushiobara city are mountainous and almost all are national forests. Private and local government forests were located on gentler slopes with average gradients of 10°. The density of the road network was relatively high, 49 m·ha^{-1}.

Forest registration data (stand ages, tree species and site indexes) and GIS data (information on roads and sub-compartment layers) from the Tochigi Prefectural Government were used in the study, as were 50 m-grid digital elevation models (DEM) from the

Geographical Survey Institute.

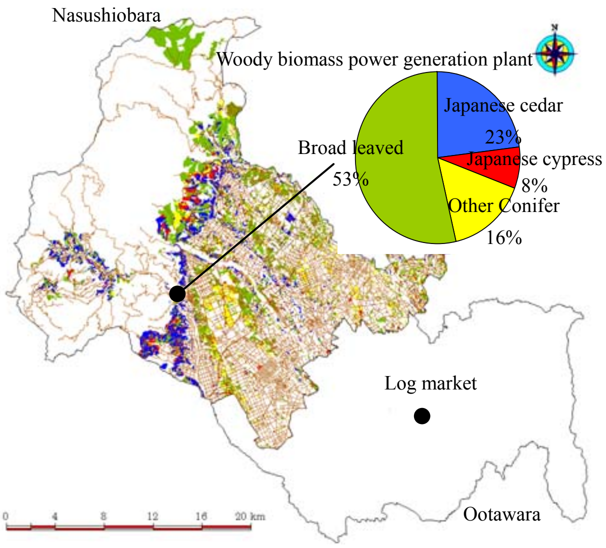


Fig. 2 Stand species

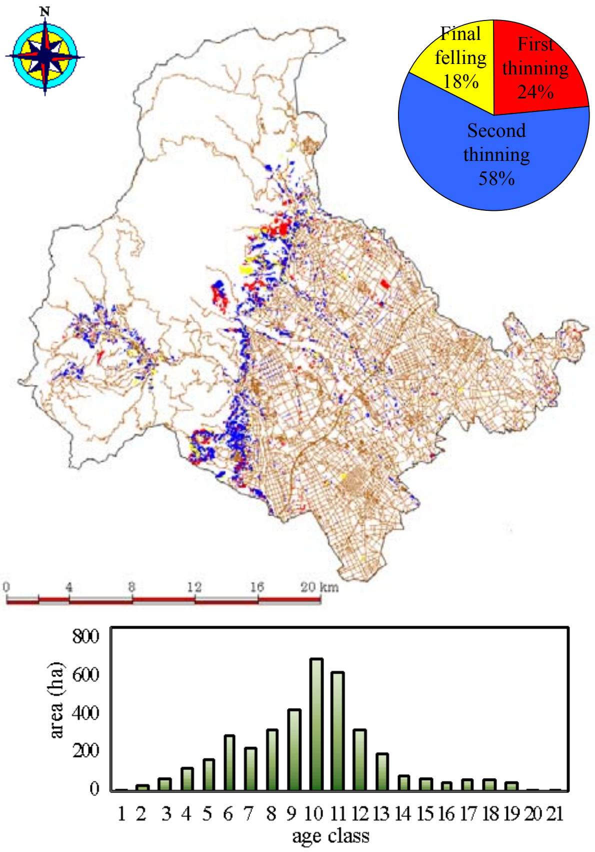


Fig. 3 Stand age class (five years each class) and sub-compartments selected as thinning and final felling operations

Methods

We estimated supply potentials and available amounts of timber and forest biomass resources from profitable sub-compartments in the following order: (1) sub-compartments for thinning and final felling operations were selected based on stand ages; (2) supply potentials were estimated based on the cutting and extraction rates; (3) forwarding and transportation distances were estimated; (4) total expenses including reforestation expenses after final felling operations were estimated; (5) incomes were estimated; (6) profits were estimated; (7) available amounts were estimated as supply potentials from profitable sub-compartments.

Estimating supply potentials of timber and forest biomass

Sub-compartments where thinning and final felling operations were assumed to be conducted were selected based on stand age (Table 1 and Fig. 3). Supply potentials were estimated based on thinning and extraction rates. The stand age and cutting rate (*Cr*) were set according to the Nakagawa regional forest plan (Tochigi Prefecture Government 2010b). Extraction rate (*Er*), timber rate (*Tr*) and forest biomass rate (*Fr*) were set according to the Mikamo Forest Owners' Cooperative's research report on extracting "forest biomass resources" (2008). Extraction rates (*Er*) for the second thinning and final felling operations were set to 109% owing to top and branch extractions (Aruga et al. 2006a). The forest biomass rate (*Fr*) is the ratio of forest biomass resources to be transported to the power generation plant to the total felled and extracted volume, whereas the timber rate (*Tr*) is the ratio of timber to be transported to the log market to the total felled and extracted volume.

Table 1. Harvesting condition of each operation classified based on stand age

Operation	Stand age (years)	Cutting rate (*Cr*)	Extracting rate (*Er*)	Timber Rate (*Tr*)	Forest biomass rate (*Fr*)
First thinning (pre-commercial)	25–39	25%	80%	0%	100%
Second thinning (commercial)	40–59	35%	109%	45%	55%
Final felling (clear cutting)	60–	100%	109%	74%	26%

Then, supply potentials of timber and forest biomass resources were estimated using the following expressions.

$$H = S \times Cr \times Er \times A = V \times A \quad (1)$$

$$H_T = H \times Tr = V_T \times A \quad (2)$$

$$H_F = H \times Fr \times Gr \quad (3)$$

Where, H is the extracted volume (m^3), S is the stock of the stems in the forest registration data ($m^3 \cdot ha^{-1}$), A is the area of sub-compartment (ha), V is the extracted volume per hectare ($m^3 \cdot ha^{-1}$); H_T is the extracted timber volume (m^3), H_F is the extracted forest biomass weight (Mg) and Gr is the volume density, which is assumed to be 0.68 $Mg \cdot m^{-3}$ based on the Mikamo Forest Owners' Cooperative survey results (2008). Water contents (dry base) for Japanese cedar and Japanese cypress are 100% and 80%, respectively.

Estimating forwarding and transport distances

Forwarding distances were estimated as average distances from the landings to all grids within the sub-compartments. Landings were set within grids in such a manner as to minimize their distances from the roads, the centers of the sub-compartments and the power generation plant. Transportation distances from the landings to the power generation plant or the log market were calculated using the shortest path algorithm, i.e., the Dijkstra method (Dijkstra 1959). If landings were not on existing roads, transportation distances were estimated using straight-line distances from landings to the nearest roads by taking into account the detour ratio that was referenced from the physiographic division (Kobayashi 1997) and the distances from the nearest roads to the power generation plant or the log market calculated using the Dijkstra method. The terrain of the study site was relatively gentle so the detour ratio was set to 0.3.

Estimating total expenses including reforestation after final felling operations

The Forest Owners' Cooperative conducts forest operations, including thinning operations by chainsaw and extracting thinned woods by mini-forwarder, on about 50 ha annually. However, mechanization is necessary for thinning and to extract thinned trees from about 4,000 ha of conifer plantations in the city. We investigated two types of timber harvesting systems, the current operation system as practiced by the Cooperative and a mechanized operation system. Felling and processing (delimbing and bucking), bunching, forwarding, and transporting under the current operation system were conducted using a chainsaw, mini grapple-loader, mini forwarder and truck, respectively, whereas the felling, bunching, processing, forwarding and transporting in the mechanized operation system were assumed to be conducted using chainsaw, mini grapple-loader, processor, forwarder and truck, respectively.

The model also examined three types of biomass harvesting systems: (1) normal extraction, which refers to the extraction of timber and forest biomass resources and the selling to a log market and a power generation plant, (2) landing sales, which refers to normal sale of timber and the selling of forest biomass resources at landings, (3) no biomass extraction, which refers to the pre-commercial thinning operations for first thinning operations and the timber extraction only for second thinning and final felling operations. In a landing sale, forest owners are assumed to extract and sell forest biomass resources by themselves to purchasers at landings and to obtain income from forest biomass sales but not for extraction operations.

After the operation systems were determined, all costs, including the direct and indirect operation expenses associated with each machine, landing establishment expenses, forest road establishment expenses and reforestation expenses, were estimated (Equ. 4).

$$A = D + L + F + I + R \tag{4}$$

where, A is all costs, D is direct operation expenses, L is landing establishment expenses, F is forest road establishment expenses, I is indirect operation expenses, and R is reforestation expenses

Labor expenses were set at 13 $USD \cdot h^{-1}$ (Nakahata et al. 2010). Direct operation expenses are shown in Table 2. Direct operation expenses included labor expenses and machinery expenses (for maintenance, management, depreciation, and fuel and oil). Forwarding and transport costs were changed according to loading capacity rates for timber and forest biomass resources on the first and second thinning and final felling operations (Table 3).

Table 2. Direct operation expenses

Machine	Operation	Expense ($USD \cdot m^{-3}$)	System	Reference
Chainsaw	Felling and processing	19	Current	Nakahata et al. 2010
Chainsaw	Felling	10	Mechanized	Nakahata et al. 2010
Processor	Processing	8.9	Mechanized	Zenkoku Ringyo Kairyo Fukyu Kyokai 2001
Mini grapple-loader	Bunching	3.0	Both	Nakahata et al. 2010
Mini forwarder	Forwarding	$(7.7 + 0.0050Lf)/Rf + 3.0$	Current	Nakahata et al. 2010
Forwarder	Forwarding	$(5.9 + 0.0052Lf)/Rf + 3.0$	Mechanized	Zenkoku Ringyo Kairyo Fukyu Kyokai 2001
Truck	Transportation	$(0.00031Lt + 7.8)/Rt$	Both	Sawaguchi 1996

Lf is the forwarding distance and Lt is the transportation distance; Rf and Rt are the loading capacity ratio, listed in Table 3.

Table 3. Loading capacity ratios

Operation	Rf	Rt
Second thinning and final felling (Timber)	1.06	1
First thinning (Biomass)	1	0.94
Second thinning and final felling (Biomass)	0.51	0.49

Landing establishment expenses L (USD) were estimated as:

$$L = 1.3V + 72 \tag{5}$$

We assumed expenses of forest road establishment between landings and the nearest existing roads to be 60 $USD \cdot m^{-1}$, when there were no road grids in the sub-compartments.

Machine transport expenses, garage maintenance expenses, overhead expenses, incidental personnel expenses, and handling fees associated with the log market were considered as indirect operation expenses (Zenkoku Ringyo Kairyo Fukyu Kyokai 2001). Machine transportation expenses were estimated by unit costs, 500 USD/machine, and the current operation system had two machines, namely mini grapple-loader and mini forwarder, and the mechanized operation system had three, namely mini grapple-loader, processor, and forwarder. Garage maintenance expenses were estimated with unit costs of 20 USD/machine/day, the number of machines, and the duration of operations. Overhead costs were estimated as 20% of direct operation costs. Incidental personnel expenses were estimated as 55% of direct personnel expenses. Handling fees associated with the log market were estimated with piling costs, 7.0 USD·m^{-3} and 10% of timber prices (USD·m^{-3}).

In addition to these timber extraction expenses, reforestation expenses included site preparation, planting, weeding, vine cutting, pruning, and forest inventory. The reforestation expenses were estimated at 25,124 USD·ha^{-1} for Japanese cedar and 28,924 USD·ha^{-1} for Japanese cypress (Okawabata 2003).

For normal extraction on first thinning operations, only thinned woods left in the forest after pre-commercial thinning were extracted as forest biomass. Therefore, all costs were estimated for forest biomass extraction (Table 4). For landing sales after first thinning operations, only the felling and processing costs and associated indirect costs were considered, but extraction costs and associated indirect costs were not considered. For pre-commercial first thinning operations (no biomass extraction), only felling costs and associated indirect costs were considered, but processing and extraction costs and associated indirect costs were not considered. Forest biomass resources are considered a by-product of timber harvesting for the second thinning and final felling operations. Therefore, operations for forest biomass extraction started after processing and all costs, excluding those for forest biomass extraction and associated indirect operation expenses, were considered to be timber extraction costs.

Table 4. Cost estimation

	Normal extraction						Landing sale						No biomass extraction					
	1		2		3		1		2		3		1		2		3	
	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F
Felling		X	X		X			X	X		X			X	X		X	
Processing		X	X		X			X	X		X				X		X	
Extracting		X	X	X	X	X		*	X	*	X	*			X		X	
Landing establishment		X	X		X			+	X		X				X		X	
Forest road establishment		X	X		X			X	X		X				X		X	
Machine transportation		X	X		X			+	X		X				X		X	
Garage maintenance		X	X	X	X	X		+	X		X				X		X	
Overhead costs		X	X	X	X	X		X	X		X			X	X		X	
Incidental personnel		X	X	X	X	X		X	X		X			X	X		X	
Handling fees			X		X				X		X				X		X	
Reforestation					X						X						X	

1, first thinning; 2, second thinning; 3, final felling.

T= timber; F=forest biomass resources. Extracting includes bunching, forwarding, and transportation.

* Frest biomass resources are assumed to be extracted by forest owners themselves whose income is derived from forest biomass sale, but not for extraction operations.

+, only mechanized operation system on which processor and mini grapple-loader are used for processing and bunching operations.

Estimating available amounts of timber and forest biomass resources from profitable sub-compartments

Incomes were estimated using supply potentials and log prices: 110 USD·m^{-3} for Japanese cedar and 220 USD·m^{-3} for Japanese cypress, and forest biomass resources: 50 USD·Mg^{-1} for normal extraction and 10 USD·m^{-3} for landing sales.

For thinning operations, subsidies are received in Japan. Subsidies were estimated using standard unit prices, areas, assessment coefficients and the subsidy rate of the Tochigi Prefectural Government (2010a). Standard unit prices were determined by ages, thinning rates, and whether extraction occurred (Table 5). The assessment coefficient and the subsidy rate were assumed to be 1.7 and 40%, respectively. For the first thinning, standard unit prices with a thinning rate of 25% and extraction were applied for normal extraction, and standard unit prices with a thinning rate of 25% and no extraction were applied for landing sales and no biomass extraction. For the second thinning operations, standard unit prices with a thinning rate of 35% and extraction were applied for all types of operations.

We also considered the subsidy for reforestation. Similar to thinning operations, subsidies were estimated with standard unit prices, areas, assessment coefficients and the subsidy rate of the Tochigi Prefectural Government (2010a). The subsidies were estimated at 12,274 USD·ha^{-1} for Japanese cedar and 12,192 USD·ha^{-1} for Japanese cypress.

After incomes were estimated, economic balances and available amounts of timber and forest biomass resources from profitable sub-compartments were estimated.

Table 5. Standard unit prices for thinning operations

	Standard unit prices (USD·ha^{-1})		
Thinning rate	Less than 30%	Less than 30%	More than 30%
Age (year)	No extraction	Extraction	Extraction
26–35	839	4,008	6,006
36–45	700	3,813	5,719
46–59	638	3,862	5,793

Results and discussion

Normal extraction

The area and the number of sub-compartments analyzed in this study, which included Japanese cedar and Japanese cypress more than 25 years old and owned by privates and local governments, were 3,331 ha and 5,165, respectively. These represented 99% of the total area and 90% of the total number of sub-compartments. Sub-compartments selected as first thinning, second thinning, and final felling operations were 24%, 58% and 18% of the total analyzed area, respectively (Fig. 3). The largest number of sub-compartments was selected for second thinning because forests in this region were mainly between 45 and 55 years old.

The relationships between supply potentials and estimated average harvesting costs are shown in Figs. 4 and 5. Maximum supply potentials of timber and forest biomass resources were 380,000 m^3 and 210,000 Mg, which was 15 times the planned harvesting volume for coniferous trees (25,000 m^3·year^{-1}, Tochigi Prefecture Government 2010b), and 50 times the annual demand of the woody gasification power generation plant (4,000 Mg·year^{-1}, Nakahata et al. 2010), in Nasushiobara city.

Estimated average timber harvesting costs for the current operation system on both second thinning and final felling operations were higher than those for a mechanized operation system (Fig. 5). The mechanized system reduced logging costs, including felling, processing, bunching, and forwarding costs, and associated indirect operation expenses, excluding machine transportation expenses, which were increased because the number of machines was increased owing to the introduction of processors (Table 6). The reduction in indirect operation expenses during final felling with the mechanized operation system was larger than that during second thinning because larger timber harvesting volumes during final felling reduced indirect operation expenses excluding machine transport expenses and the larger reductions in indirect operation expenses covered the increased machine transport expenses.

Estimated average timber harvesting costs at maximum supply potentials for second thinning were higher than those for final felling because harvesting volumes for second thinning were smaller than those for final felling. Subsequently, forest road establishment costs per m^3 for second thinning were larger than those for final felling, although the costs of final felling included reforestation expenses (Fig. 4 and Table 6). Estimated average timber harvesting costs for no biomass extraction were the same as those for normal extraction.

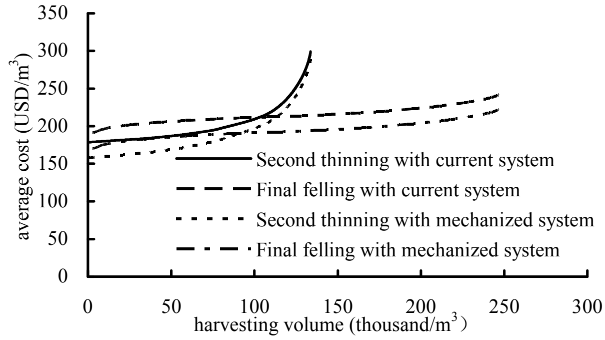


Fig. 4 The relationships between supply potentials of timber and estimated average harvesting costs with normal extraction

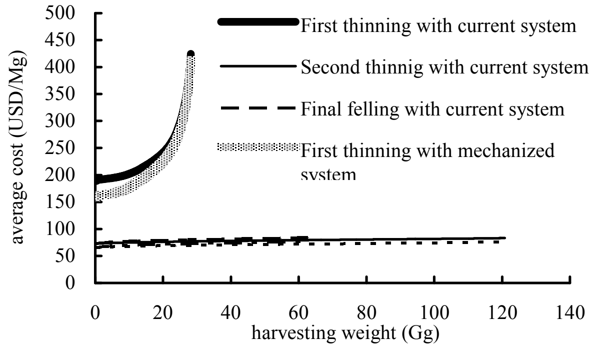


Fig. 5 The relationships between supply potentials of forest biomass resources and estimated average harvesting costs with normal extraction

Estimated average forest biomass harvesting costs at maximum supply potentials for first thinning operations were the highest (420 USD·Mg^{-1}) because total costs were estimated for small amounts of forest biomass resources (Fig. 5). Estimated average forest biomass harvesting costs at maximum supply potentials for final felling operations were higher than those for second thinning operations owing to smaller amounts of forest biomass harvesting volumes for final felling operations. Similar to the timber harvesting costs, the mechanized operation system reduced logging costs and associated indirect operation expenses (Table 6).

Estimated average timber and forest biomass harvesting costs at maximum supply potentials for first thinning operations were also the highest because total costs were estimated for small amounts of forest biomass resources (Table 6). Estimated average timber and forest biomass harvesting costs at maximum supply potentials for final felling excluding reforestation costs were lower than those for second thinning owing to larger amounts of timber and forest biomass harvesting volumes on final felling. Mechanized operation systems also reduced logging costs and associated indirect operation expenses (Table 6).

Table 6. Costs of and income from normal extraction with maximum supply potentials

	Operation	Timber (USD·m^{-3})			Biomass (USD·Mg^{-1})				Timber and biomass (USD·m^{-3})			
		Second thinning	Final felling	Total	First thinning	Second thinning	Final felling	Total	First thinning	Second thinning	Final felling	Total
Current operation system	Logging	56	39	45	49	32	32	34	33	37	35	35
	Transportation	16	15	15	17	31	32	30	11	19	17	17
	Landing	6.4	3.3	4.4	57	-	-	0.76	3.9	2.8	2.4	2.7
	Forest road	92	15	42	191	-	-	25	130	40	11	31
	Indirect	129	107	115	162	20	20	39	110	102	100	102
	Reforestation	-	61	40	-	-	-	-	-	-	45	22
	Total cost	299	243	262	425	83	84	129	289	199	210	210
Mechanized operation system	Logging	54	38	43	46	27	27	29	31	34	32	33
	Transportation	15	15	15	17	31	32	30	11	19	17	17
	Landing	6.4	3.3	44	57	-	-	0.76	3.9	2.8	2.4	2.7
	Forest road	9,2	15	42	191	-	-	25	130	40	11	31
	Indirect	121	89	101	153	18	18	36	104	87	82	85
	Reforestation	-	61	40	-	-	-	-	-	-	45	22
	Total cost	289	222	246	413	76	77	121	281	182	189	191
Income	Timber	118	120	118	-	-	-	-	-	50	88	46
	Biomass	-	-	-	50	50	50	50	34	19	9.3	21
	Subsidies	50	30	36	65	-	-	87	44	22	22	33
	Total income	168	151	155	115	50	50	59	78	91	119	100

Logging includes felling, processing, bunching, and forwarding. Indirect operation expenses include machine transportation expenses, garage maintenance expenses, overhead expenses, incidental personnel expenses, and handling fees associated with the log market.

Estimated average forest biomass harvesting costs at maximum supply potentials for first thinning operations were the highest (420 USD·Mg^{-1}) because total costs were estimated for small amounts of forest biomass resources (Fig. 5). Estimated average forest biomass harvesting costs at maximum supply potentials for final felling operations were higher than those for second thinning operations owing to smaller amounts of forest biomass harvesting volumes for final felling operations. Similar to the timber harvesting costs, the mechanized operation system reduced logging costs and associated indirect operation expenses (Table 6).

Estimated average timber and forest biomass harvesting costs at maximum supply potentials for first thinning operations were also the highest because total costs were estimated for small amounts of forest biomass resources (Table 6). Estimated average timber and forest biomass harvesting costs at maximum supply potentials for final felling excluding reforestation costs were lower than those for second thinning owing to larger amounts of timber and forest biomass harvesting volumes on final felling. Mechanized operation systems also reduced logging costs and associated indirect operation expenses (Table 6).

Landing sales

For pre-commercial first thinning, only felling and processing costs and associated indirect costs were considered. Therefore, estimated average harvesting costs of timber and forest biomass resources at maximum supply potentials (Table 7) were reduced significantly compared with those for normal extraction (Table 6). For second thinning and final felling, estimated average harvesting costs of timber and forest biomass resources at maximum supply potentials (Table 7) were also reduced significantly compared with those for normal extraction (Table 6) because there were no biomass extraction costs.

Mechanized operation systems, excluding pre-commercial first thinning, reduced estimated average harvesting costs of timber and forest biomass resources at maximum supply potentials (Table 7). Estimated average harvesting costs of timber and forest biomass resources at maximum supply potentials with the mechanized operation system for pre-commercial first thinning were higher than those with the current operation system. This is because expenses for landing establishment, machine transport, and garage maintenance were necessary for the mechanized operation systems to use mini grapple-loaders for bunching operations and processors for processing operations.

Available amounts of resources from profitable sub-compartments

Estimated average harvesting costs of timber and forest biomass at minimum supply potentials were 170 USD·m^{-3} (Fig. 4) and 70 USD·Mg^{-1} (Fig. 5), respectively. The mechanized operation system reduced estimated average costs of timber and forest biomass. However, the unit timber price of 110 USD·m^{-3} for Japanese cedar and the price for forest biomass of 50 USD·Mg^{-1} for normal extraction were lower than estimated average harvesting costs of timber and forest biomass resources at minimum supply potentials, although the unit timber price for Japanese cypress (220 USD·m^{-3}) was higher (Table 6). Therefore, the area and the number of profitable sub-compartments for normal extraction were small (Fig. 6 and Table 8). The area and the number of profitable sub-compartments for second thinning were larger than those for final felling because final felling included reforestation expenses, driving costs higher. Yamaguchi et al. (2010) did not consider reforestation expenses for final felling, and their areas and numbers of profitable sub-compartments for final felling were larger than those for second thinning. Therefore, including reforestation expenses in the analysis had a large impact on the profitability of forestry operations and harvest of forest biomass resources. For first thinning operations with the mechanized operation system, only one sub-compartment was profitable. This sub-compartment was relatively large, 12 ha (Table 8).

Table 7. Costs of and income from landing sales with maximum supply potentials

	Operation	Timber and biomass (USD·m^{-3})			
		First thinning	Second thinning	Final felling	Total
Current operation system	Logging	19	24	29	26
	Transportation	-	6.5	11	83
	Landing	-	2.8	2.4	24
	Forest road	130	40	11	31
	Indirect	59	56	78	67
	Reforestation	-	-	45	22
	Total cost	209	129	176	157
Mechanized operation system	Logging	19	23	27	25
	Transportation	-	6.5	11	8.3
	Landing	3.9	2.8	2.4	2.7
	Forest road	130	40	11	31
	Indirect	68	52	65	59
	Reforestation	-	-	45	22
	Total cost	221	124	162	148
Income	Timber	-	49	90	66
	Biomass	10	5.7	2.7	4.5
	Subsidies	90	22	21	21
	Total income	19	76	114	91

Logging includes felling, processing, bunching, and forwarding. Indirect operation expenses include machine transport, garage maintenance, overhead, incidental personnel expenses, and handling fees associated with the log market.

The area and the number of profitable sub-compartments for landing sales were larger than those for normal extraction because the costs of landing sales were lower, although incomes were also lower than those of normal extraction (Tables 6 and 7). Costs and incomes of second thinning and final felling operations with no biomass extraction were the same as those with only timber extraction for normal extraction (Table 6), while costs were only for felling and associated indirect expenses and incomes were only the subsidy for first thinning with no biomass extraction. Because we assumed a low unit price (50 USD·Mg^{-1}) of forest biomass for normal extraction, the area and the number of profitable sub-compartments with no biomass extraction were larger than those with normal extraction, while the area and the number of profitable sub-compartments with no biomass extraction were smaller than those for landing sales (Table 8). Therefore, the area and the number of profitable sub-compartments for landing sales were the largest among the extraction methods compared in this study.

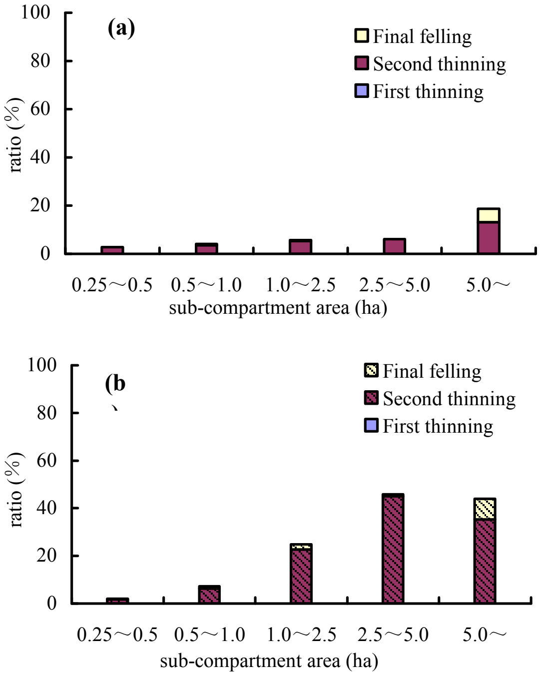


Fig. 6 Sub-compartment area and ratio of profitable sub-compartments for landing sales. (a) current system; (b): mechanized system

Although supply potentials of timber and forest biomass were 380,000 m^3 and 210,000 Mg, respectively, the available amounts of timber and forest biomass for landing sales supplied by mechanized systems (Table 8) were only 49,429 m^3 and 33,333 Mg, respectively, which represented 13.0% and 15.7% of the supply potentials.

Effects of operational conditions on profitable sub-compartments on landing sales

For both thinning and final felling, larger stands were more profitable (Fig. 6). Sub-compartments with landing sales and mechanized operation systems, especially those of more than 2.5 ha, were more profitable. Introduction of mechanized operation systems increased the number of machines with resulting increases in machine transport expenses. However, the machine transport expenses were the same for all sub-compartments, without relation to sub-compartment area. Thus, larger sub-compartment areas with subsequently larger harvesting volumes reduced unit expenses of machine transport per m^3. Therefore, timber harvest is more profitable on larger areas and with larger harvesting volumes. This implies that small sub-compartments should be consolidated so that large machines can be operated efficiently in mechanized operation systems.

According to the relationship between forest road establishment lengths for sub-compartments and ratios of profitable sub-compartments (Fig. 7), almost all the profitable sub-compartments were located along existing roads. Forest road establishment had a big negative impact on the profitability of forestry operations.

Table 8. Areas and numbers of profitable sub-compartments and available amounts of resources

	Operation system	Operation	Area	No.	Ratio (%)		Available amounts		Ratio (%)	
					Area	No.	Timber (m^3)	Biomass (Mg)	Timber	Biomass
Normal extraction	Current operation system	First thinning	0	0	0.0	0.0	0	0	0.0	0.0
		Second thinning	23	7	1.2	0.2	710	641	0.5	0.5
		Final felling	0	0	0.0	0.0	0	0	0.0	0.0
		Total	23	7	0.7	0.1	710	641	0.2	0.3
	Mechanized operation system	First thinning	12	1	1.5	0.1	0	231	0.0	0.8
		Second thinning	65	37	3.3	1.2	2,291	2,070	1.7	1.7
		Final felling	2	2	0.4	0.2	901	229	0.4	0.4
		Total	78	40	2.3	0.8	3,192	2,530	0.8	1.2
Landing sales	Current operation system	First thinning	0	0	0.0	0.0	0	0	0.0	0.0
		Second thinning	165	156	8.4	5.1	6,772	6,118	5.1	5.1
		Final felling	27	7	4.5	0.7	8,571	2,180	3.5	3.5
		Total	192	163	5.7	3.2	15,343	8,298	4.0	3.9
	Mechanized operation system	First thinning	0	0	0.0	0.0	0	0	0.0	0.0
		Second thinning	514	242	26.2	7.9	31,988	28,897	23.9	23.9
		Final felling	59	30	10.0	3.2	17,441	4,436	7.1	7.1
		Total	573	272	17.2	5.3	49,429	33,333	13.0	15.7
No biomass extraction	Current operation system	First thinning	0	0	0.0	0.0	0	0	0.0	0.0
		Second thinning	101	99	5.1	3.2	3,643	0	2.7	0.0
		Final felling	12	4	2.1	0.4	3.929	0	1.6	0.0
		Total	113	103	3.4	2.0	7,572	0	2.0	0.0
	Mechanized operation system	First thinning	0	0	0.0	0.0	0	0	0.0	0.0
		Second thinning	197	116	10.1	3.8	9,024	0	6.7	0.0
		Final felling	56	26	9.5	2.7	16,716	0	6.8	0.0
		Total	253	142	7.6	2.7	25,740	0	6.8	0.0

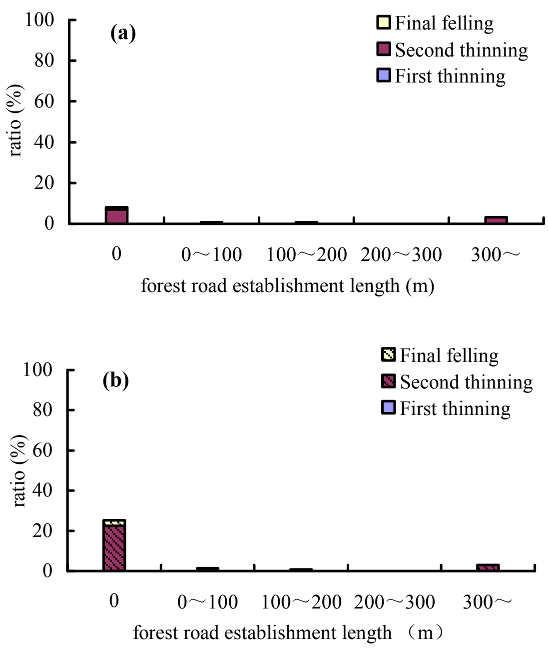
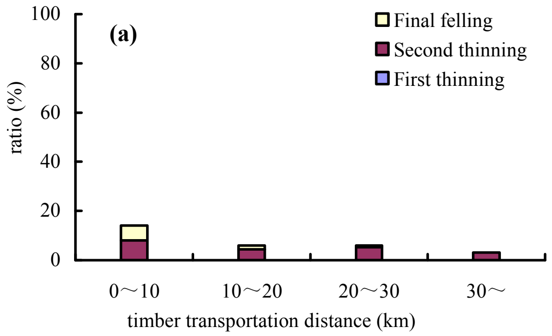


Fig. 7 Forest road establishment lengths and ratio of profitable sub-compartments for landing sales. (a): current system; (b): mechanized system

According to the relationship between timber transport distances and the ratios of profitable sub-compartments (Fig. 8), longer distances had higher transport costs and smaller ratios of profitable sub-compartments in the current operation system (Fig. 2). However, for 20–30 km transport distances, profitability increased for mechanized operation systems because larger sub-compartments were located between 20 and 30 km from log markets and larger sub-compartments increased the profitability of forestry operations (Fig. 9).

According to the relationship between forwarding distances and profitability (Fig 10), longer forwarding distances should result in higher costs based on cost estimation equations (Table 2), and consequently smaller numbers of profitable sub-compartments. In fact, however, longer forwarding distances resulted in greater profitability. Forwarding distances were estimated as average distances from the landings to all grids within the sub-compartments. Thus, the more profitable larger sub-compartments tended to have longer forwarding distances. Therefore, longer forwarding distances resulted in a larger number of profitable sub-compartments.



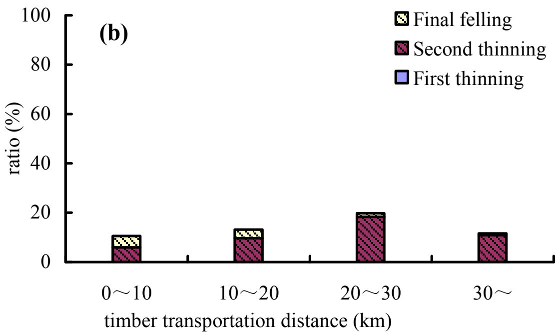


Fig. 8 Timber transportation distance and ratio of profitable sub-compartments for landing sales. (a): current system; (b): mechanized system

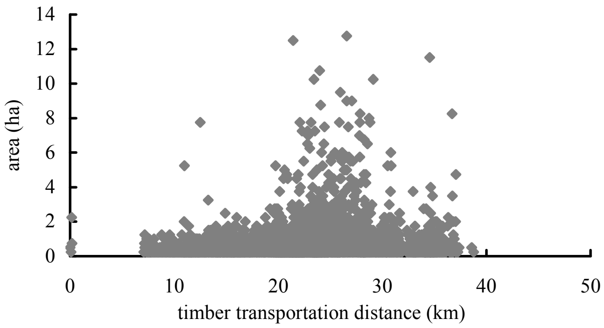


Fig. 9 Timber transportation distance and sub-compartment area

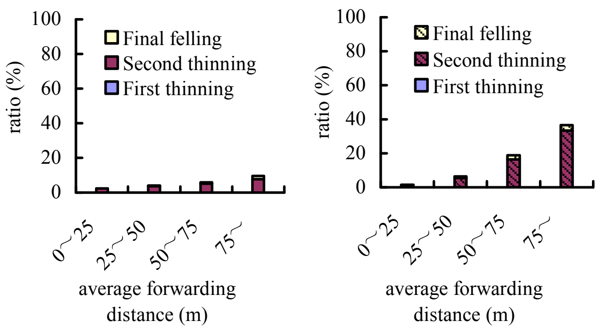


Fig. 10 Forwarding distance and ratio of profitable sub-compartments for landing sales. (Left: current system; Right: mechanized system)

Effects of operational conditions on available amounts of resources on landing sale

The areas and numbers of profitable sub-compartments after final felling were smaller than those for second thinning operations (Table 9). When reforestation costs were not considered, the areas and the numbers of profitable sub-compartments for final felling were larger than those for second thinning (Table 9). Then, the available amounts of timber and forest biomass resources were increased to 121,704 m^3 and 51,714 Mg, which were 32.0% and 24.4% of the supply potentials for landing sales with mechanized operation systems (Table 9).

Forest road-building expenses had large negative impacts on profits (Fig. 7). However, forest road-building should be conducted with the public budget. When forest road-building expenses were not considered, the area and the number of profitable sub-compartments increased (Table 9). Then, available amounts of timber and forest biomass also increased to 63,465 m^3 and 43,509 Mg, respectively, and they were 16.7% and 20.6% of the supply potentials for landing sales with mechanized operation systems (Table 9). Thus, forest road-building conducted with the public budget was crucial to improve profitability as well as available amounts of timber and forest biomass resources.

Conclusion

Reforestation costs had large negative impacts on the profits from final felling and available amounts of timber and forest biomass. Profitable sub-compartments were very few when reforestation expenses were considered. This highlights the current situation in Japanese forestry, where many forest owners are unwilling to conduct reforestation after final felling. Therefore, it is important to develop low-cost reforestation methods or to extend rotation ages and reduce the number of reforestations in order to improve the profitability of forestry and the sustainable use of forest biomass resources in Japan.

The total area and the number of profitable sub-compartments for landing sales were larger than those with no biomass extraction. Therefore, harvest of forest biomass has contributed to profits under sustainable forest management with a certain biomass harvesting system. For landing sales, more sub-compartments were profitable in cases where operations were mechanized. Therefore, mechanization is necessary to promote thinning and to extract thinned trees in this region.

For thinning and final felling, larger sub-compartment areas increased profitability. Therefore, it is necessary to consolidate small sub-compartments so that large machines can efficiently operate. Most profitable sub-compartments were located along existing roads. Forest road-building had a big negative impact on profitability and should be conducted with public budgets to improve profitability and increase the available amounts of timber and forest biomass.

We estimated only the supply potentials and available amounts of timber and forest biomass based on the current situation. In order to plan power generation plants considering available amounts of forest biomass, future supply potentials and available amounts of forest biomass should be projected. We considered forest road establishment between landings and the nearest connecting roads as straight-line distances by taking into account the detour ratio. However, forest road networks should be established considering a wide range of areas. The next study will examine these analyses and develop a model to help forest planners establish forest plans with future supply potentials and available amounts of forest biomass resources.

Table 9. Areas and numbers of profitable sub-compartments and available amounts of resources for landing sales

	Operation system	Operation	Area	No.	Ratio (%)		Available amounts		Ratio (%)	
					Area	No.	Timber (m^3)	Biomass (Mg)	Timber	Biomass
Landing sales	Current operation system	First thinning	0	0	0.0	0.0	0	0	0.0	0.0
		Second thinning	165	156	8.4	5.1	6,772	6,118	5.1	5.1
		Final felling	27	7	4.5	0.7	8,571	2,180	3.5	3.5
		Total	192	163	5.7	3.2	15,343	8,298	4.0	3.9
	Mechanized operation system	First thinning	0	0	0.0	0.0	0	0	0.0	0.0
		Second thinning	514	242	26.2	7.9	31,988	28,897	23.9	23.9
		Final felling	59	30	10.0	3.2	17,441	4,436	7.1	7.1
		Total	573	272	17.2	5.3	49,429	33,333	13.0	15.7
No reforestation cost	Current operation system	First thinning	0	0	0.0	0.0	0	0	0.0	0.0
		Second thinning	165	156	8.4	5.1	6,772	6,118	5.1	5.1
		Final felling	62	56	10.6	5.9	18,247	4,641	7.4	7.4
		Total	227	212	6.8	4.1	25,020	10,759	6.6	5.1
	Mechanized operation system	First thinning	0	0	0.0	0.0	0	0	0.0	0.0
		Second thinning	514	242	26.2	7.9	31,988	28,897	23.9	23.9
		Final felling	258	181	44.1	19.1	89,716	22,817	36.4	36.4
		Total	773	423	23.2	8.2	121,704	51,714	32.0	24.4
No road establishment cost	Current operation system	First thinning	0	0	0.0	0.0	0	0	0.0	0.0
		Second thinning	208	222	10.6	7.2	8,410	7,598	6.3	6.3
		Final felling	27	7	4.5	0.7	8,571	2,180	3.5	3.5
		Total	235	229	7.0	4.4	16,981	9,777	4.5	4.6
	Mechanized operation system	First thinning	0	0	0.0	0.0	0	0	0.0	0.0
		Second thinning	677	322	34.5	10.5	42,166	38,092	31.5	31.5
		Final felling	73	40	12.4	4.2	21,299	5,417	8.6	8.6
		Total	749	362	22.5	7.0	63,465	43,509	16.7	20.6

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