Development of a Model to Estimate the Annual Available Amount of Forest Biomass Resources under Profitable Forest Management—Case Study of Nasushiobara City and Kanuma Area in Tochigi prefecture, Japan

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Keywords: forest biomass resources, profitable forest management, economic balance, annual available amount, annual demand

Abstract: The purpose of this study was to develop a model to estimate the annual available amount of forest biomass resources under profitable forest management in the Nasushiobara city and Kanuma area of Tochigi prefecture, Japan. Economic balances regarding 60-year rotation were estimated based on two types of timber-harvesting systems (conventional operation system conducted by chainsaw and mini-forwarder, and mechanized operation system introducing processor and forwarder), and three types of forest biomass harvesting systems (normal extraction, landing sale, and no biomass extraction) in each subcompartment. The most economical timber and forest biomass harvesting system for each subcompartment was applied. As a result, the number of profitable, nonprofitable, and roadless subcompartments were 1,801; 1,625; and 2,330 of the total 5,756 subcompartments in Nasushiobara city whereas they were 8,940; 3,014; and 20,897 of the total 32,851 subcompartments in the Kanuma area. Then, the annual available amount of forest biomass resources was

Received July 22, 2012; Accepted October 25, 2012

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estimated as the annual supply potential of profitable subcompartments. The annual available amount of the forest biomass resources was 7,805 m³/year and 50,313 m³/year in Nasushiobara city and Kanuma area, respectively. This available amount meets the annual demand of 6,000 m³/year of a 500 kW woody biomass power generation plant planned in Nasushiobara city, and the annual demand of 12,000 m³/year of a chip production factory in the Kanuma area.

1. Introduction

In Tochigi prefecture, for the operation of facilities such as biomass power plants, chip production factories, and pellet plants, woody biomass is required. These resources mainly receive sawmill residue and construction waste wood. However, there are concerns regarding the adequacy of supplies of these materials because the number of entrepreneurs, who have set up biomass power plants, to countermeasure climate change has increased. Furthermore, feed-in tariffs (FIT) were introduced in Japan in July 1, 2012. In FIT, the purchase price of electricity generated with unused materials such as logging residue was 32 yen/kWh without tax, for materials such as sawmill residue it was 24 yen/kWh without tax, and for recycled materials such as construction waste wood was 13 yen/kWh without tax (Agency for Natural Resources and Energy, 2012). Power generation with unused materials was given incentives to promote the use of logging residue.

In addition, the Tochigi prefecture area is 640,785 ha, out of which approximately 54.5% is covered by forests (Tochigi Prefectural Government, 2009). About half of these forests are manmade (44.9%), and their volume is 42,255,000 m³ (62.4%). Because of delays in thinning operations, which was a serious problem for these manmade forests in Japan, the Tochigi Prefectural Government introduced a new tax—Tochigi no genkina moridukuri kenmin zei—to make forests healthy, along with subsidies for thinning operations, in April 2008 (Tochigi Prefectural Government, 2010a). As a result, thinning operations were

conducted on 2,663 ha in 2009, but almost all thinning operations were precommercial. Therefore, a large amount of thinned woods was left in the forests.

Numerous studies have been conducted to examine 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 that expressed them in units of kilometer-scale meshes or cities and towns. Furthermore, Aruga *et al.* (2006a) established a technique to estimate regional harvesting volumes and costs of both timber and logging residues in units of sub-compartments. Moreover, 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 it at a national level.

In addition to these methods for the estimation of 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, whereas Kinoshita *et al.* (2010) established a technique to express them in units of cities and towns. However, these studies have not considered regeneration expenses, which are important for conducting forest management, especially in plantation forests such as Japanese cedar and Japanese cypress

in Japan. In contrast, Murakami *et al.* (2011) developed a method to extract production forests based on economic balances while considering the regeneration expenses. The study defined production forests as forests where expected revenue from clear-cutting surpassed costs such as harvesting and regeneration expenses. The revenue and costs were estimated based on forest registration and GIS data. However, that study considered thinning operations as costs in the regeneration expenses and did not consider any revenue from thinning operations because of the current situation in Japan, where nearly all thinning operations are precommercial and a large amount of thinned woods is left in the forests.

In this study, we developed a method to extract production forests considering forest biomass harvesting, which uses materials such as logging residue. We also defined production forests as forests where the expected revenues surpass all costs from planting to final harvesting. We have considered costs as well as revenue from thinning operations unlike Murakami *et al.* (2011). Then, we developed a model to estimate the annual available amount of forest biomass resources from profitable subcompartments considering the regeneration expenses. Finally, we examined the effects of regeneration costs, forest road network, and extending forestry operation sites on the annual available amount of forest biomass resources.

2. Study Sites and Data

The study sites were the Nasushiobara city and Kanuma area in Tochigi prefecture, Japan (Figure 1). The gross area of Nasushiobara city is 59,280 ha; the forest area is 38,689 ha and covers 65% of the gross area. The area of national forests is 24,981 ha, and the area of private and local government forests is 13,708 ha. We studied major plantation species such as Japanese cedar and Japanese cypress owned

by privates and local governments. The area and number of subcompartments of Japanese cedar and Japanese cypress owned by privates and by local governments were 2,850 ha and 7,340, and 1,103 ha and 2,521, respectively (Figure 2). These forests are mainly 45–55 years old. The northern parts of Nasushiobara city are mountainous. However, these parts are almost the national forests, and the private and local government forests are located on relatively gentle slopes. The average slope angle is rather low, 10° , and the road network density is rather high, 27 m/ha. An agrarian organization in Nasunogahara area in Tochigi Prefecture is willing to conduct thinning operations and extract thinned woods for woody biomass power generation (Figure 2) cooperated with a Forest Owners' Cooperative in Nasushiobara city to maintain forests for soil and water conservation and to nurture river sources.

Figure 1. Study site.

The Kanuma area consists of Kanuma city and Nishikata town (Figure 1). The gross area is 52,200 ha and forest area is 35,593 ha (68% of the gross area). The area of national forests is only 1,642 ha, and the area of private and local government forests is 33,951 ha. The area and number of subcompartments of Japanese cedar and Japanese cypress privately owned and that owned by local governments are 17,341 ha and 30,104, and 9,950 ha and 19,957, respectively (Figure 2). These forests are also 45–55 years old. The western parts of Kanuma area are mountainous. The average slope angle is rather high, 22° , and the road network density is rather low, 18 m/ha. The site index, which ranks the order of the productivity of the stands, was high relative to Nasushiobara city, and that made the Kanuma area one of the prominent forestry areas in Tochigi Prefecture. However, the forestry industry has been in decline for a long time. Therefore, bioenergy is attracting attention because the energy use of forest biomass resources is expected to revitalize the forestry industry as well as the maintenance of the appropriate ecological, economic, and social functions of manmade forests. A chip production factory to supply chips to a woody biomass power generation plant is located in Kanuma area.

In this study, we used forest registration data (stand ages, tree species, and site indexes) and GIS data (information on roads and subcompartment layers) from the Tochigi Prefectural Government, and the 50 m grid digital elevation model (DEM) of the Geographical Survey Institute. The area and number of subcompartments of Japanese cedar and Japanese cypress privately owned and that owned by the local government of Nasushiobara city were 2,761 ha and 4,456, and 918 ha and 1,300 on the 50 m mesh whereas those of Kanuma area were 17,247 ha and 22,735, and 7,262 ha and 10,116, respectively. The number of subcompartments on the 50 m mesh in both areas was significantly less than the actual number of subcompartments because

Figure 2. Stand species.

Left of the figure is Nasushiobara city and right is the Kanuma area.

there were many small subcompartments below 0.25 ha that could not be recognized on the 50 m mesh. Nonetheless, the actual area was not significantly reduced.

3. Methods

In this study, we estimated the production forests and annual available amount of forest biomass resources based on the profitable subcompartments in the following order: 1) estimation of the supply potential of timber and logging residue based on the cutting and extraction rates of thinning and final-felling operations during a 60-year rotation; 2) estimation of total expenses from planting to final-felling operations; 3) estimation of revenue from thinning and final-felling operations during a 60-year rotation; 4) estimation of economic balances during a 60-year rotation; 5) extraction of the production forests as profitable subcompartments; and 6) estimation of the annual available amount of forest biomass resources from profitable subcompartments.

3.1 Estimating the Supply Potential of Timber and Logging Residues

Thinning and final-felling operations were assumed to be conducted based on stand ages (Table 1). The supply potential of timber and logging residue on each subcompartment during the 60-year rotation were estimated based on the cutting and extraction rates (Table 1). The stand age, cutting rate (Cr), extraction rate (Er), logging residue rate (Lr), and timber rate (Tr) were set in accordance with the Forest Owners' Association's research report on extracting "forest biomass resources" (2008). Extraction rates (Er) for the second-thinning and final-felling operations were set to 109% because of top and branch extractions (Aruga *et al.*, 2006a). The logging residue rate (Lr) is the ratio of logging residue to be transported to the power generation plant in Nasushiobara city or the chip production factory in Kanuma city to the total felled and extracted volume, whereas the timber rate (Tr) is the ratio of timbers to be transported to log markets to the total felled and extracted volume (Figure 2).

Table 1. Harvesting conditions of each operation classified based on stand ages.

	First thinning (precommercial)	Second thinning (commercial)	Final felling (clear cutting)
Stand age (years)	25	40	60
Cutting rate (Cr)	25%	35%	100%
Extracting rate (Er)	80%	109%*	109%*
Logging residue rate (Lr)	100%	55%	26%
Timber rate (Tr)	0%	45%	74%

*Tops and branches extraction

Subsequently, the amount of timber and logging residue was estimated using the following equations.

$$[1] \quad H = S \times Cr \times Er \times A = V \times A$$

$$[2] \quad H_T = H \times Tr$$

$$[3] \quad H_L = H \times Lr$$

H is the extracted volume (m^3), S is the stock of the stems in the forest registration data (m^3/ha), A is the area of the subcompartments (ha), V is the extracted volume per hectare (m^3/ha), H_T is the extracted timber volume (m^3), and H_L is the extracted logging residue volume (m^3).

3.2 Estimating the Total Expenses including Regeneration Expenses after Final-Felling Operations

The Forest Owners' Cooperative conducts thinning operations by chainsaw, and extracts thinned woods by mini-forwarder approximately 50 ha annually. However, mechanization is necessary to promote thinning operations and extract thinned woods. This study investigated the conventional and the mechanized operation system. Felling and processing, bunching, forwarding, and transporting of the conventional operation system were conducted by 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 by chainsaw, grapple loader, processor, forwarder, and truck. The bucket capacities of the base machine for mini grapple loader, grapple loader, and processor were 0.15, 0.45, and 0.45 m^3 , respectively. The loading capacities of mini forwarder without grapple-crane and forwarder with grapple-crane were 2.0 tons and 2.8 tons, respectively.

The model also examined three types of forest biomass harvesting systems: 1) normal extraction, which means both timber and forest biomass resources extraction and selling to log markets, the power generation plant, or the chip production factory, 2) landing sale, which means normal timber sale and selling logging residue at landings, and

3) no biomass extraction, which means precommercial thinning operations for first-thinning operations and only timber extraction for second-thinning and final-felling operations. In the landing sale, the forest owners were assumed to extract and sell the logging residue to and at landings by themselves, and to receive income from the logging residue sale, but not to have income from the extraction operations.

After the operation systems were determined, all costs, such as the direct and indirect operation expenses associated with each machine, strip road and landing establishment expenses, and regeneration expenses, were estimated (Eq.[4]).

$$[4] \quad A = D + S + L + I + R$$

A : all costs, D : direct operation expenses, S : strip road establishment expenses, L : landing establishment expenses, I : indirect operation expenses, and R : regeneration expenses.

The direct operation expenses are shown in Table 2, and include labor and machinery expenses (maintenance expenses, management expenses, depreciation expenses, and fuel and oil expenses). Forwarding and transporting costs were changed according to the loading capacity rate for timber and logging residues on first- and second-thinning, and final-felling operations (Table 3). Forwarding distances were estimated as average distances from the landings to all grids within the subcompartments. Landings were set within grids to minimize their distances from the roads, the centers of gravity in the subcompartment, and the power generation plant in Nasushiobara city or the chip production factory in Kanuma city. Transporting distances from the landings to the power generation plant in Nasushiobara city or the chip production factory in Kanuma city, and the log markets were calculated using the shortest path algorithm, i.e., the Dijkstra method (Dijkstra, 1959). If the subcompartments were not near existing roads, the supply potential

of these subcompartments was not evaluated as the available amounts.

Table 2. Direct operation expenses.

Machine	Operation	Expense (yen/m ³)	System	Reference
Chainsaw	Felling	$53/Vn+65$	Both	Nakahata <i>et al.</i> , 2011
Chainsaw	Processing	$39/Vl+329$	Conventional	Nakahata <i>et al.</i> , 2011
Processor	Processing	$207/Vl+161$	Mechanized	Nakahata <i>et al.</i> , 2011
Mini grapple-loader	Bunching	1,999	Conventional	Nakahata <i>et al.</i> , 2011
Grapple-loader	Bunching	1,199	Mechanized	Nakahata <i>et al.</i> , 2011
Mini forwarder	Forwarding	$(769+0.508Lf)/Rf$	Conventional	Nakahata <i>et al.</i> , 2011
Forwarder	Forwarding	$(378+0.301Lf)/Rf$	Mechanized	Nakahata <i>et al.</i> , 2011
Truck	Transporting	$(778+0.031Lt)/Rt$	Both	Sawaguchi, 1996

Vn is the stem volume (m³/stem), Vl is the extracted volume per stem (m³/stem), Lf is forwarding distance (m), Lt is the transporting distance (m), Rf and Rt are the loading capacity rate shown in Table 3.

Table 3. Loading capacity rate.

	First thinning (Biomass)	Second thinning Final felling (Biomass)	Second thinning Final felling (Timber)
Rf	1.00	0.51	1.06
Rt	0.94	0.49	1.00

Strip roads were assumed to be established for forwarding operations. Strip-road density, d (m/ha) was related to the average slope angle of each subcompartment, θ (degree) in Figure 3:

$$[5] \quad d = 956.72\theta^{-0.52}$$

Then, strip-road costs, S (yen), were estimated by multiplying the strip-road density, d (m/ha) with the following unit strip-road costs, s (yen/m):

$$[6] \quad s = 67e^{0.116\theta} \text{ for the conventional operation system,}$$

$$[7] \quad s = 220e^{0.117\theta} \text{ for the mechanized operation system}$$

(Sawaguchi, 1996).

Figure 3. Average slope angle and strip road density.

Landing-establishment expenses, L (yen) were estimated with the following equation generated from landing areas and landing-establishment productivity (Zenkoku Ringyo Kairyo Fukyu Kyokai, 2001), and a machinery expense of back-hoe which was assumed to be the same with grapple loader:

$$[8] \quad L = 187.63V$$

Machine transportation expenses, garage maintenance expenses, incidental personnel expenses, overhead costs, and handling fees associated with the log market were considered as indirect operation expenses. Machine transportation expenses were estimated by unit costs, 50,000 yen/machine (Zenkoku Ringyo Kairyo Fukyu Kyokai, 2001), and the number of machines, which were two, a mini grapple loader and mini-forwarder in the conventional operation system, and three, a grapple loader, a processor, and a forwarder in the mechanized operation system.

Garage maintenance expenses were estimated to 2,000 yen/machine/day. Incidental personnel expenses were estimated as 55% of the direct personnel expenses. Overhead costs were estimated as 20% of the direct operation costs. Handling fees associated with the log market were estimated with piling costs as 700 yen/m³ and 10% of the timber prices (yen/m³).

In addition to the timber and forest biomass extraction costs, the regeneration expenses including site preparation, planting, weeding, vine cutting, pruning, and forest inventory were considered. The regeneration expenses were estimated at 2,512,376 yen/ha for Japanese cedar and 2,892,365 yen/ha for Japanese cypress (Okawabata, 2003).

On normal extraction of the first-thinning operations, only logging residue (thinned woods left in the forest) after precommercial thinning operations were extracted as forest biomass resources. Therefore, all costs were for logging residues extraction (Table 4). The logging residue was considered as a by-product of timber harvesting on second-thinning and final-felling operations. Therefore, operations for logging residue extraction started after processing and all costs, excluding logging residue extraction and associated indirect costs, were considered as timber extraction costs. On the landing sale of the first-thinning operations, only felling, processing, and associated indirect costs were considered. Extraction costs and associated indirect costs were not considered because income was assumed to come from the logging residues sale, but not from the extraction operations. On no extraction of biomass in first-thinning (precommercial thinning) operations, only felling costs and associated indirect costs were considered, but processing and extraction costs, and associated indirect costs were not considered.

Table 4. Cost estimation.

	Normal extraction						Landing sale						No biomass extraction					
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
	T	L	T	L	T	L	T	L	T	L	T	L	T	L	T	L	T	L
Felling		X	X		X		X	X	X		X	X	X		X	X	X	
Processing		X	X		X		X	X	X		X	X		X	X		X	
Bunching		X	X	X	X	X		X	X		X	X		X	X		X	
Forwarding		X	X	X	X	X		X	X		X	X		X	X		X	
Transporting		X	X	X	X	X		X	X		X	X		X	X		X	
Landing-establishment		X	X		X		X	X	X		X	X		X	X		X	
Machine transportation		X	X		X		X	X	X		X	X		X	X		X	
Garage-maintenance		X	Y	Y	Y	Y		X	X		X	X		X	X		X	
Incidental personnel		X	Y	Y	Y	Y		X	X	X		X	X	X	X		X	
Overhead costs		X	Y	Y	Y	Y		X	X	X		X	X	X	X		X	
Handling fees			X		X			X	X			X		X	X		X	

1 is the first-thinning operation, 2 is the second-thinning operation, 3 is the final-felling operation.

T is for timber, L is for logging residue.

X is for the whole cost consideration, Y is the cost consideration according to timber and logging residues volumes.

3.3 Estimating Revenue from Thinning and Final-Felling Operations during 60-year Rotation

Income was estimated using the supply potential and log prices: 11,000 yen/m³ for Japanese cedar and 22,000 yen/m³ for Japanese cypress, and for forest biomass resources, 3,400 yen/m³ for normal extraction and 1,000 yen/m³ for landing sale.

For thinning operations, subsidies were estimated with standard unit prices, areas, assessment coefficients, and the subsidy rate of the Tochigi Prefectural Government (2010b). The subsidy on first-thinning operations for normal extraction was 235,504 yen/ha, the subsidy on the first-thinning operations for landing sale and no biomass extraction was 64,291 yen/ha, and the subsidy on second-thinning operations for all types of operations was 338,188 yen/ha. The subsidies for strip road establishment (Table 5) were also estimated with standard unit prices, length, assessment coefficients, and the subsidy rate of the Tochigi Prefectural Government (2010b).

Table 5. Subsidies for strip road establishment (yen/m).

Average slope angle (degree)	Conventional	Mechanized
5	40	159
10	60	191
15	91	230
20	137	276
25	147	477
30	183	850

This study also considered the subsidy for regeneration. Like thinning operations, subsidies were estimated with standard unit prices, areas, assessment coefficients, and the subsidy rate of the Tochigi Prefectural Government (2010b). The subsidies were estimated at 1,227,400 yen/ha for Japanese cedar and 1,219,240 yen/ha for Japanese cypress.

3.4 Extracting Production Forests as Profitable Subcompartments.

After economic balances were estimated with income and costs during the 60-year rotation, the production forests were extracted as profitable subcompartments. Then, the annual available amount of forest biomass resources was estimated as the supply potential from profitable subcompartments.

4. Results and Discussion

The supply potential of timber and logging residue was 1,572,395 m³ and 972,672 m³ in Nasushiobara city (Table 6), and 12,587,431 m³ and 7,868,852 m³ in the Kanuma area for 60 years (Table 7). Therefore, the annual supply potential of timber and logging residue were 26,207 m³/year and 16,211 m³/year in Nasushiobara city, and 209,791 m³/year and 131,148 m³/year in Kanuma area, respectively. The annual supply potential of timber, 26,207 m³/year, was over the planned harvesting coniferous tree volumes in Nasushiobara city, 25,700 m³/year, (Tochigi

Prefecture Government, 2011). The annual supply potential of logging residue of 16,211 m³/year in Nasushiobara city was 2.7 times the annual demand of the planned woody biomass power generation plant of 6,000 m³/year (Nakahata *et al.*, 2011). Conversely, the annual supply potential of timber in the Kanuma area of 209,791 m³/year was 5.7 times the planned harvesting coniferous tree volume of 36,600 m³/year (Tochigi Prefecture Government, 2010c). The annual supply potential of the logging residue in the Kanuma area of 131,148 m³/year was 10.9 times of the annual production of chips at the chip production factory in Kanuma city of 12,000 m³/year (Shimotsuke newspaper, 2009).

The most economical timber and forest biomass harvesting system for each sub-compartment could be classified as being one of the seven types of systems illustrated in Figure 4. The most common type for the final felling operation was the mechanized operation system with landing sales. For the second thinning operation, the most common type was the conventional or mechanized operation system with landing sales. In contrast, the most common type for the first thinning operation was the conventional operation system with normal extraction or landing sales. When the most economical timber and forest biomass harvesting system for each subcompartment was applied, the number of profitable, nonprofitable, and roadless subcompartments was 1,801; 1,625; and 2,330 of the total 5,756 subcompartments in Nasushiobara city whereas they were 8,940; 3,014; and 20,897 of the total 32,851 subcompartments in the Kanuma area (Table 8 and Figure 5).

Then, the annual available amount of forest biomass resources was estimated as the annual supply potential of the profitable subcompartments. The available amount of timber and logging residue was 754,524 m³ and 468,299 m³ in Nasushiobara city (Table 6), and 4,826,605 m³ and 3,018,756 m³ in the Kanuma area during 60 years (Table 7). Therefore, the annual available amount of timber and logging

Table 6. Supply potentials and available amount of timber and forest biomass resources in Nasushiobara city (m^3).

Supply Potential			
	Timber	Biomass	Total
First Thinning	0	182,561	182,561
Second Thinning	211,657	281,187	492,844
Final Felling	1,360,737	508,925	1,869,662
Total	1,572,395	972,672	2,545,067
Annual	26,207	16,211	42,418
Available Amounts Including Regeneration			
	Timber	Biomass	Total
First Thinning	0	88,572	88,572
Second Thinning	102,180	135,746	237,925
Final Felling	652,344	243,981	896,325
Total	754,524	468,299	1,222,823
Annual	12,575	7,805	20,380
Available Amounts Excluding Regeneration			
	Timber	Biomass	Total
First Thinning	0	113,598	113,598
Second Thinning	131,725	174,996	306,721
Final Felling	846,572	316,623	1,163,195
Total	978,296	605,218	1,583,514
Annual	16,305	10,087	26,392

residue was 12,575 m^3/year and 7,805 m^3/year in Nasushiobara city, and 80,443 m^3/year and 50,313 m^3/year in the Kanuma area, respectively. The annual available amount of timber of 12,575 m^3/year was half the planned coniferous tree-harvesting volume in Nasushiobara city of 25,700 m^3/year (Tochigi Prefecture Government, 2011). The annual available amount of logging residue of 7,805 m^3/year in Nasushiobara city was over the annual demand of the planned woody biomass power generation plant of 6,000 m^3/year (Nakahata *et al.*, 2011). Conversely, the annual available amount of timber in the Kanuma area of 80,443

Table 7. Supply potentials and available amount of timber and forest biomass resources in Kanuma area (m³).

Supply Potential			
	Timber	Biomass	Total
First Thinning	0	1,526,346	1,526,346
Second Thinning	1,712,658	2,275,270	3,987,928
Final Felling	10,874,773	4,067,236	14,942,010
Total	12,587,431	7,868,852	20,456,283
Annual	209,791	131,148	340,938

Available Amounts Including Regeneration			
	Timber	Biomass	Total
First Thinning	0	586,868	586,868
Second Thinning	656,583	872,272	1,528,854
Final Felling	4,170,022	1,559,616	5,729,638
Total	4,826,605	3,018,756	7,845,360
Annual	80,443	50,313	130,756

Available Amounts Excluding Regeneration			
	Timber	Biomass	Total
First Thinning	0	642,282	642,282
Second Thinning	719,907	956,398	1,676,305
Final Felling	4,581,161	1,713,384	6,294,545
Total	5,301,068	3,312,064	8,613,132
Annual	88,351	55,201	143,552

m³/year was 2.2 times of the planned coniferous tree-harvesting volume of 36,600 m³/year (Tochigi Prefecture Government, 2010c). The annual available amount of logging residue in the Kanuma area of 50,313 m³/year was 4.2 times the annual production of chips at the chip production factory in Kanuma city of 12,000 m³/year (Shimotsuke newspaper, 2009).

4.1 Regeneration Costs

The number of profitable subcompartments increased without considering the regeneration costs (Table 8). This showed the current situation of Japanese forestry where many forest owners are not willing

Table 8. The number and area of subcompartments.

Nasushiobara city				
	Including Regeneration		Excluding Regeneration	
	No. Sub-compartment	Area (ha)	No. Sub-compartment	Area (ha)
Profitable	1,801	1,787.75	3,384	2,304.00
Deficit	1,625	527.00	42	10.75
Roadless	2,330	1,364.25	2,330	1,364.25
Total	5,756	3,679.00	5,756	3,679.00

Kanuma area				
	Including Regeneration		Excluding Regeneration	
	No. Sub-compartment	Area (ha)	No. Sub-compartment	Area (ha)
Profitable	8,940	9,070.00	11,888	9,941.75
Deficit	3,014	888.25	66	16.50
Roadless	20,897	14,551.00	20,897	14,551.00
Total	32,851	24,509.25	32,851	24,509.25

to conduct regeneration operations after final felling.

Similar to the number of subcompartments, the available amount of timber and logging residue without considering the regeneration costs increased to 978,296 m³ and 605,218 m³ in Nasushiobara city (Table 6) and 5,301,068 m³ and 3,312,064 m³ in the Kanuma area for 60 years (Table 7). Therefore, the annual available amount of timber and logging residue also increased to 16,305 m³/year and 10,087 m³/year in Nasushiobara city, and 88,351 m³/year and 55,201 m³/year in the Kanuma area, respectively. It is important to develop low-cost regeneration operations after final felling or to extent the rotation ages while reducing the number of regeneration operations for sustainable forest management and sustainable use of forest biomass resources in Japan.

Figure 4. The most economical timber and forest biomass harvesting system for each sub-compartment.

Left of the figure is Nasushiobara city and right is the Kanuma area.

4.2 Forest Road Network

The number of roadless subcompartments was 2,330 and 20,897 in Nasushiobara city and the Kanuma area, respectively, which represents 40% and 64% of the total number of subcompartment in these areas (Table 8). Therefore, it is expected to increase the annual available amount of logging residue by establishing forest road networks. In this section, forest road networks were planned to connect landings, which were not near existing roads by the Dijkstra method using the

Figure 5. Profitable subcompartments including regeneration cost.

Left of the figure is Nasushiobara city and right is the Kanuma area.

closest neighboring roads (Figure 6). Forest road networks should be established by public funds. Therefore, the expenses for forest road establishment were not considered in this section.

The number of profitable and nonprofitable subcompartments was 2,879 and 2,877 of the total number of subcompartments (5,756) in Nasushiobara city whereas in the Kanuma area they were 23,551 and 9,300, respectively, (Table 9). The number of profitable subcompartments significantly increased in both areas. The annual available amount of timber and logging residue also increased to 19,084 m³/year and 11,849 m³/year in Nasushiobara city (Table 10), and 184,019 m³/year and 115,213 m³/year in the Kanuma area (Table 11), respectively. However, the road density of Nasushiobara city and the Kanuma area was 43.5 m/ha and 87.0 m/ha, respectively, after the establishment of the forest road network. The cost of establishing a high-density forest road network in the Kanuma area would be too much, because of the many roadless subcompartments in the area.

Figure 6. Forest road network establishment based on subcompartments.

Left of the figure is Nasushiobara city and right is the Kanuma area.

4.3 Extending Forestry Operation Sites while Merging Subcompartments

Since all indirect costs were fixed, the smaller the volume, the higher the cost. Therefore, cost reductions are expected by extending forestry operation sites while merging subcompartments. Forest road establishment expenses are expected to decrease because the number of landings, which were not near existing roads and should be connected, also decreased in this study assuming a landing in each operation site. In this section, extending forestry operation sites was considered while merging subcompartments in the same watersheds. As a result, the number of subcompartments, 5,756, was reduced to the number of extended forestry operation sites, 1,519, in Nasushiobara city while the number of subcompartments, 32,851, was reduced to the number of extended forestry operation sites, 1,237, in the Kanuma area. The average area of subcompartments, 0.64 ha, was increased to the average area of the

Table 9. The number and area of subcompartments and extended operation sites.

Nasushiobara city				
	Forest road		Extended sites	
	No. Sub-compartment	Area (ha)	No. extended sites	Area (ha)
Profitable	2,879	2,718.25	1,456	3,645.50
Deficit	2,877	960.75	63	33.50
Roadless	0	0.00	0	0.00
Total	5,756	3,679.00	1,519	3,679.00

Kanuma area				
	Forest road		Extended sites	
	No. Sub-compartment	Area (ha)	No. Extended sites	Area (ha)
Profitable	23,551	21,689.50	1,237	24,509.25
Deficit	9,300	2,819.75	0	0.00
Roadless	0	0.00	0	0.00
Total	32,851	24,509.25	1,237	24,509.25

extended forestry operation sites, 2.42 ha, in Nasushiobara city while the average area of the subcompartments, 0.75 ha, was increased to the average area of the extended forestry operation sites, 19.81 ha, in the Kanuma area. The road density of Nasushiobara city and Kanuma area was 30.8 m/ha and 26.4 m/ha, respectively, after the establishment of forest road network based on the extended forestry operation sites (Figure 7). The road network density was similar to the target density in Japan.

The number of profitable and nonprofitable extended forestry operation sites was 1,456 and 63 of the total 1,519 extending forestry operation sites in Nasushiobara city (Table 9). In the Kanuma area, all of the 1,237 extending forestry operation sites were profitable. Therefore, the annual available amount of timber and logging residue in the

Table 10. Available amount of timber and forest biomass resources in Nasushiobara city (m³).

Forest road network			
	Timber	Biomass	Total
First Thinning	0	134,549	134,549
Second Thinning	155,163	206,134	361,297
Final Felling	989,899	370,229	1,360,128
Total	1,145,062	710,912	1,855,975
Annual	19,084	11,849	30,933

Extended operation site			
	Timber	Biomass	Total
First Thinning	0	181,285	181,285
Second Thinning	210,103	279,123	489,226
Final Felling	1,350,360	505,044	1,855,404
Total	1,560,608	965,306	2,525,915
Annual	26,010	16,088	42,099

Kanuma area were the same with an annual supply potential of 209,791 m³/year and 131,148 m³/year, respectively, (Table 11). The annual available amount of timber and forest biomass resources in Nasushiobara city also increased to 26,010 m³/year and 16,088 m³/year (Table 10), respectively.

5. Conclusions

The purpose of this study was to develop a model to estimate the annual available amount of forest biomass resources under profitable forest management in Nasushiobara city and the Kanuma area of Tochigi prefecture, Japan. As a result, the number of profitable, nonprofitable, and roadless subcompartments were 1,801; 1,625; and 2,330, respectively, of the total 5,756 subcompartments in Nasushiobara city whereas they were 8,940; 3,014; and 20,897 of the total 32,851 subcompartments in the Kanuma area. The annual available amount of forest biomass re-

Table 11. Available amount of timber and forest biomass resources in Kanuma area (m³).

Forest road network			
	Timber	Biomass	Total
First Thinning	0	1,345,625	1,345,625
Second Thinning	1,506,232	2,001,033	3,507,264
Final Felling	9,534,935	3,566,128	13,101,063
Total	11,041,167	6,912,785	17,953,952
Annual	184,019	115,213	299,233

Extended operation site			
	Timber	Biomass	Total
First Thinning	0	1,526,346	1,526,346
Second Thinning	1,712,658	2,275,270	3,987,928
Final Felling	10,874,773	4,067,236	14,942,010
Total	12,587,431	7,868,852	20,456,283
Annual	209,791	131,148	340,938

sources was 7,805 m³/year and 50,313 m³/year in Nasushiobara city and the Kanuma area, respectively. The annual available amount of forest biomass resources meets the annual demand of a 500 kW woody biomass power generation plant planned in Nasushiobara city and the annual production of a chip production factory in the Kanuma area, respectively.

This study just estimated the annual available amount of forest biomass resources with total revenues and costs during the 60-year rotation. However, the estimation should be conducted with considering the current situation of forest resources, forestry, forest and energy industries and projecting their future situation while discounting the future revenues and costs to the present net values although this study did not. The Japan Forest Agency has conducted a measure on the long-term rotation management because revenues from final-felling operations could not cover the regeneration costs under the current

Figure 7. Forest road network establishment based on the extended forestry operation sites.

Left of the figure is Nasushiobara city and right is the Kanuma area.

conditions. Extending the cutting ages is expected to increase revenue. However, this study did not consider the effect of changing the log prices along with log quality; it will be analyzed in our next study. Establishing the forest road network and extending the forestry operation sites by merging the small subcompartments was also examined. However, this study did not examine how to establish the forest road network and to extend the forestry operation sites. A next study will estimate the annual available amount of forest biomass resources while planning to establish the forest road network and to extend the forestry operation sites. In addition, the study will also examine the results and plans that may decrease the cost.

Acknowledgement

We are grateful to the Tochigi Prefecture Government for providing the required data. This study was supported by Nissei Zaidan.

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