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# Estimating Annual Available Amounts of Forest Biomass Resources with Total Revenues and Costs during the 60-Year Rotation in a Mountainous Region in Japan

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***Abstract***

*This study extracted production forests and estimated the annual available amounts of forest biomass resources under profitable forest management. Production forests were extracted as sub-compartments where expected revenues surpassed all costs, from planting to final harvesting, for a 60-year rotation. These revenues and costs were estimated for two types of timber harvesting systems (a conventional operation system using a chainsaw and mini-forwarder, and a mechanized operation system using a processor and forwarder) and three types of forest biomass harvesting systems (normal extraction, landing sales, and no biomass extraction) in each sub-compartment using a geographic information system. Then, annual available amounts of forest biomass resources were estimated on the basis of annual supply potentials from production forests. The model was then applied to Nasushiobara City and the Kanuma area in Tochigi Prefecture, Japan. As a result, the number of profitable sub-compartments was estimated as 2,814 out of a total of 5,756 in Nasushiobara City, and 22,872 out of a total of 32,851 in the Kanuma area. The annual amounts of available forest biomass resources were estimated as 11,849 $m^3\ y^{-1}$ and 115,213 $m^3\ y^{-1}$ in Nasushiobara City and the Kanuma area, respectively. These amounts largely exceed the annual demands of a 500 kW woody biomass power generation plant planned in Nasushiobara City (6,000 $m^3\ y^{-1}$) and a chip production factory located in the Kanuma area (12,000 $m^3\ y^{-1}$), respectively.*

*€1 = 143 yen on March 13, 2011*

*Keywords: economic balance, geographic information system, harvesting system, production forest, supply potential*

## 1. Introduction

Japan is dependent on the imports of oil, coal, and natural gas for the majority of its energy supply. The energy self-sufficiency rate in 2010 was just 5% (Japan Forestry Agency 2013). In order to secure a stable supply of energy, alternatives to fossil fuel, for example »renewable energy« such as solar, wind, rivers, geothermal heat, and biomass will need to be developed. Among various biomass resources in Japan, woody biomass in particular attracts attention. This is not just because it is abundant, but also because its energy use is expected to contribute to revitalizing forests and forestry product industries, which have been depressed for the last 30 years. Maintaining the relevant ecological, economic, and social functions of man-made forests, which are behind in tending, is also important.

In July 2011, the »Feed-in Tariff (FIT) Scheme for Renewable Energy Use« was introduced in accordance with new legislation entitled the »Act on Purchase of Renewable Energy Sourced Electricity by Electric Utilities«. Under the FIT program, electricity generated from woody biomass is to be procured for 20 years at a fixed price (without tax) for unused materials such as the logging residue: 32 yen/kWh, general materials such as sawmill residue: 24 yen/kWh, and recycled materials such as construction waste wood: 13 yen/kWh (Agency for Natural Resources and Energy 2012). Power generated from unused materials is offered incentives. Therefore, use of logging residue will be promoted in the near future.

Numerous studies have examined the availability of woody biomass resources using GIS. 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 and Sakai (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 and Nakata (2007) and Yamamoto et al. (2010) developed techniques that expressed them in units of kilometer-scale grids of cities and towns. Furthermore, Nord-Larsen and Talbot (2004), Aruga et al. (2006a), Rørstad et al. (2010), and Aruga et al. (2011) discussed the long-term feasibility of timber and forest biomass resources by predicting future forest resources using growth models while optimizing the allocation of fuel wood using linear programming or random search. Moreover, Aruga et al. (2006b) and Panichelli and Gnansounou (2008) discussed the scales and locations of bio-energy facilities based on the relationship between the annual available amounts and the procurement costs of forest biomass resources, whereas Ranta (2005), Möller and Nielsen (2007), and Viana et al. (2010) 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) and Nakahata et al. (2014) 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) and Kamimura et al. (2012) 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 sustainable forest management.

In contrast, Aruga et al. (2013) developed a method for extracting production forests based on economic balances by considering regeneration expenses after final felling operations. Aruga et al. (2013) defines production forests as sub-compartments where expected revenues surpassed all costs of thinning and final felling operations. Then, Aruga et al. (2013) estimated available amounts of timber and forest biomass resources from profitable sub-compartments. Regeneration expenses include site preparation, planting, weeding, vine cutting, pruning, and forest inventory. About 2,500 seedlings/ha are assumed to be planted and weeding operations are assumed to be conducted once a year for ten years after planting in this study. Then, vine cutting operations are assumed to be conducted 10 and 12 years after planting and pruning operations are assumed to be conducted 15 and 25 years after planting. However, Aruga et al. (2013) estimated only the supply potentials and available amounts of timber and forest biomass resources based on the current situation.

In order to plan power generation plants considering available amounts of forest biomass resources, future supply potentials and available amounts of forest biomass resources should be projected. Therefore, this study first estimated revenues and costs of precommercial and commercial thinning operations as well as final felling operations with two types of timber harvesting systems (a conventional operation system using a chainsaw and mini-forwarder, and a mechanized operation system using a processor and forwarder) and three types of forest biomass harvesting systems (normal extraction, landing sales, and no biomass extraction) in each sub-compartment using a geographic information system. Then, production forests were extracted as sub-compartments where expected revenues surpassed all costs, from planting to final harvesting, for a 60-year rotation. Finally, the most economical timber and forest biomass harvesting system for each sub-compartment was determined and annual available amounts of forest biomass resources were estimated on the basis of annual supply potentials from production forests.

## 2. Study sites and data

The study sites were Nasushiobara City (Aruga et al. 2013) and the Kanuma area (Aruga et al. 2011) in Tochigi Prefecture, Japan. The gross area of Nasushiobara City is 59,280 ha, and the forest area is 38,689 ha (65% of the gross area). The area of national forests is 24,981 ha and that of private and local government forests is 13,708 ha. In this study, major plantation species such as Japanese cedar (*Cryptomeria japonica*) and Japanese cypress (*Chamaecyparis obtusa*), owned by private individuals and organizations as well as local

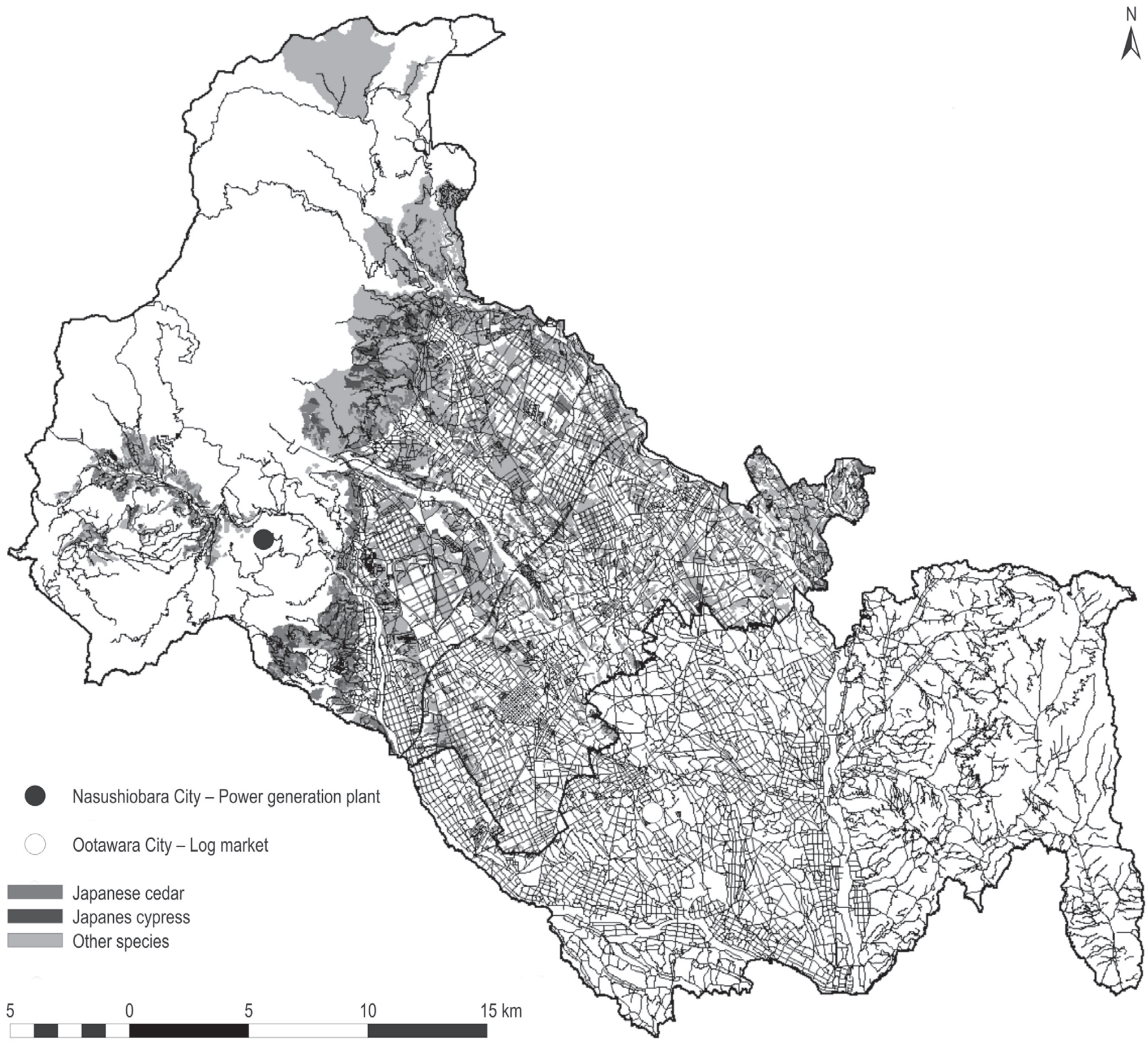


**Fig. 1** Stand species of Nasushiobara City

governments, were analyzed. Private individuals and organizations along with local governments own 7,340 sub-compartments of Japanese cedar comprising 2,850 ha, and 2,521 sub-compartments of Japanese cypress comprising 1,103 ha (Fig. 1). The average slope angle is relatively low (10°) and the road network density is relatively high (27 m/ha). An agrarian organization in the Nasunogahara area in Tochigi Prefecture is willing to conduct thinning operations and extract thinned woods for woody biomass power generation in cooperation with a Forest Owners' Co-operative in Nasushiobara City in order to nurture river resources as well as maintain forests for soil and water conservation.

The Kanuma area consists of Kanuma City and the town of Nishikata. The gross area is 52,200 ha and the forest area is 35,593 ha (68% of the gross area). The area of national forests is only 1,642 ha and that of private and local government forests is 33,951 ha. Private individuals and organizations as well as local governments own 30,104 sub-compartments of Japanese cedar comprising 17,341 ha and 19,957 sub-compartments of Japanese cypress comprising 9,950 ha (Fig. 2). The average slope angle is relatively high (22°) and the road network density is relatively low (18 m/ha). The Kanuma area was one of the famous forestry areas in Tochigi Prefecture (the site index that ranks the order of stand production capacity was higher than that for

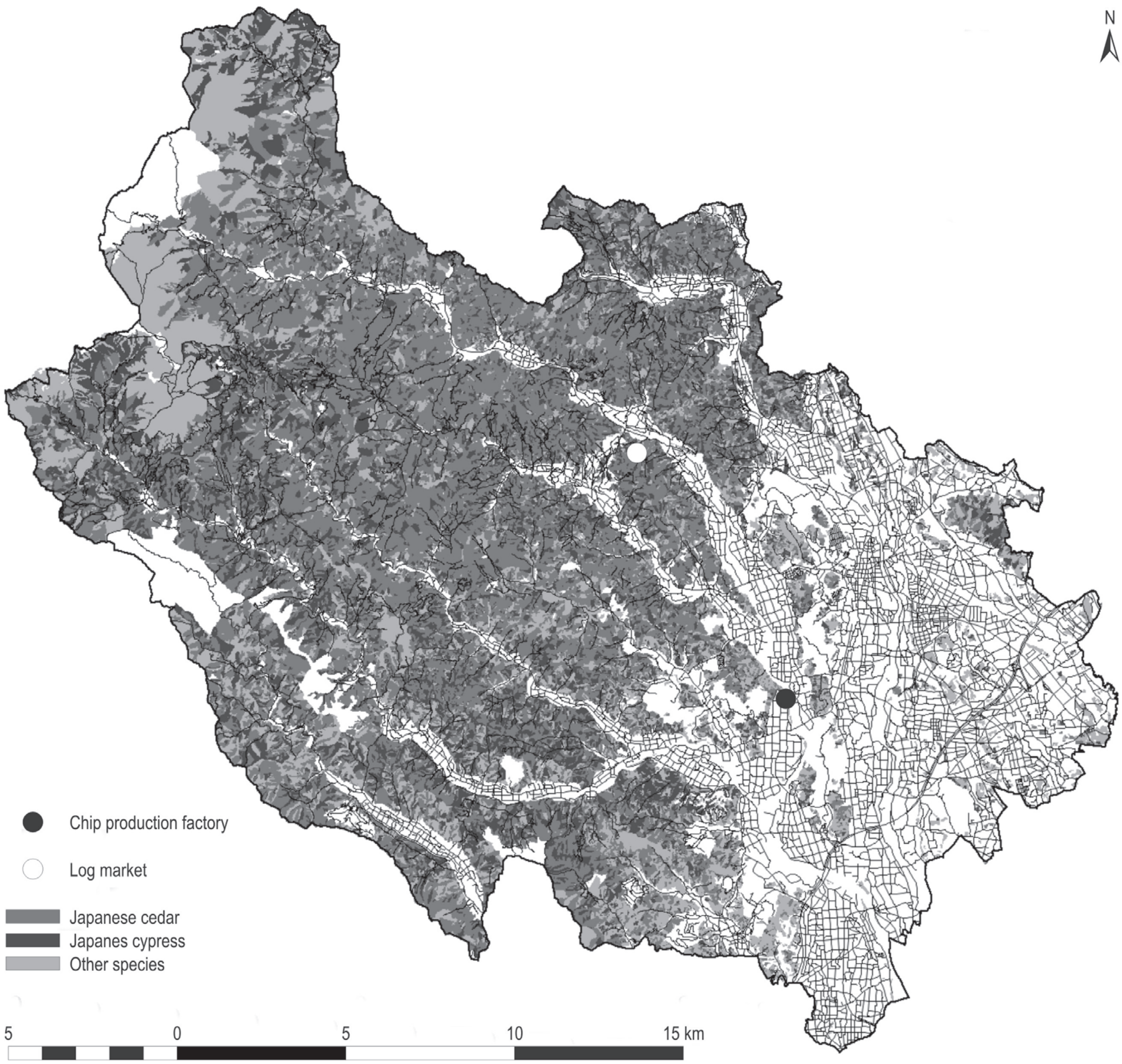


**Fig. 2** Stand species of the Kanuma area

Nasushiobara City). A chip production factory, aimed at supplying a portion of the chips to a woody biomass power generation plant, is located in the Kanuma area.

Forest-registration data (stand ages, tree species, and site indices) and GIS data (information on roads and sub-compartment layers) from the Tochigi Prefectural Government were used in the study, as were 50 m grid digital elevation models (DEMs) from the Geographical Survey Institute. Private individuals and organizations as well as local governments of Nasushiobara City own 4,456 sub-compartments of Japanese cedar comprising 2,761 ha and 1,300 sub-compartments of Japanese cypress comprising 918 ha based on 50 m meshes. Those of the Kanuma area owned 22,735 sub-compartments of Japanese cedar comprising 17,247 ha and 10,116 sub-compartments of Japanese cypress comprising 7,262 ha. The sub-compartments in both areas were significantly fewer than the actual numbers because there were many small sub-compartments of less 0.25 ha that could not be recognized with 50-m meshes. However, the areas were not significantly smaller than the actual areas.

**Table 1** Direct operating expenses

| Machine | Operation | Expense, yen $m^{-3}$ | System | Reference |
|---|---|---|---|---|
| Chainsaw | Felling | $53 / V_n + 65$ | Both | Nakahata et al. 2011 |
| Chainsaw | Processing | $39 / V_l + 329$ | Conventional | Nakahata et al. 2011 |
| Processor | Processing | $207 / V_l + 161$ | Mechanized | Nakahata et al. 2011 |
| Mini grapple-loader | Bunching | 1,999 | Conventional | Nakahata et al. 2011 |
| Grapple-loader | Bunching | 1,199 | Mechanized | Nakahata et al. 2011 |
| Mini forwarder | Forwarding | $(769 + 0.508\ L_f) / R_f$ | Conventional | Nakahata et al. 2011 |
| Forwarder | Forwarding | $(378 + 0.301\ L_f) / R_f$ | Mechanized | Nakahata et al. 2011 |
| Truck | Transporting | $(778 + 0.031\ L_t) / R_t$ | Both | Sawaguchi 1996 |

$V_n$ – stem volume, $m^3$ $stem^{-1}$; $V_l$ – extracted volume per stem, $m^3$ $stem^{-1}$;
$L_f$ – forwarding distance, m; $L_t$ – transporting distance, m; $R_f$ and $R_t$ – loading capacity rates

## 3. Methods

Production forests were extracted and annual available amounts of forest biomass resources were estimated in the following order: 1) estimation of supply potentials of timber and logging residues based on the cutting and extraction rates in thinning and final felling operations during a 60-year rotation; 2) estimation of total expenses from planting to final felling operations during a 60-year rotation; 3) estimation of revenues from thinning and final felling operations during a 60-year rotation; 4) estimation of economic balances during a 60-year rotation; 5) extraction of profitable sub-compartments as production forests; and 6) estimation of annual available amounts of forest biomass resources on the basis of annual supply potentials from profitable sub-compartments. A simple version of »Methods« will be described below. Full technical details will be found in an earlier paper (Aruga et al. 2013).

Thinning and final felling operations were assumed to be conducted based on stand ages. First (pre-commercial), second (commercial) thinning and final felling operations were assumed to be conducted at 25, 40, and 60 years old, respectively. Supply potentials of timber and forest biomass resources on each sub-compartment were estimated from the cutting, extraction, timber, and forest biomass rates. The rate of forest biomass to whole tree for pre-commercial thinning operations was 100% whereas those for commercial thinning operations and final felling operations were 55% and 26%, respectively.

This study investigated a conventional operation system and a mechanized operation system. This study also examined three types of forest biomass harvesting systems: 1) normal extraction, 2) landing sales, and 3) no biomass extraction. All costs, including the direct and indirect operating expenses associated with each machine, strip-road and landing establishment expenses, and regeneration expenses, were estimated (Eq. 1).

$$A = D + S + L + I + R \tag{1}$$

Here, $A$, $D$, $S$, $L$, $I$, and $R$ denote all costs, direct operating expenses, strip-road establishment expenses, landing establishment expenses, indirect operating expenses, and regeneration expenses, respectively.

Direct operating expenses, given in Table 1 (Nakahata et al. 2011, Sawaguchi 1996), included labor and machinery expenses (maintenance, management, depreciation, fuel, and oil expenses). The stem volume $V_n$ ($m^3$ $stem^{-1}$) of each sub-compartment was estimated using yield tables (Forest Experiment Station 1955, 1961) with stand species, ages, and site indices in the forest registration, and the extracted volume per stem, $V_l$ ($m^3$ $stem^{-1}$) was estimated by multiplying $V_n$ with the stem extraction rate (80% for the first thinning and final felling operations and 50% for the second thinning operation). Forwarding and transporting costs were changed according to the loading capacity rates for timber and forest biomass resources upon the first thinning, second thinning, and final felling operations.

Forwarding distances were estimated by the average distances from the landings to all grids within the sub-compartments. Landings were set within grids so as to minimize their distances from roads, centers of gravity in the sub-compartment, and the power gen-

**Table 2** 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 | |
| Bunching | | X | X | X | X | X | | | X | | X | | | | X | | X | |
| Forwarding | | X | X | X | X | X | | | X | | X | | | | X | | X | |
| Transporting | | X | X | X | X | X | | | X | | X | | | | X | | X | |
| Landing establishment | | X | X | | X | | | | X | | X | | | | X | | X | |
| Machine transportation | | X | X | | X | | | | X | | X | | | | X | | X | |
| Garage maintenance | | X | Y | Y | Y | Y | | | X | | X | | | | X | | X | |
| Incidental personnel | | X | Y | Y | Y | Y | | X | X | | X | | | X | X | | X | |
| Overhead costs | | X | Y | Y | Y | Y | | X | X | | X | | | X | X | | X | |
| Handling fees | | | X | | X | | | | X | | X | | | | X | | X | |

1 – first thinning; 2 – second thinning; 3 – final felling
T – timber; F – forest biomass resources
X – entire cost consideration; Y – cost consideration according to timber and forest biomass volumes

eration plant in Nasushiobara City or chip production factory in Kanuma City. Transporting distances from the landings to log markets and to the power generation plant in Nasushiobara City or chip production factory in Kanuma City were calculated with the Dijkstra method (Dijkstra 1959). If sub-compartments were unconnected to existing roads, forest road networks were planned to connect landings by the Dijkstra method. The expenses of forest road establishment, which should be paid for by public budgets, were not considered in this study.

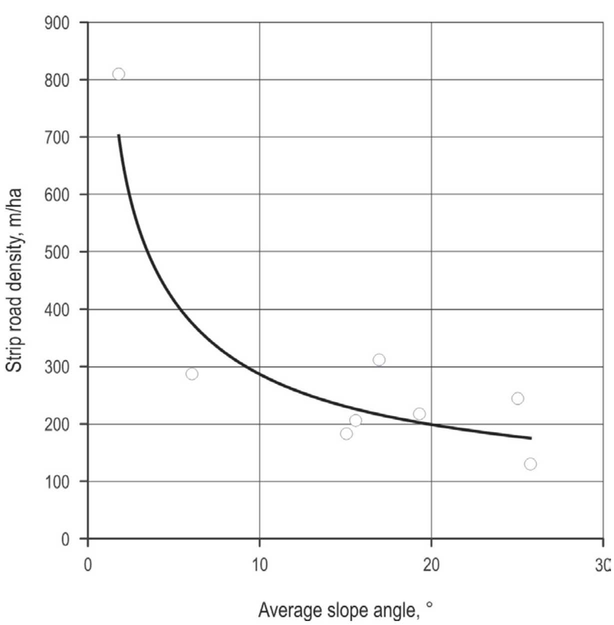


**Fig. 3** Average slope angle and strip road density

Strip roads were assumed to be established for forwarding operations. The strip-road density $d$ (m ha$^{-1}$) was assumed to be related to the average slope angle of each sub-compartment, $\theta$ (°), according to the following equation (Fig. 3):

$$d = 956.72\,\theta^{-0.52} \qquad (2)$$

The strip-road cost $S$ (yen) was then estimated by multiplying $d$ by the following unit strip-road cost $s$ (yen m$^{-1}$):

$s = 67\,e^{0.116\,\theta}$ for the conventional operation system (Sawaguchi 1996) (3)

$s = 220\,e^{0.117\,\theta}$ for the mechanized operation system (Sawaguchi 1996) (4)

The expenses of the landing-establishment $L$ (yen) were estimated by the following equation:

$$L = 187.63\,V \qquad (5)$$

Here, $V$ is the extracted volume per hectare (m$^3$ ha$^{-1}$). Machine transportation expenses, garage-maintenance expenses, incidental personnel expenses, overhead costs, and handling fees associated with the log market were considered as indirect operating expenses (Zenkoku Ringyo Kairyo Fukyu Kyokai 2001).

In addition to these timber and forest biomass extraction costs, regeneration expenses included those for site preparation, planting, weeding, vine cutting, pruning, and forest inventory. The regeneration expenses were estimated as 2,512,376 yen ha$^{-1}$ for Japanese cedar and 2,892,365 yen ha$^{-1}$ for Japanese cypress (Okawabata 2003).

For normal extraction of the first thinning operation, only thinned woods left in the forest after precommercial thinning were extracted as forest biomass resources. Therefore, all costs were related to forest biomass extraction (Table 2). Logging residues upon the second thinning and final felling operations were considered as a by-product of timber harvesting. Therefore, operations for forest biomass extraction started after processing, and all costs, excluding those for forest biomass extraction as well as associated indirect costs, were considered as timber extraction costs. For landing sales of the first thinning operation, only felling and processing costs as well as associated indirect costs were considered. For the case of no biomass extraction of the first thinning operation, only felling costs and associated indirect costs were considered whereas processing and extraction costs as well as associated indirect costs were not.

For the first thinning operation of landing sales, only felling and processing operations were assumed and timber extraction was not considered. For no timber extraction, use of the processor was an unrealistic assumption even for the processing operation of the mechanized operation system. Therefore, chainsaw felling and processing operations were assumed. Therefore, small-sized strip roads for the conventional operation system were assumed to be constructed upon the first thinning operation of the mechanized operation system, and those for the mechanized operation system were assumed to be constructed upon the second thinning operation of the mechanized operation system. For the first thinning operation of no biomass extraction, no timber or forest biomass extraction was assumed. Therefore, strip roads were assumed to be constructed for the second thinning operation, unlike normal extraction and landing sales, for which they were assumed to be constructed upon the first thinning operation.

Incomes were estimated using supply potentials and log prices: 11,000 yen m$^{-3}$ for Japanese cedar, 22,000 yen m$^{-3}$ for Japanese cypress, and 3,400 or 1,000 yen m$^{-3}$ for normal extraction or landing sales, respectively, of forest biomass resources. For thinning operations, the subsidy was estimated by the standard unit cost, area, assessment coefficient, and subsidy rate (Tochigi prefectural government 2010). Subsidies on the first thinning operation for normal extraction, the first thinning operation for landing sales or no biomass extraction, and the second thinning operation for all types of operations were 235,504 yen ha$^{-1}$, 64,291 yen ha$^{-1}$, and 338,188 yen ha$^{-1}$, respectively. For strip-road establishment on sub-compartments where thinning operations were conducted with subsidies, the subsidy (Table 3) was also estimated with the standard unit cost, length, assessment coefficient, and subsidy rate (Tochigi prefectural government 2010). In this study, the subsidy for regeneration was also considered. Subsidies were estimated as 1,227,400 yen ha$^{-1}$ for Japanese cedar and 1,219,240 yen ha$^{-1}$ for Japanese cypress.

**Table 3** Subsidies for strip-road establishment (yen m$^{-1}$)

| Average slope angle, ° | Conventional | Mechanized |
|---|---|---|
| 5 | 40 | 159 |
| 10 | 60 | 191 |
| 15 | 91 | 230 |
| 20 | 137 | 276 |
| 25 | 147 | 477 |
| 30 | 183 | 850 |

## 4. Results and discussion

### 4.1 Normal extraction

Upon the first thinning operation with the conventional operation system, only a few sub-compartments on large areas and gentle slopes were profitable (Table 4). However, upon the first thinning operation with the mechanized operation system, no sub-compartments were profitable. With the mechanized operation system, machine transportation expenses were high and the extracted volumes of the first thinning operation were small. Therefore, machine transportation expenses per extracted volume were high. This was the reason why no sub-compartments were profitable upon the first thinning operation. Upon the second thinning and final felling operations, there were more profitable sub-compartments with the mechanized operation system than with the conventional operation system, because although machine transportation expenses with the former were higher, productivity was also higher and subsequent costs were lower. In particular, upon the final felling operation, almost all sub-compartments were profitable with the mechanized operation system.

**Table 4** Profitable sub-compartments with normal extraction

| | | Nasushiobara City | | | | | Kanuma area | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No. of sub-compartments | Area, ha | Rate, % | | Average slope angle, ° | No. of sub-compartments | Area, ha | Rate, % | | Average slope angle, ° |
| | | | | No. | Area | | | | No. | Area | |
| Conventional Operation System | First thinning | 19 | 80 | 0.3 | 2.2 | 4.9 | 10 | 35 | 0.0 | 0.1 | 11.2 |
| | Second thinning | 1,634 | 1,752 | 28.4 | 47.6 | 9.6 | 10,399 | 8,135 | 31.7 | 33.2 | 21.6 |
| | Final felling | 1,812 | 1,839 | 31.5 | 50.0 | 9.4 | 12,355 | 10,268 | 37.6 | 41.9 | 21.4 |
| | Total without R* | 1,530 | 1,452 | 26.6 | 39.5 | 8.8 | 10,682 | 8,250 | 32.5 | 33.7 | 21.5 |
| | Total with R* | 658 | 737 | 11.4 | 20.0 | 9.7 | 7,543 | 6,492 | 23.0 | 26.5 | 22.2 |
| Mechanized Operation System | First thinning | 0 | 0 | 0.0 | 0.0 | 0.0 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| | Second thinning | 2,161 | 2,609 | 37.5 | 70.9 | 11.9 | 16,155 | 19,139 | 49.2 | 78.1 | 22.7 |
| | Final felling | 5,550 | 3,628 | 96.4 | 98.6 | 9.5 | 32,822 | 24,502 | 99.9 | 100.0 | 21.5 |
| | Total without R* | 3,218 | 2,968 | 55.9 | 80.7 | 9.6 | 21,058 | 20,920 | 64.1 | 85.4 | 21.6 |
| | Total with R* | 1,022 | 1,352 | 17.8 | 36.8 | 9.3 | 7,927 | 8,589 | 24.1 | 35.0 | 21.2 |

*Regeneration expenses

The proportions of profitable sub-compartments in Nasushiobara City and the Kanuma area, without considering regeneration costs, were 27% and 33%, respectively, with the conventional operation system and 56% and 64%, respectively, with the mechanized operation system. Similarly to the second thinning and final felling operations, there were more profitable sub-compartments with the mechanized operation system than with the conventional operation system. However, the profitable sub-compartments in Nasushiobara City and the Kanuma area in consideration of the regeneration costs decreased to 11% and 23%, respectively, with the conventional operation system and 18% and 24%, respectively, with the mechanized operation system. This shows the current state of affairs of Japanese forestry, in which many forest owners are unwilling to conduct regeneration operations after final felling operations.

## 4.2 Landing sales

Upon the first thinning operation, the proportions of profitable sub-compartments were 36% and 14% in Nasushiobara City and the Kanuma area, respectively (Table 5). There were more profitable sub-compartments than with normal extraction (Table 4). However, upon the second thinning operation of the mechanized operation system, the numbers were similar to those for normal extraction in Nasushiobara City and lower in the Kanuma area because strip roads for the conventional operation system were assumed to be constructed upon the first thinning operation and those for the mechanized operation system were assumed to be constructed upon the second thinning operation. On the other hand, profitable sub-compartments also increased significantly relative to those with normal extraction upon the second thinning operation of the conventional operation system. Upon the final felling operation, almost all sub-compartments were profitable with the conventional operation system and all sub-compartments were profitable with the mechanized operation system.

Relative to normal extraction, profitable sub-compartments in Nasushiobara City and the Kanuma area, without considering regeneration costs, increased significantly to 100% and 97%, respectively, with the conventional operation system and 94% and 96%, respectively, with the mechanized operation system. However, unlike normal extraction, the proportions with the mechanized operation system were smaller than those with the conventional operation system owing to strip-road construction upon the second thinning operation of the mechanized operation system. Similarly to normal extraction, profitable sub-compartments in Nasushiobara City and the Kanuma area in consideration of the regeneration costs decreased to 31% and 49%, respectively, with the conven-

**Table 5** Profitable sub-compartments with landing sales

| | | Nasushiobara City | | | | | Kanuma area | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No. of sub-compartments | Area, ha | Rate, % | | Average slope angle, ° | No. of sub-compartments | Area, ha | Rate, % | | Average slope angle, ° |
| | | | | No. | Area | | | | No. | Area | |
| Conventional Operation System | First thinning | 2,095 | 1,328 | 36.4 | 36.1 | 5.9 | 4,419 | 1,894 | 13.5 | 7.7 | 9.9 |
| | Second thinning | 4,760 | 3,430 | 82.7 | 93.2 | 9.6 | 32,532 | 24,430 | 99.0 | 99.7 | 21.6 |
| | Final felling | 5,645 | 3,652 | 98.1 | 99.3 | 9.6 | 32,713 | 24,475 | 99.6 | 99.9 | 21.4 |
| | Total without R* | 5,755 | 3,679 | 100.0 | 100.0 | 9.7 | 31,941 | 24,281 | 97.2 | 99.1 | 21.1 |
| | Total with R* | 1,779 | 1,855 | 30.9 | 50.4 | 9.5 | 16,211 | 17,664 | 49.3 | 72.1 | 21.9 |
| Mechanized Operation System | First thinning | 2,095 | 1,328 | 36.4 | 36.1 | 5.9 | 4,419 | 1,894 | 13.5 | 7.7 | 9.9 |
| | Second thinning | 2,335 | 2,322 | 40.6 | 63.1 | 7.6 | 11,009 | 12,416 | 33.5 | 50.7 | 17.7 |
| | Final felling | 5,756 | 3,679 | 100.0 | 100.0 | 9.7 | 32,851 | 24,509 | 100.0 | 100.0 | 21.5 |
| | Total without R* | 5,423 | 3,570 | 94.2 | 97.0 | 8.9 | 31,680 | 24,191 | 96.4 | 98.7 | 21.0 |
| | Total with R* | 2,648 | 2,484 | 46.0 | 67.5 | 8.9 | 21,029 | 20,328 | 64.0 | 82.9 | 20.9 |

*Regeneration expenses

tional operation system and 46% and 64%, respectively, with the mechanized operation system, although the proportions were higher than those with normal extraction. Therefore, landing sales were effective as an economical timber and forest biomass harvesting system at these research sites.

### 4.3 No biomass extraction

The first thinning operations were assumed to be pre-commercial and all costs were covered by subsidies (Table 6). Strip roads were assumed to be constructed upon the second thinning operation, unlike normal extraction and landing sales in which strip roads were assumed to be constructed upon the first thinning operation. For the conventional operation system, normal biomass extraction expenses were higher than strip-road establishment expenses. Therefore, there were more profitable sub-compartments without biomass extraction than with normal extraction upon the second thinning operation of the conventional operation system. On the other hand, there were fewer profitable sub-compartments without biomass extraction than with normal extraction upon the second thinning operation of the mechanized operation system, owing to the high costs of strip-road establishment for the latter case. In both operation systems and areas, the profitable sub-compartments without biomass extraction were fewer than those with landing sales upon the second thinning operation. Upon the final felling operation, the number of profitable sub-compartments without biomass extraction was higher than that with normal extraction and equal to or lower than that with landing sales.

The number of profitable sub-compartments without considering regeneration costs was higher than that with normal extraction and lower than that with landing sales. Profitable sub-compartments decreased when regeneration costs were considered. However, similar to the case when regeneration costs are not considered, the number was higher than that with normal extraction and lower than that with landing sales. Therefore, forest biomass harvesting contributed to economic balances under sustainable forest management with a certain biomass harvesting system (e.g., landing sales) at these research sites.

### 4.4 Most economical timber and forest biomass harvesting system during a 60-year rotation

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 listed in Table 7. 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.

**Table 6** Profitable sub-compartments with no biomass extraction

| | | Nasushiobara City | | | | | Kanuma area | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No. of sub-compartments | Area, ha | Rate, % | | Average slope angle, ° | No. of sub-compartments | Area, ha | Rate, % | | Average slope angle, ° |
| | | | | No. | Area | | | | No. | Area | |
| Conventional Operation System | First thinning | 5,756 | 3,679 | 100.0 | 100.0 | 9.7 | 32,851 | 24,509 | 100.0 | 100.0 | 21.5 |
| | Second thinning | 3,302 | 3,001 | 57.4 | 81.6 | 9.8 | 21,495 | 21,259 | 65.4 | 86.7 | 21.5 |
| | Final felling | 4,827 | 3,447 | 83.9 | 93.7 | 9.4 | 32,713 | 24,475 | 99.6 | 99.9 | 21.4 |
| | Total without R* | 3,786 | 3,186 | 65.8 | 86.6 | 9.9 | 29,941 | 23,781 | 91.1 | 97.0 | 21.0 |
| | Total with R* | 1,492 | 1,411 | 25.9 | 38.4 | 9.3 | 13,421 | 14,010 | 40.9 | 57.2 | 21.7 |
| Mechanized Operation System | First thinning | 5,756 | 3,679 | 100.0 | 100.0 | 9.7 | 32,851 | 24,509 | 100.0 | 100.0 | 21.5 |
| | Second thinning | 1,844 | 1,983 | 32.0 | 53.9 | 7.2 | 8,195 | 9,546 | 24.9 | 38.9 | 17.0 |
| | Final felling | 5,756 | 3,679 | 100.0 | 100.0 | 9.7 | 32,851 | 24,509 | 100.0 | 100.0 | 21.5 |
| | Total without R* | 4,915 | 3,448 | 85.4 | 93.7 | 9.2 | 31,303 | 24,107 | 95.3 | 98.4 | 21.0 |
| | Total with R* | 2,213 | 2,201 | 38.4 | 59.8 | 8.7 | 19,230 | 19,557 | 58.5 | 79.8 | 21.4 |

*Regeneration expenses

**Table 7** Most economical timber and forest biomass harvesting system for each sub-compartment

| | First thinning | Second thinning | Final felling | Nasushiobara City | | | | Kanuma area | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | No. of sub-compartments | Area, ha | Average area, ha | Average slope angle, ° | No. of sub-compartments | Area, ha | Average area, ha | Average slope angle, ° |
| *a* | 3 | M2 | M2 | 734 | 713 | 0.97 | 18.0 | 12,841 | 12,691 | 0.99 | 25.2 |
| *b* | C1 | C2 | C2 | 97 | 336 | 3.46 | 25.0 | 334 | 1,177 | 3.52 | 25.6 |
| *c* | C1 | C2 | M2 | 27 | 70 | 2.57 | 3.7 | 29 | 71 | 2.43 | 12.8 |
| *d* | C2 | M2 | M2 | 153 | 199 | 1.30 | 6.2 | 1,044 | 869 | 0.83 | 11.8 |
| *e* | C2 | C2 | C2 | 974 | 395 | 0.41 | 13.6 | 9,082 | 4,980 | 0.55 | 24.8 |
| *f* | C2 | C2 | M2 | 3,639 | 1,424 | 0.39 | 6.5 | 9,209 | 3,032 | 0.33 | 13.8 |
| *g* | M1 | M2 | M2 | 132 | 544 | 4.12 | 17.5 | 312 | 1,691 | 5.42 | 24.2 |
| Total | | | | 5,756 | 3,680 | 0.64 | 9.7 | 32,851 | 24,509 | 0.75 | 21.5 |

C – conventional operation system; M – mechanized operation system
1 – normal extraction; 2 – landing sale; 3 – no biomass extraction

In contrast, the most common type for the first thinning operation was the conventional operation system with normal extraction or landing sales.

The most economical timber and forest biomass harvesting system for a sub-compartment was influenced by the area and average slope angle of the sub-compartment (Table 7). In terms of area, *b*, *c*, and *g* were classified as having large areas; *a* and *d* were classified as having medium areas; and *e* and *f* were classified as having small areas. The biomass harvesting systems of *b*, *c*, and *g* were classified as normal extraction because the areas were large, the extracted volumes were relatively large, and indirect costs were subsequently reduced despite the first thinning operation. The biomass harvesting systems of *a*, *d*, *e*, and *f* on smaller areas were classified as landing sales or pre-commercial thinning upon the first thinning operation.

In terms of average slope angles, *a*, *b*, *e*, and *g* were classified as being on steep slopes while *c*, *d*, and *f* were

**Table 8** Profitable sub-compartments with the most economical timber and forest harvesting system for each sub-compartment

| | First thinning | Second thinning | Final felling | Nasushiobara City | | | | Kanuma area | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Profitable | | Rate, % | | Profitable | | Rate, % | |
| | | | | No. of sub-compartments | Area, ha | No. of sub-compartments | Area | No. of sub-compartments | Area, ha | No. of sub-compartments | Area |
| *a* | 3 | M2 | M2 | 538 | 588 | 73.3 | 82.5 | 9,674 | 11,616 | 75.3 | 91.5 |
| *b* | C1 | C2 | C2 | 90 | 311 | 92.8 | 92.6 | 330 | 1,148 | 98.8 | 97.6 |
| *c* | C1 | C2 | M2 | 27 | 70 | 100.0 | 100.0 | 29 | 71 | 100.0 | 100.0 |
| *d* | C2 | M2 | M2 | 153 | 199 | 100.0 | 100.0 | 1,044 | 869 | 100.0 | 100.0 |
| *e* | C2 | C2 | C2 | 704 | 270 | 72.3 | 68.4 | 7,603 | 4,397 | 83.7 | 88.3 |
| *f* | C2 | C2 | M2 | 1,175 | 715 | 32.3 | 50.2 | 3,882 | 1,647 | 42.2 | 54.3 |
| *g* | M1 | M2 | M2 | 127 | 520 | 96.2 | 95.6 | 310 | 1,676 | 99.4 | 99.1 |
| Total | | | | 2,814 | 2,672 | 48.9 | 72.6 | 22,872 | 21,423 | 69.6 | 87.4 |

C – conventional operation system; M – mechanized operation system
1 – normal extraction; 2 – landing sale; 3 – no biomass extraction

classified as being on gentle slopes. The timber harvesting systems of *a*, *b*, *e*, and *g* on steep slopes were categorized under only the conventional or mechanized operation system. Although the road density was reduced on steep terrain, unit roading costs increased, and hence, subsequent roading costs increased. Therefore, the timber harvesting systems on steep slopes were categorized exclusively under either the conventional or mechanized operation system in order to reduce roading costs for a 60-year rotation. In contrast, the timber harvesting systems of *c*, *d*, and *f* on gentle slopes were categorized under mixed timber operation systems consisting of both the conventional and mechanized operation systems. Therefore, roading costs of both the conventional and mechanized operation systems were included, although they were low because of the gentle slopes.

All sub-compartments of *c* and *d* were profitable because the areas were relatively large and the slopes were gentle (Table 8). However, only 36% and 45% of the sub-compartments of *f* on gentle slopes were profitable in Nasushiobara City and the Kanuma area, respectively, because their areas were small. The proportions of profitable sub-compartments of *g* and *b* on large areas and steep slopes were about 90%, and those of *a* and *e* on smaller areas and steeper slopes were about 80%. The proportion of profitable sub-compartments on large areas was thus higher.

The numbers of profitable and deficit sub-compartments were 2,814 and 2,942 among a total of 5,756 sub-compartments in Nasushiobara City. In contrast, the corresponding numbers were 22,872 and 9,979 among a total of 32,851 sub-compartments in the Kanuma area. The numbers of profitable sub-compartments, when considering regeneration costs, were higher than those before applying the most economical timber and forest biomass harvesting system to each sub-compartment.

### 4.5 Annual available amounts of forest biomass resources

The supply potentials of timber and forest biomass resources were 1,572,395 $m^3$ and 972,672 $m^3$, respectively, in Nasushiobara City (Table 9) and 12,587,431 $m^3$ and 7,868,852 $m^3$, respectively, in the Kanuma area for a 60-year period (Table 10). Therefore, the annual supply potentials of timber and forest biomass resources were 26,207 $m^3\ y^{-1}$ and 16,211 $m^3\ y^{-1}$, respectively, in Nasushiobara City and 209,791 $m^3\ y^{-1}$ and 131,148 $m^3\ y^{-1}$, respectively, in the Kanuma area.

The annual available amounts of timber and forest biomass resources were estimated on the basis of the annual supply potentials from profitable sub-compartments with the most economical timber and forest biomass harvesting system. As a result, the annual available amounts of timber and forest biomass resources were 19,084 $m^3\ y^{-1}$ and 11,849 $m^3\ y^{-1}$, respectively, in Nasushiobara City (Table 9) and 184,019 $m^3\ y^{-1}$ and 115,213 $m^3\ y^{-1}$, respectively, in the Kanuma area (Table 10). These amounts largely exceed the annual demands of a 500 kW woody biomass power generation plant scheduled to be built in Nasushiobara City (6,000 $m^3\ y^{-1}$) and a chip production factory in the Kanuma area (12,000 $m^3\ y^{-1}$), respectively.

**Table 9** Supply potentials and available amounts of timber and forest biomass resources in Nasushiobara City, $m^3$

| | Supply Potential | | | Available Amounts | | |
|---|---|---|---|---|---|---|
| | Timber | Biomass | Total | Timber | Biomass | Total |
| First Thinning | 0 | 182,561 | 182,561 | 0 | 134,549 | 134,549 |
| Second Thinning | 211,657 | 281,187 | 492,844 | 155,163 | 206,134 | 361,297 |
| Final Felling | 1,360,737 | 508,925 | 1,869,662 | 989,899 | 370,229 | 1,360,128 |
| Total | 1,572,395 | 972,672 | 2,545,067 | 1,145,062 | 710,912 | 1,855,975 |
| Annual | 26,207 | 16,211 | 42,418 | 19,084 | 11,849 | 30,933 |

**Table 10** Supply potentials and available amounts of timber and forest biomass resources in the Kanuma area, $m^3$

| | Supply Potential | | | Available Amounts | | |
|---|---|---|---|---|---|---|
| | Timber | Biomass | Total | Timber | Biomass | Total |
| First Thinning | 0 | 1,526,346 | 1,526,346 | 0 | 1,345,625 | 1,345,625 |
| Second Thinning | 1,712,658 | 2,275,270 | 3,987,928 | 1,506,232 | 2,001,033 | 3,507,264 |
| Final Felling | 10,874,773 | 4,067,236 | 14,942,010 | 9,534,935 | 3,566,128 | 13,101,063 |
| Total | 12,587,431 | 7,868,852 | 20,456,283 | 11,041,167 | 6,912,785 | 17,953,952 |
| Annual | 209,791 | 131,148 | 340,938 | 184,019 | 115,213 | 299,233 |

## 5. Conclusions

This study extracted production forests and estimated the annual available amount of forest biomass resources under profitable forest management. Production forests were extracted as sub-compartments where expected revenues surpassed all costs, from planting to final harvesting, for a 60-year rotation. Iuchi (2004), Yoshioka and Sakai (2005), Yagi and Nakata (2007), Kamimura et al. (2009), Yamamoto et al. (2010), Yamaguchi et al. (2010), Kamimura et al. (2012), Aruga et al. (2013) and Nakahata et al. (2014) estimated only the supply potentials and available amounts of timber and forest biomass resources based on the current situation. This study could project future supply potentials and available amounts of forest biomass resources in order to plan power generation plants considering available amounts of forest biomass resources. Furthermore, Aruga et al. (2006ab), Kinoshita et al. (2009), Kinoshita et al. (2010), and Aruga et al. (2011) projected future supply potentials and available amounts of forest biomass resources, but did not consider regeneration expenses for the sustainability of forest management which this study included. Moreover, this study examined the most economical timber and forest biomass harvesting system temporally and spatially.

The model was then applied to Nasushiobara City and the Kanuma area in Tochigi Prefecture, Japan. As a result, the proportions of profitable sub-compartments without considering regeneration costs were higher than those considering regeneration costs. This is indicative of the current state of affairs of Japanese forestry, where many forest owners are unwilling to perform regeneration operations after final felling operations. Therefore, it is important to develop low-cost regeneration operations or to extend rotation ages by reducing the number of regeneration operations for sustainable forest management and hence sustainable use of forest biomass resources amid the current forestry situation in Japan. According to forest biomass harvesting, the number of profitable sub-compartments without biomass extraction was higher than that with normal extraction and lower than that with landing sales. Therefore, forest biomass harvesting contributed to economic balances under sustainable forest management with a certain system of biomass harvesting.

The most economical timber and forest biomass harvesting system for each sub-compartment was also determined in this study. Profitable sub-compartments increased by applying the most economical timber and forest biomass harvesting system to each sub-compartment. The annual amounts of available forest biomass resources largely exceed the annual demands of a 500 kW woody biomass power generation plant scheduled to be built in Nasushiobara City and a chip production factory in the Kanuma area, respectively.

This model could help forest planners consider biomass harvesting when establishing forest plans.

The proportion of profitable sub-compartments on large areas was higher than on small areas. Therefore, costs are expected to decrease by extending forestry-operation sites while merging sub-compartments. The Japan Forest Agency has implemented measures on »coordination and consolidation of forestry practices«. Such measures will ensure coordination among a number of small forest owners to conduct forestry practices on a large scale. In future studies, we intend to expand forestry-operation sites while merging sub-compartments in order to reduce the costs. The Japan Forest Agency has also implemented measures for long-term rotation management because revenues from final felling operations cannot cover regeneration costs under the current conditions. Extending the cutting ages is expected to increase revenues owing to an improvement in log prices. However, in the present study, the effects of changing log prices were not considered. Future studies will also address log prices along with log quality.

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