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Estimating Availability of Logging Residue using Forest Management Data at Aggregated Stands of the Takahara Area of Tochigi Prefecture, Japan

Kazuhiro Aruga*, Ryo Uemura
Utsunomiya University, Faculty of Agriculture, Utsunomiya 321-8505, Japan

Abstract

With the endpoint of securing a steady supply of logging residue, this study projects the supply potential and availability of logging residue by using 2005–2011 forest management records and 2012–2016 forest management plans for the Takahara area of Tochigi prefecture, Japan. Forest management plans do not list thinning methods (such as those of a precommercial or commercial variety); therefore, the relationship between stand ages and commercial thinning operation rates is analyzed using forest management records, and commercial thinning rates are estimated with stand ages. Trends vis-à-vis supply potential and logging residue availability between 2005 and 2016 are examined: the supply potential of logging residue from precommercial thinning operations significantly increased between 2009 and 2010, on account of a new tax levied in April 2008; on the other hand, a steady supply of logging residue is projected by using forest management plans. In forest management plans, it is assumed that precommercial and commercial thinning operations are conducted within the same subcompartments. Therefore, the profitability of subcompartments can be improved with commercial thinning operations, and the available logging residue amounts from precommercial thinning operations are estimated in forest management plans. Meanwhile, no available logging residue amounts from precommercial thinning operations are estimated through the use of forest management records. The available logging residue amounts of aggregated stands are increased; by aggregating stands, the stand areas can be increased to more than 6 ha and be made profitable, even with longer forwarding distances.

Keywords: Available amount, Forest management plan, Forest management record, Logging residue, Subsidy, Supply potential

1. Introduction

In July 2011, the Feed-in Tariff (FIT) Scheme for Renewable Energy Use was introduced in Japan, in accordance with new legislation entitled the Act on the Purchase of Renewable Energy-Sourced Electricity by Electric Utilities. Under the FIT program, electricity generated from woody biomass must be procured at a fixed price (without tax) for over 20 years for (a) unused materials such as logging residue (at USD 0.32/kWh), (b) general materials such as sawmill residue (at USD 0.24/kWh), and (c) recycled materials such as construction waste wood (at USD 0.13/kWh) (ANRE, 2012). Incentives have promoted the use of power generated from unused materials, and they are expected to promote the use of logging residue in the near future.

The price of USD 0.32/kWh for unused materials was determined based on a model plant featuring 5 MW of direct combustion and 60.000 ton/year of annual consumption. However, forest ownership in Japan is characterized by a large number of small, fragmented, and scattered forest owners (Forestry Agency of Japan, 2009). Therefore, it is difficult to supply the amount of 60,000 ton/year stably from such small, fragmented, and scattered forests. To promote the use of logging residue from these forests, the price of USD 0.40/kWh for unused materials for a power generation plant with less than 2 MW of direct combustion was set, starting from April 2015.

Nord-Larsen et al. (2004), Rørstad et al. (2010), and Aruga et al. (2006) 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. On the other hand, Uemura et al. (2013) investigated stands aggregated with subcompartments in the Takahara area of Tochigi prefecture, using subsidy applications and 2008 forest management records. The Takahara Forest Owners' Cooperative has aggregated subcompartments, established road networks, and promoted the mechanization of aggregated stands to improve

*Corresponding author: Tel: +81 286495544 E-mail: aruga@cc.utsunomiya-u.ac.jp
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operational efficiency and reduce operation costs. Uemura et al. (2013) have also estimated the annual availability of timber and logging residue for aggregated stands as the annual supply potential from profitable stands.

Furthermore, Uemura et al. (2015) estimated annual potential and availability and examined trends, using forest management records for several fiscal years between 2005 and 2010. The supply potential and availability of logging residue, particularly from precommercial thinning operations, significantly increased starting in 2009, owing to a tax newly initiated in April 2008 (Tochigi Prefectural Government, 2010a).

To help secure a steady supply of logging residue, this study projected the supply potential and availability of logging residue by using 2005–2011 forest management records and 2012–2016 forest management plans in the Takahara area of Tochigi prefecture, Japan. In the forest management plans, thinning methods (i.e., those of a precommercial or commercial variety) were not listed; therefore, the relationship between stand ages and commercial thinning operation rates were analyzed by using forest management records, and commercial thinning rates were estimated with stand ages. Then, trends vis-à-vis supply potential and the availability of logging residue between 2005 and 2016 were examined.

2. Materials and Methods

2.1. Study Site and Data

The study site is the Takahara area of Tochigi prefecture, Japan (Figure 1). The Takahara area consists of Yaita, Shiobara, Sakura, Shioya, and Takanezawa. Its gross area is 73,302 ha, of which 38,474 ha (52%) comprises forest area. It has 17,318 ha of national forests, and the total area of private and local government forests is 21,156 ha. Species in private and local government forests consist of Japanese cedar (8,073 ha; 38%), Japanese cypress (5,552 ha; 26%), other conifers (1,519 ha; 7%), broad-leaved species (5,971 ha; 28%), and bamboo (41 ha; 0.2%).

The area and number of subcompartments of private and local government forests (combined) are 21,156 ha and 49,823, respectively. These forests are almost 45–55 years old. Their average slope angle is rather low, at 23%, and their road network density is rather high, at 43.7 m/ha.

In this study, we use forest registration data (stand ages, tree species, stocks, etc.), geographic information system (GIS) data (information on roads and subcompartment layers), and forest management records (locations and rates of thinning operations) of the Tochigi Prefectural Government, as well as 10-m-grid digital elevation models (DEMs) from the Geographical Survey Institute. The data obtained from the Tochigi Prefectural Government were converted into 10-m-grid raster data, to render it consistent with the DEM data.

We used forest management records from 2005–2011 that were drawn from subsidy records. Therefore, no final felling operations unrelated to subsidies were included in the records. In this study, planting operations were assumed to occur the year after the final felling operations. Forest management records included between 1,269 and 2,255 (average of 1,813) subcompartments annually. However, only 77% of the forest management records successfully combined with forest registration and GIS data, and the combined forest management records included between 1,135 and 1,950 subcompartments each year (average of 1,398). Owing to data improvements, the combination rates for forest management records with forest registration data and GIS data increased from 66% in 2005 to 89% in 2011.

Precommercial thinning operation areas ranged from 143 to 536 ha/year (average of 271 ha/year); commercial thinning operation areas ranged from 118 to 573 ha/year (average of 364 ha/year), and final felling operation areas ranged from 8 to 32 ha/year (average of 23 ha/year) (Figure 2, Table 1). Because the forests were almost 45–55 years old, many thinning operations were conducted and very few final felling operations were conducted (Figure 3), owing to the low profitability of such operations after regeneration-related expenses in the current state of Japanese forestry (Aruga et al., 2013). Given delays in thinning operations—a serious problem for man-made forests in Japan—in April 2008, the Tochigi Prefectural Government introduced a new tax; as a result, precommercial thinning operations increased significantly from 2009 (Figure 2).

In addition, we referenced forest management plans from 2012 to 2016 that had been established by the Takahara Forest Owners' Cooperative. The Cooperative moved from forest operation plans to forest management plans just after the plan system changed, as the Cooperative had long-term operational contracts with forest owners. Sixteen forest management units ranged from 64 to 1,598 ha each. The total area and number of the subcompartments that related to the forest management plans were 11,118 ha and 28,951, respectively—thus representing 53% and 58% of the area and number of subcompartments of private and local government forests (combined). The number of forest management plans ranged from 1,023 to 1,379 (average of 1,186) subcompartments annually. The rates at which forest management plans with forest registration data and with GIS data were successfully combined ranged from 89% to 98% (average of 92%). The number of combined forest management plans included between 999 and 1,226 (average of 1,089) subcompartments annually.

Each area of thinning operations ranged from 376 to 421 ha/year (average of 403 ha/year), and final felling operation areas ranged from 2 and 11 ha/year each (average of 7 ha/year) (Figure 2, Table 1). Thinning methods (such as those of a precommercial or

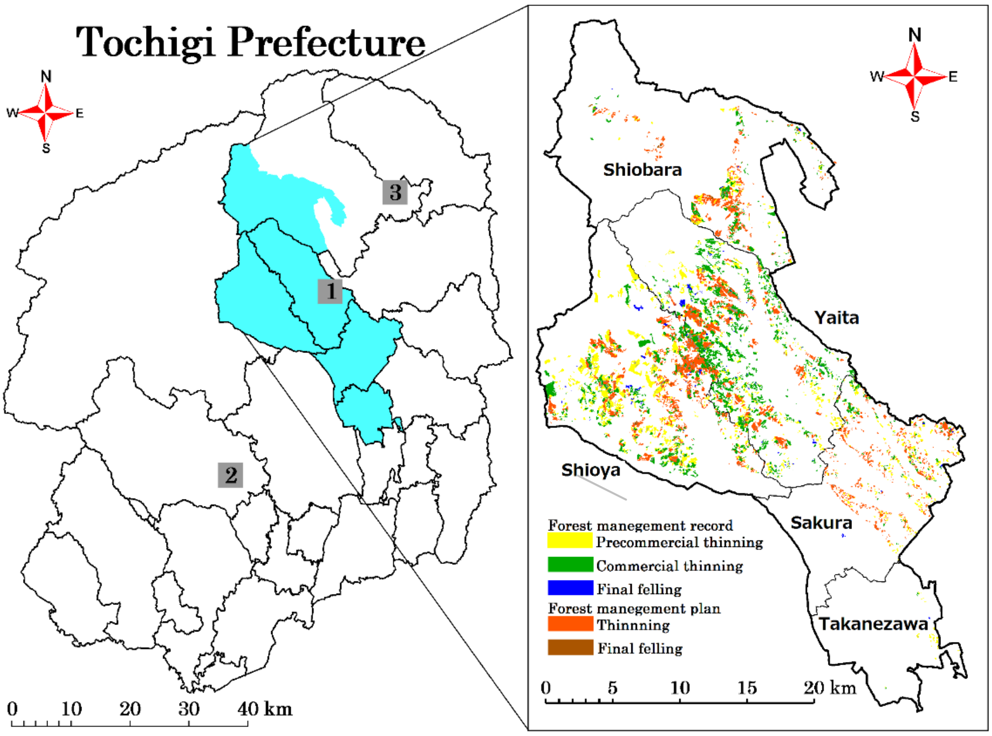

Figure 1. Distribution map of operation sites, log markets, and factories (1: Yaita log market, 2: Chip production factory in Kanuma city, 3: Pellet production factory in Nasushiobara city)

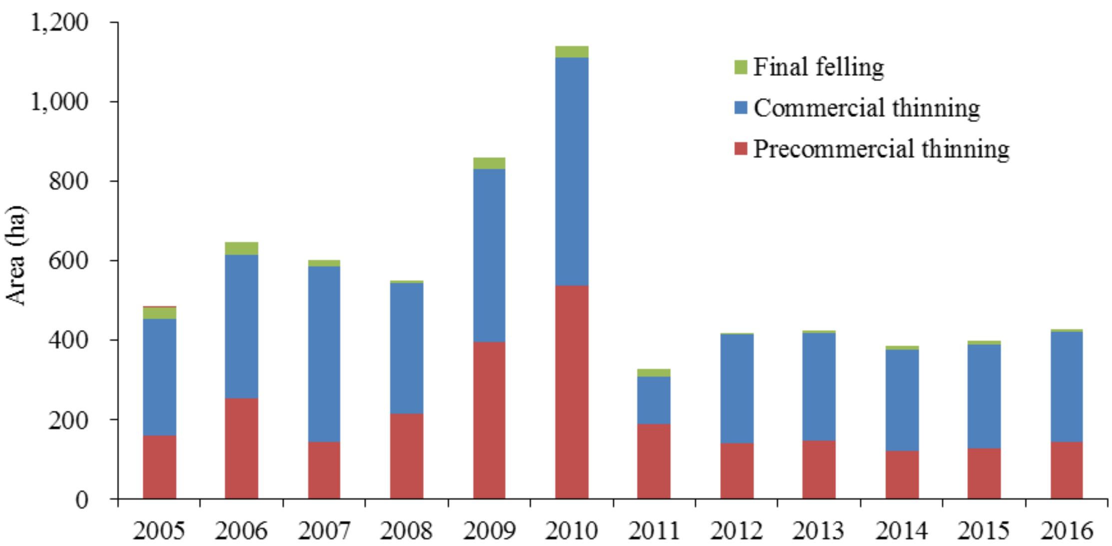

Figure 2. Area, in hectares, of three types of operation site

Table 1. Average areas in forest management records and plans

	Records		Plans		Total	
	Area (ha/year)	Ratio (%)	Area (ha/year)	Ratio (%)	Area (ha/year)	Ratio (%)
Precommercial thinning	271	41	136	33	215	39
Commercial thinning	364	55	267	65	323	58
Final felling	23	3	7	2	16	3
Total	657	100	411	100	554	100

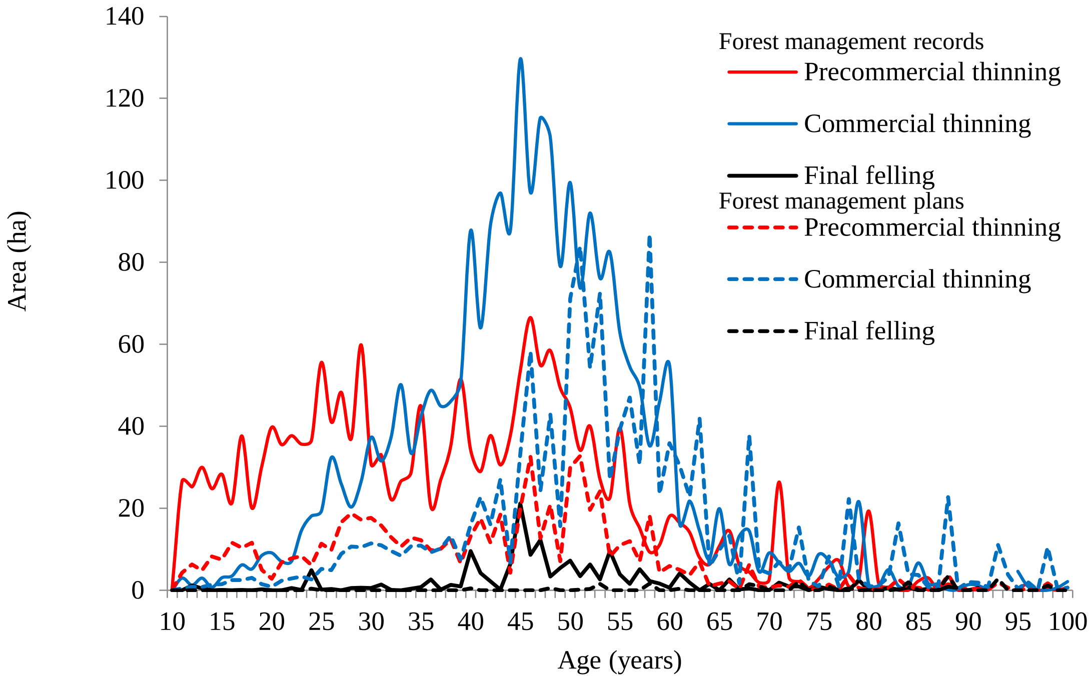

Figure 3. Frequency distribution of operation site areas

commercial variety) were not listed in forest management plans; therefore, the relationship between stand ages and commercial thinning operation rates were analyzed, and commercial thinning rates were estimated with stand ages (Figure 4). As a result, annual precommercial thinning operation areas ranged from 121 to 147 ha/year each (average of 136 ha/year), and those of commercial thinning ranged from 255 to 277 ha/year each (average of 267 ha/year) (Figure 2, Table 1).

The number and areas cited in the forest management plans were smaller than those in the forest management records, because forest management records included forest operations by logging companies other than the Takahara Forest Owners' Cooperative, and forest management plans did not include precommercial thinning operations promoted by the new tax. The number and areas of precommercial and commercial thinning operations, and the final felling operations in forest management plans, accounted for 71%, 75%, and 35% of forest management records from 2005 to 2008, respectively, prior to the increase in precommercial thinning operations by virtue of the new tax.

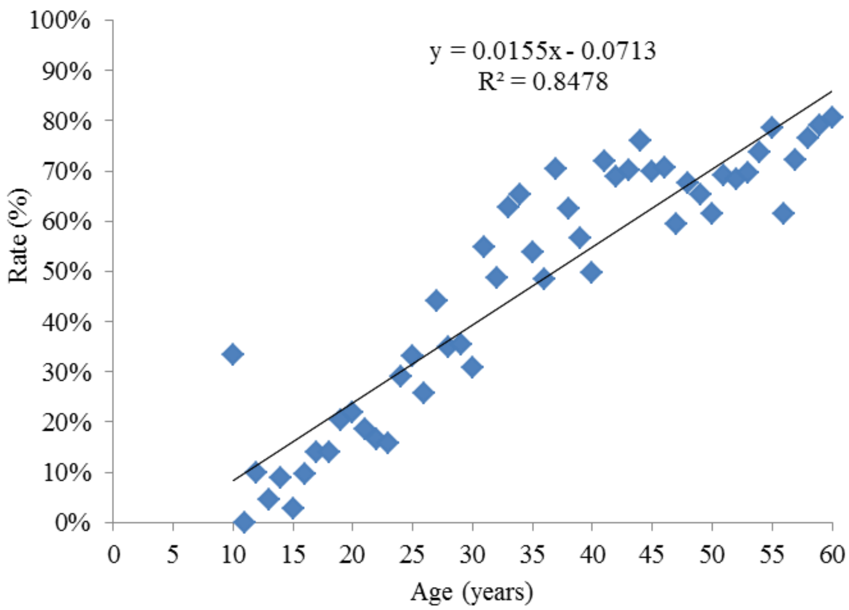

Figure 4. Forest ages and commercial thinning operation rates (2005–2011)

2.2. Methods

In this study, available logging residue amounts were projected, using the following steps: 1) the system-aggregated neighboring subcompartments were estimated (Uemura et al., 2013), 2) supply potentials were estimated on the basis of cutting and extraction rates, 3) forwarding and transportation distances were estimated, 4) total expenses incurred during thinning and final felling operations for each operation system were estimated, 5) incomes were estimated, with or without a subsidy, 6) profitability was estimated, and 7) available amounts were projected as supply potentials from profitable stands. Full technical details can be found in the literature (Yamaguchi et al., 2014a; Uemura et al., 2013; Uemura et al., 2015).

The system aggregated the adjacent subcompartments, with a total of 15,232 (1,269 annually) subcompartments being aggregated to 4,645 (387 annually) aggregated stands. The average area was increased from 0.44 ha for subcompartments to 1.43 ha for aggregated stands (Figure 5). In the forest management records, a total of 9,789 (1,398 annually) subcompartments were aggregated to 2,950 (421 annually) aggregated stands. The average area was increased from 0.47 ha for subcompartments to 1.56 ha for aggregated stands. In the forest management plans, a total of 5,443 (1,089 annually) subcompartments were aggregated to 1,695 (339 annually) aggregated stands. The average area was increased from 0.38 ha for subcompartments to 1.21 ha for aggregated stands.

Estimation of the supply potential of timber and logging residue was based on the cutting rate (*Cr*), extraction rate (*Er*), timber rate (*Tr*), and logging residue rate (*Lr*). The cutting rate (*Cr*) was 100% of the final felling operations and the thinning ratio of each subcompartment in the forest management records and plans. The extraction rate (*Er*)—the ratio of the extracted volume to the felled tree volume (stocks of stems)—was assumed to be 123% and 124% for Japanese cedar and Japanese cypress (Greenhouse Gas Inventory Office of Japan, 2006), respectively, considering branch extractions. The timber rate (*Tr*) is the ratio of the timber to be transported to log markets to the total felled and extracted tree volume, whereas the logging residue rate (*Lr*) is the ratio of the logging residue to be transported to the factories to the total felled and extracted tree volume. *Tr* and *Lr* are 10% and 90% of the stocks in precommercial thinning operations, respectively; each represented 50% of the stocks in the thinning operation, and 75% and 25% of the stocks in the final felling operations, respectively.

The Yaita log markets and two factories in Tochigi prefecture were assumed to be the destinations of timber and logging residue (Figure 1). The chip production factory in Kanuma city produced 12,000 m^3 of chips each year, and the annual demand for raw materials at the pellet plant in Nasushiobara city was 3,000 tons (Yamaguchi et al., 2014a). Forwarding distances were estimated as the average distances from landings to all grids within the subcompartments; landings were set within the grids so as to minimize their distance from the roads, the centers of gravity in the subcompartment, and factories. Transportation distances from the landings to the Yaita log market and the factories were calculated through the use of the shortest path algorithm (i.e., the Dijkstra method) (Dijkstra, 1959).

The direct and indirect operation expenses associated with each machine, as well as strip road and landing establishment expenses, were estimated. Direct expenses included labor and machinery expenses (maintenance, management, depreciation, and fuel and oil expenses). Machine transportation expenses, garage maintenance expenses, overhead costs, handling fees associated with the log market, and consumption tax were considered indirect operation expenses (Zenkoku Ringyo Kairyo Fukyu Kyokai, 2001).

Revenue was estimated using supply potential and log prices for Japanese cedar and other species (USD 100.00/m^3), Japanese cypress (USD 200.00/m^3), and logging residue (USD 30.00/ton). Besides, two unit prices were assumed for each of Japanese cedar and other species (USD 80.00/m^3 and USD 120.00/m^3), Japanese cypress (USD 160.00/m^3 and USD 240.00/m^3), and logging residue (USD 60.00/ton and USD 100.00/ton). A logging residue price of USD 60.00/ton was assumed with additional subsidies, and price of USD 100.00/ton was assumed if FITs had been introduced in Japan.

For thinning operations, subsidies were received in Japan; these subsidies (Table 2) were estimated using standard unit costs, areas, assessment coefficients, and the subsidy rate of the Tochigi Prefectural Government (2010b). Standard unit costs were determined on the basis of age and thinning rate. The assessment coefficient and the subsidy rate were assumed to be 1.7 and 4/10, respectively.

A new subsidy system was initiated in 2011. The subsidy offered through the new system was received for thinning in operation areas larger than 5 ha and with extracted volumes exceeding 10 m^3/ha. To promote the extraction of thinned wood, subsidies were increased in line with the extracted volumes (Table 3).

In Japan, subcompartments with subsidized thinning operations also received subsidies for the establishment of strip roads. Standard unit costs for the establishment of strip roads were determined using the average slope angle (degrees) and the road width. Then, subsidies (Table 4) were estimated using standard unit costs, length, assessment coefficients, and the subsidy rate of the Tochigi Prefectural Government (2010b). Again, the assessment coefficient and the subsidy rate were assumed to be 1.7 and 4/10, respectively.

After estimating the economic balances from revenue and costs, production forests were extracted as profitable stands. Then, the availability of timber and logging residue was estimated by using the supply potential of the profitable stands.

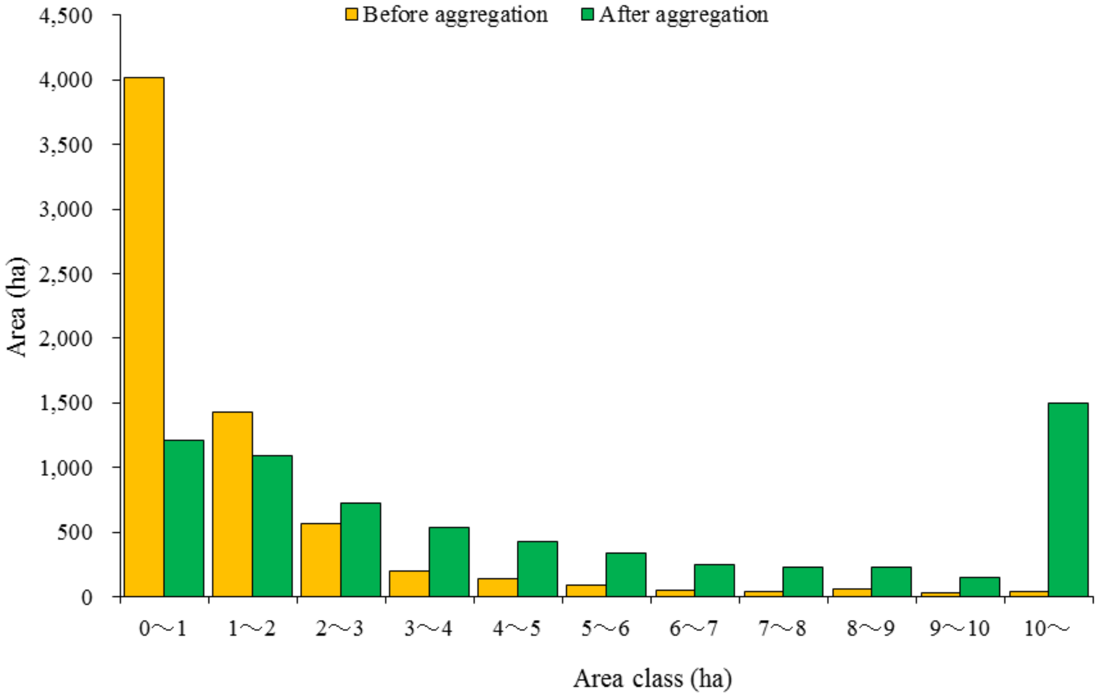

Figure 5. Areas before and after aggregation

Table 2. Subsidies for thinning operations before 2011 (USD/ha)

Thinning ratio	Stand age (years) <15	16–25	26–35	36–45	46–60
20%	2,047.35	2,355.04	2,369.90	2,254.57	2,283.48
30%	3,077.88	3,529.10	3,551.45	3,381.88	3,425.20

Table 3. Subsidies for thinning operations after 2011 (USD/ha)

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

Table 4. Subsidies for strip road establishment (USD/m)

Average slope angle	Width 2.5 m	3.5 m
Gradual (<15 degrees)	1.02	1.53
Medium (15–30 degrees)	2.03	3.58
Steep (>30 degrees)	5.01	12.62

3. Results and Discussion

3.1 Supply Potentials

The supply potentials of timber and logging residue were 18,783 m^3/year and 23,191 tons/year, of which 7% (1,403 m^3/year) and 46% (10,731 tons/year) were from precommercial thinning operations, 72% (13,574 m^3/year) and 49% (11,393 tons/year) were from commercial thinning operations, and 20% (3,805 m^3/year) and 5% (1,067 tons/year) were from final felling operations (Figure 6, Figure 7). Because the forests were almost 45–55 years old, many thinning operations had been conducted (Table 1); therefore, the supply potentials of timber and the logging residue of commercial thinning operations were the highest. The supply potentials of timber from final felling operations were higher than those from precommercial thinning operations, although very few final felling operations had been conducted.

The supply potentials of timber and logging residue in the forest management plans were lower than those in the forest management records, because the latter included forest operations in this area by logging companies other than the Takahara Forest Owners' Cooperative, and because forest management plans did

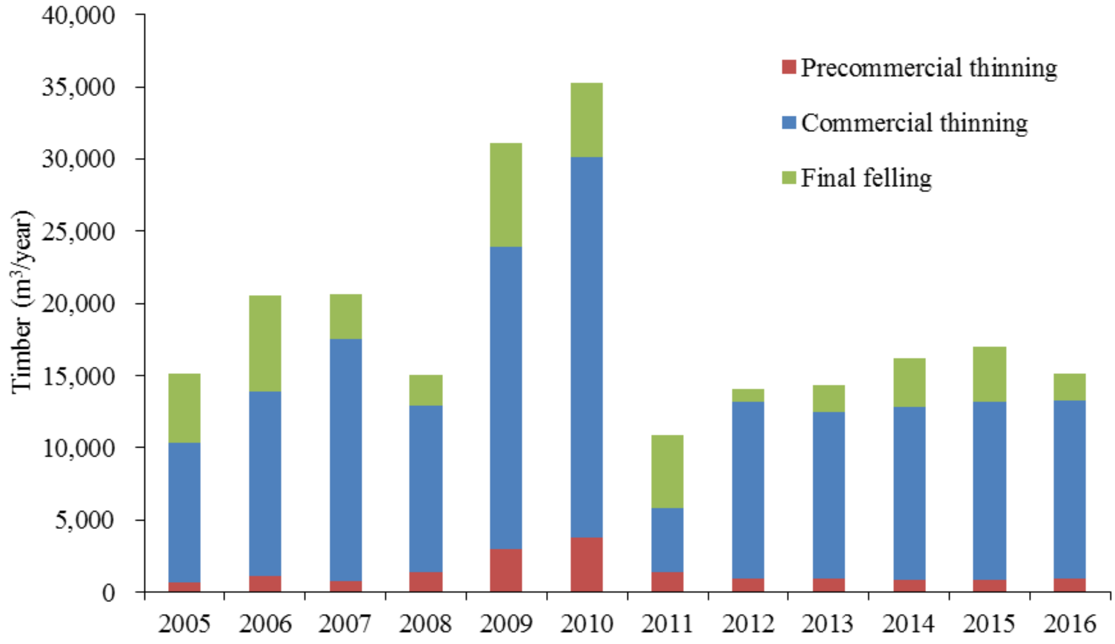

Figure 6. Supply potentials of timber (2005–2016)

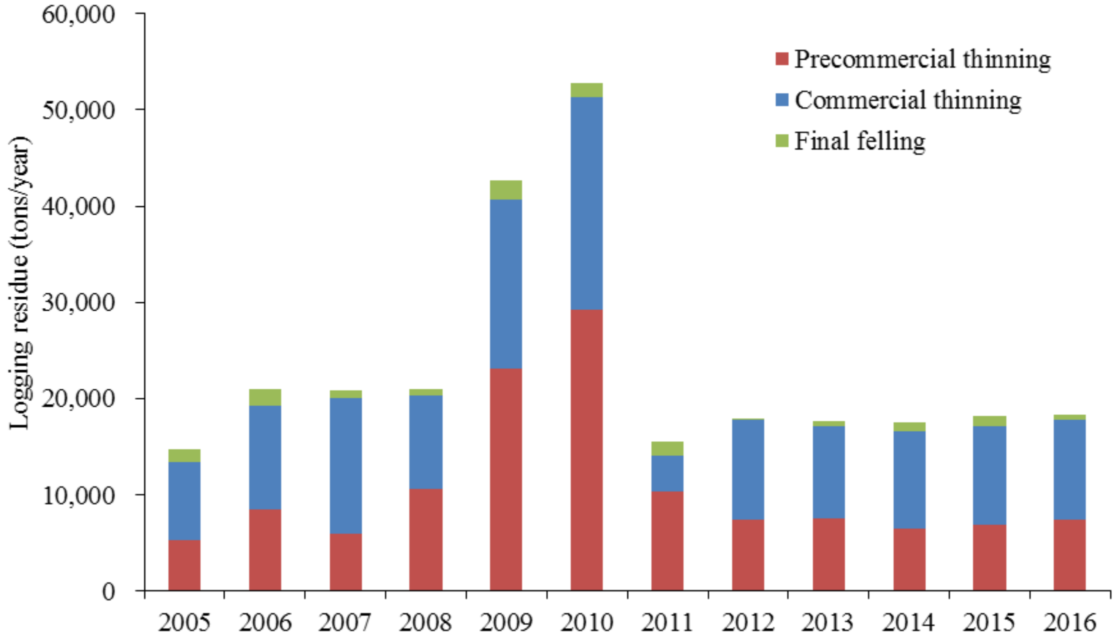

Figure 7. Supply potentials of logging residues (2005–2016)

not include precommercial thinning operations promoted by the new tax. The supply potentials of timber and the logging residue in the forest management plans were 86% and 92% of those in the forest management records, respectively, from 2005 to 2008—the period before precommercial thinning operations were increased by virtue of the new tax.

3.2 Available Amounts without Subsidy

The available logging residue amounts from profitable subcompartments with a price of USD 100.00/m^3 for Japanese cedar and other species, USD 200.00/m^3 for Japanese cypress, and a USD 30.00/ton logging residue price without subsidy were 299 tons/year; of this, 1% (2 tons/year) were from precommercial thinning operations, 14% (39 tons/year) were from commercial thinning operations, and 86% (249 tons/year) were from final felling operations (Figure 8). Precommercial thinning operations accounted for 46% of the supply potential of logging residue; however, the available amounts of logging residue from precommercial thinning operations occupied only 1%; almost all available logging residue amounts were from final felling operations.

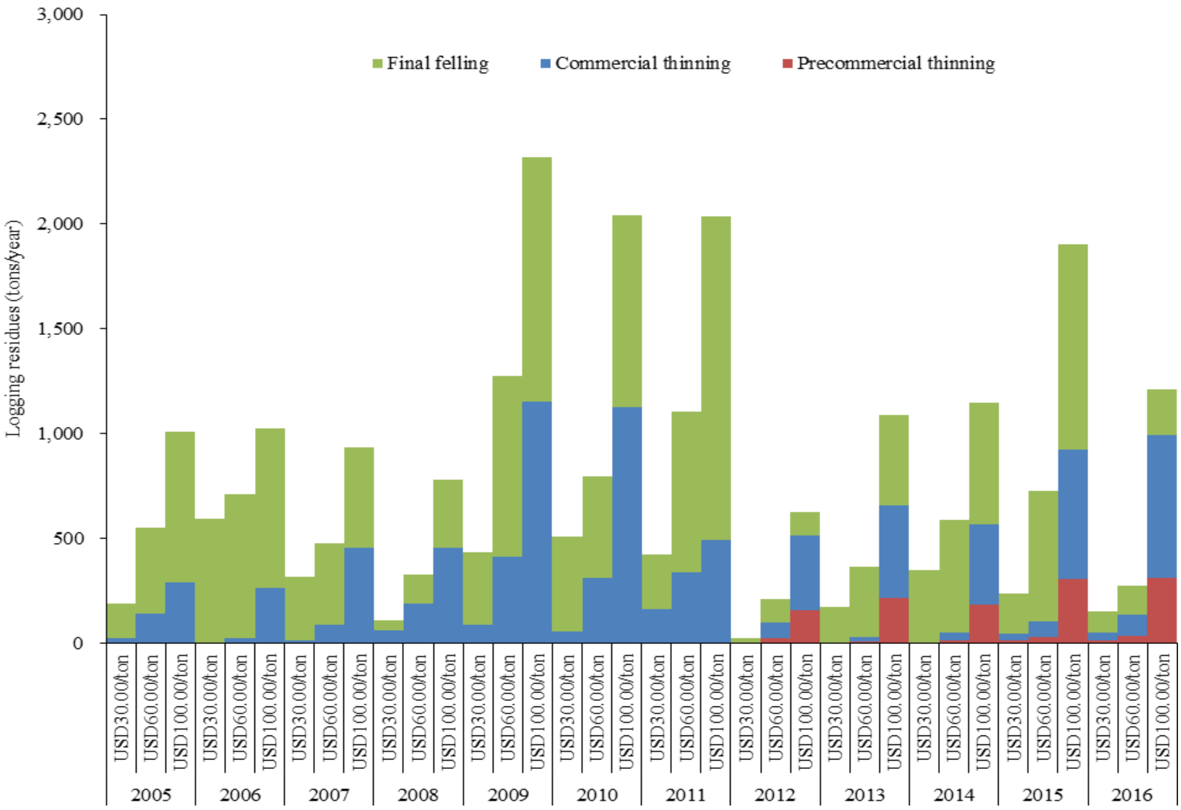

Figure 8. Available amounts of logging residues (with the price of Japanese cedar and other species being USD 100.00/m^3, that of Japanese cypress being USD 200.00/m^3, and without subsidy) in profitable subcompartments

In forest management plans, thinning methods such as those of a precommercial or commercial variety were not listed, and in this study, commercial thinning rates were estimated by using stand ages. It was assumed that precommercial and commercial thinning operations were conducted within the same subcompartments. Therefore, the profitability of subcompartments was improved as a result of commercial thinning operations, and the available logging residue amounts from precommercial thinning operations were estimated in the forest management plans—whereas no available logging residue amount from precommercial thinning operations were estimated in the forest management records. The available logging residue amounts had increased in line with logging residue prices.

The available logging residue amounts were increased for aggregated stands (Figure 9). In particular, the available logging residue amounts from precommercial thinning operations were estimated for aggregated stands, whereas in the forest management records, no available logging residue amount from precommercial thinning operations were estimated for subcompartments.

3.3 Available Amounts with Subsidy

The available logging residue amounts from profitable aggregated stands with a price of USD 100.00/m^3 for Japanese cedar and other species, USD 200.00/m^3 for Japanese cypress, USD 30.00/ton for logging residue, and subsidies were 6,812 tons/year; of this, 30% (2,077 tons/year) were from precommercial thinning operations, 63% (4,286 tons/year) from commercial thinning operations, and 7% (449 tons/year) from final felling operations (Figure 10). The available logging residue amounts were increased with a subsidy. In particular, the available logging residue amounts from precommercial thinning operations were increased in forest management plans, because the profitability of subcompartments were improved with commercial thinning operations.

The available logging residue amounts with unit prices of logging residue of USD 30.00, USD 60.00, and USD 100.00/ton were increased to 6,812 tons/year, 11,150 tons/year, and 16,655 tons/year, respectively. Additionally, the ratios of the available amounts to supply potentials with logging residue unit prices of USD 30.00, USD 60.00, and USD 100.00/ton were increased to 29%, 48%, and 72%, respectively. The increases in the logging residue unit prices of USD 30.00, USD 60.00, and USD 100.00/ton were 16, 12, and 8 times the available amounts without a subsidy, respectively.

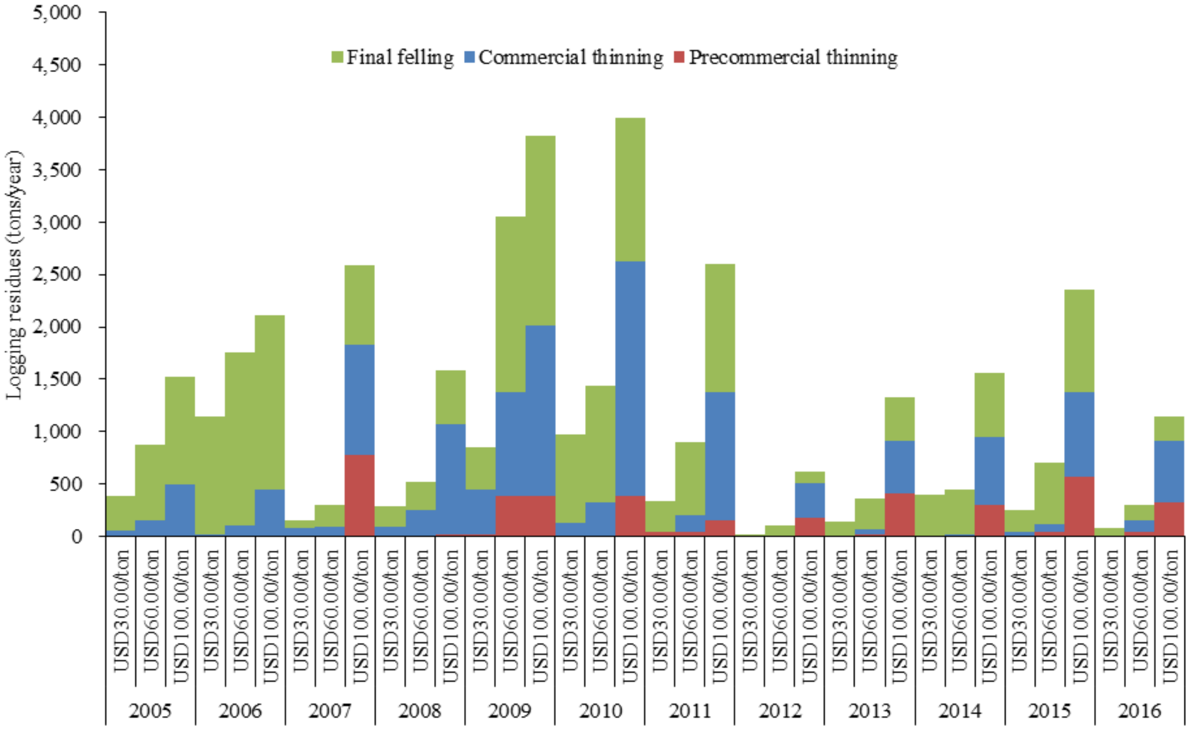

Figure 9. Available amounts of logging residues (with the price of Japanese cedar and other species being USD 100.00/m^3, that of Japanese cypress being USD 200.00/m^3, and without subsidy) in profitable aggregated stands

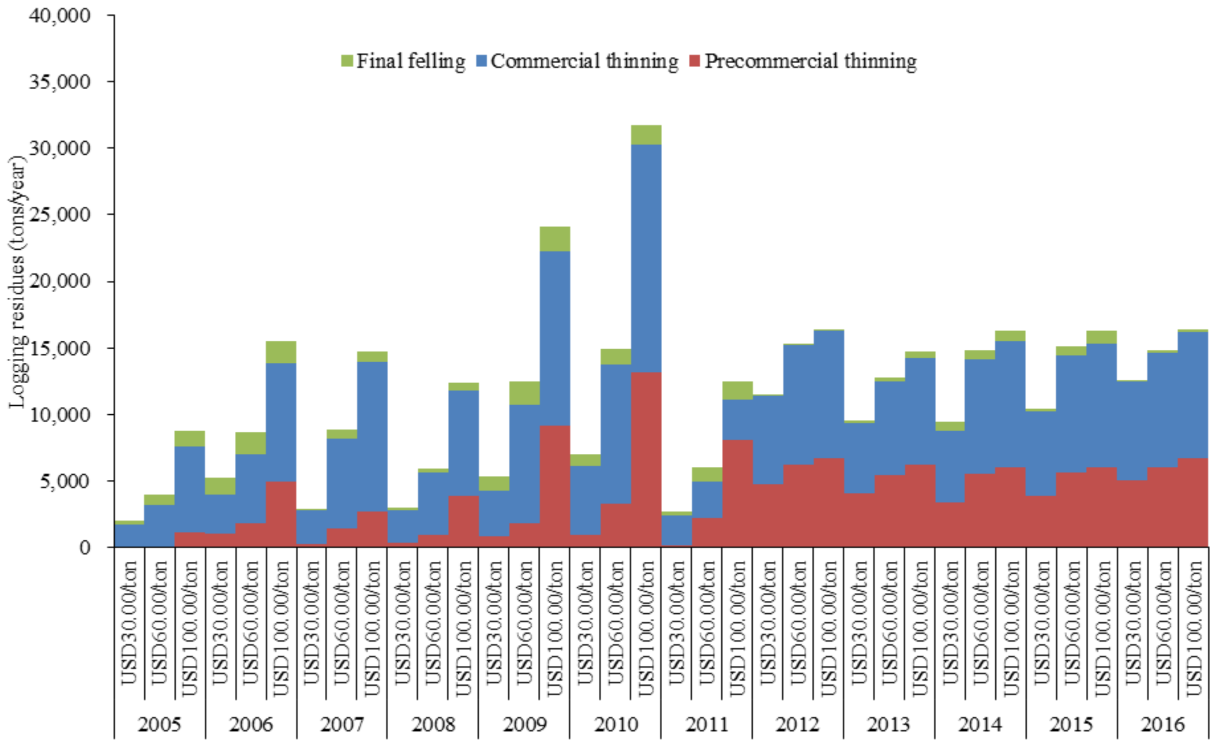

Figure 10. Available amounts of logging residues (with the price of Japanese cedar and other species being USD 100.00/m^3, that of Japanese cypress being USD 200.00/m^3, and with subsidy) in profitable aggregated stands

The available logging residue amounts were increased in line with timber prices (Figures 11 and 12). In particular, the available logging residue amounts from final felling operations increased, because the supply potentials of timber from final felling operations were greater than those from thinning operations. Almost all logging residue values from final felling operations were estimated as the available amounts bearing a price of USD120.00/m^3 for Japanese cedar and other species, USD240.00/m^3 for Japanese cypress, USD100.00/ton for logging residue, and subsidy.

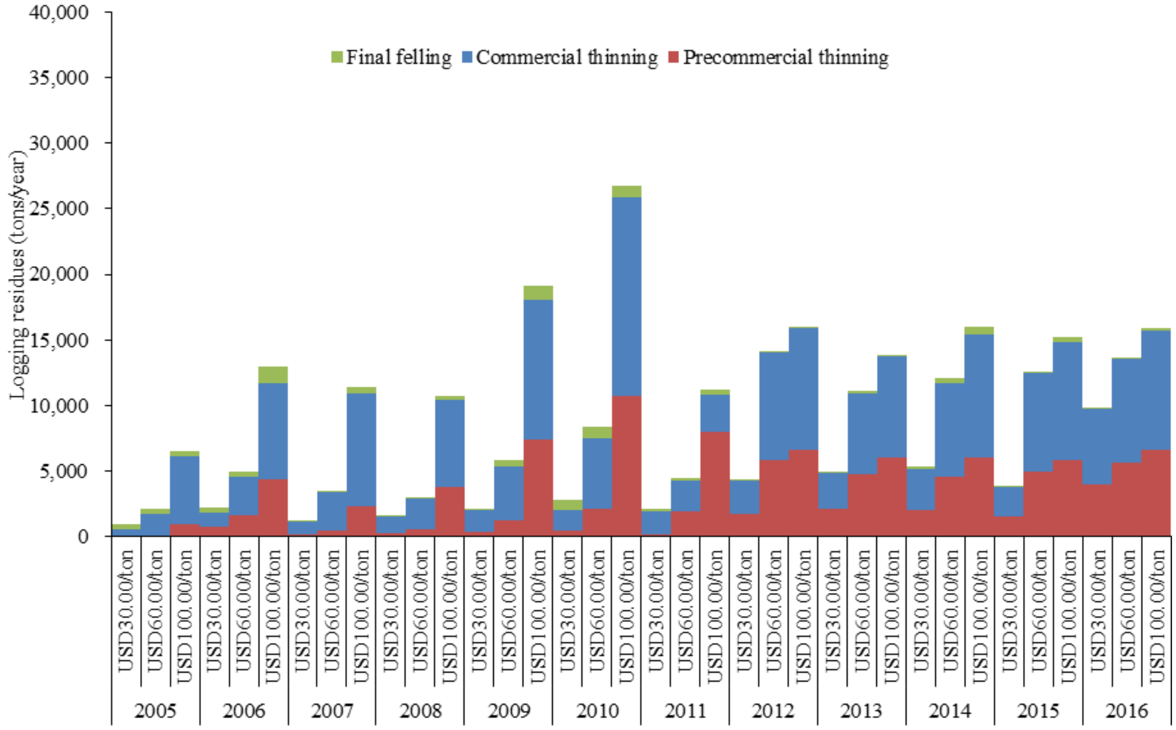

Figure 11. Available amounts of logging residues (with the price of Japanese cedar and other species being USD 80.00/m^3, that of Japanese cypress price being USD 160.00/m^3 and with subsidy) in profitable aggregated stands

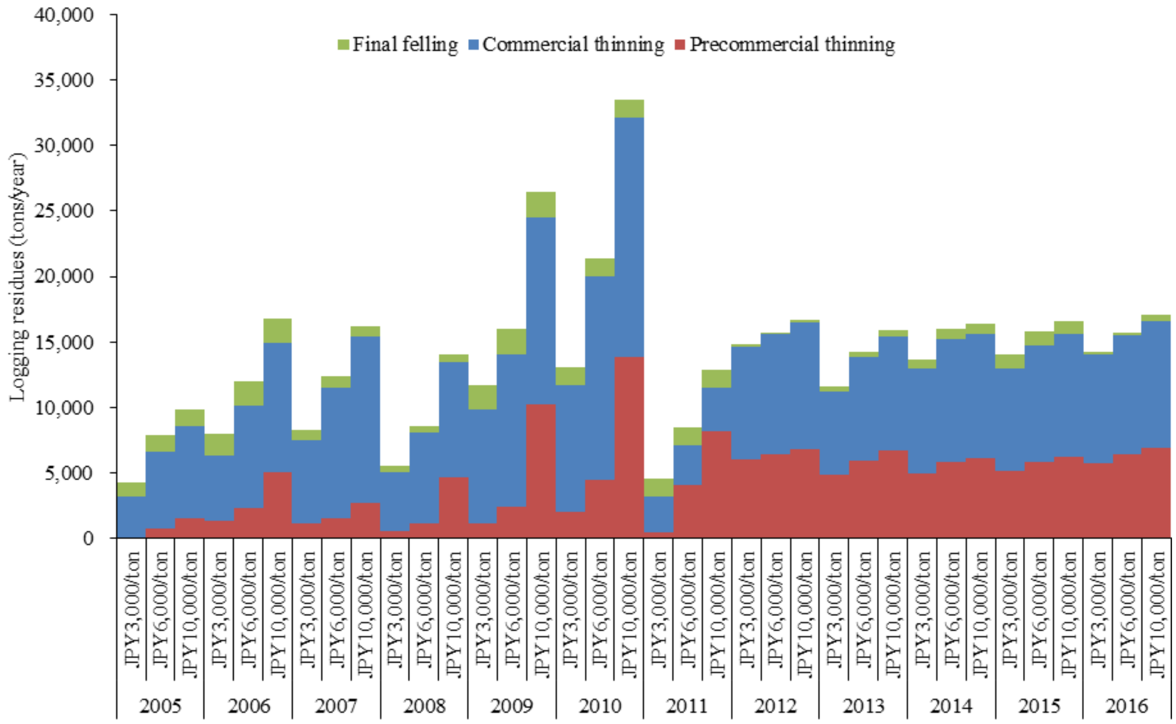

Figure 12. Available amounts of logging residues (with the price of Japanese cedar and other species being USD 120.00/m^3, that of Japanese cypress being USD 240.00/m^3, and with subsidy) in profitable aggregated stands

3.4 Effects of Stand Conditions on Profitability of Aggregated Stands

Profitable aggregated stands without a subsidy mainly consisted of final felling operations. The profitable aggregated stands of thinning operations were increased with subsidies. The most effective stand conditions were those pertaining to terrain slope angle: a relatively gentle terrain causes a higher rate of profitable aggregated stands (RPAS) because extraction costs as well as strip road establishment costs were reduced (Figure 13).

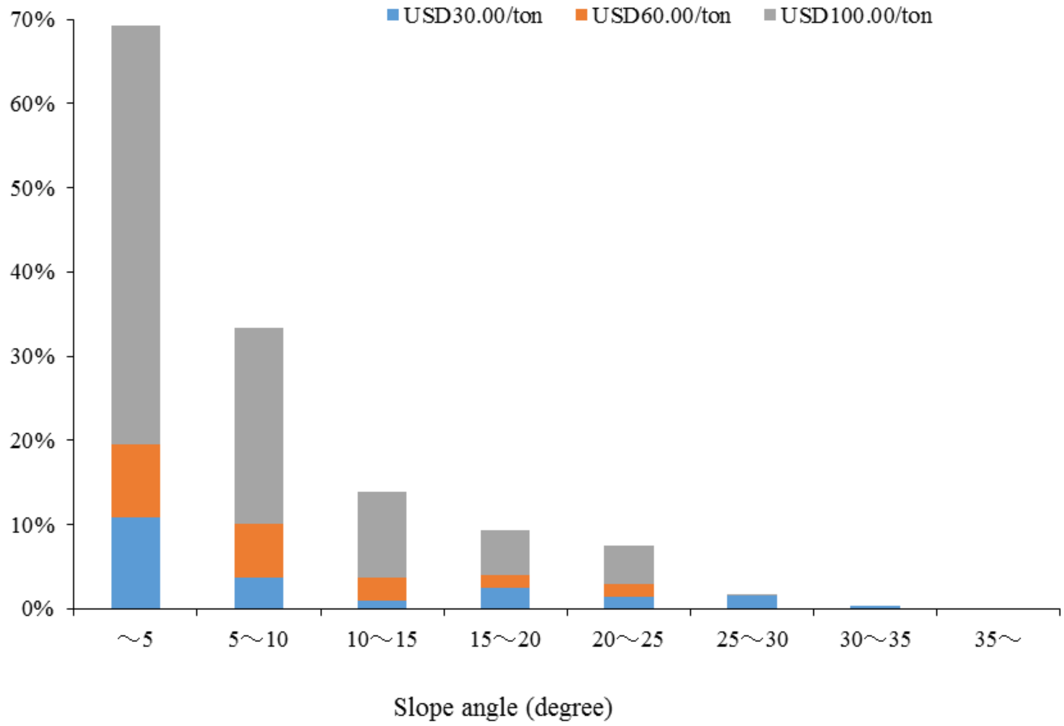

Figure 13. Rate of profitable aggregated stands, according to slope angle (with the price of Japanese cedar and other species being USD 100.00/m^3, that of Japanese cypress being USD 200.00/m^3, and with subsidy)

Larger areas were expected to have increased RPAS values, and because all costs included indirect costs (which were almost all fixed costs), the larger the volumes were, the lower the costs would be. However, RPASs were reduced until an area of 6 ha was reached, because in the current study, forwarding distances were estimated as average distances from the landings to all grids within the aggregated stands, and larger areas tended to have longer forwarding distances and subsequently higher forwarding costs (Figure 14, Figure 15). In Yamaguchi et al. (2014b), nearly profitable subcompartments were smaller than 4 ha, because almost all subcompartments were smaller than 5 ha to begin with. By aggregating stands, the number of stand areas larger than 6 ha was increased, and we found that those stands were profitable, even with longer forwarding distances.

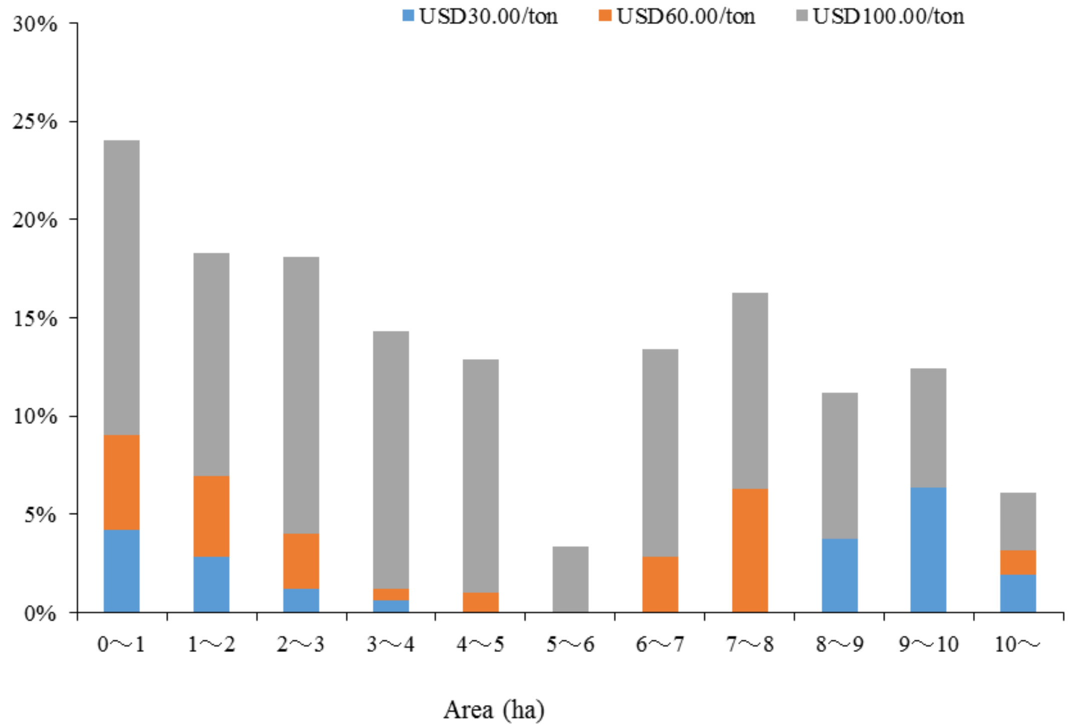

Figure 14. Rate of profitable aggregated stands, according to area (with the price of Japanese cedar and other species price being USD 100.00/m^3, that of Japanese cypress being USD 200.00/m^3, and with subsidy)

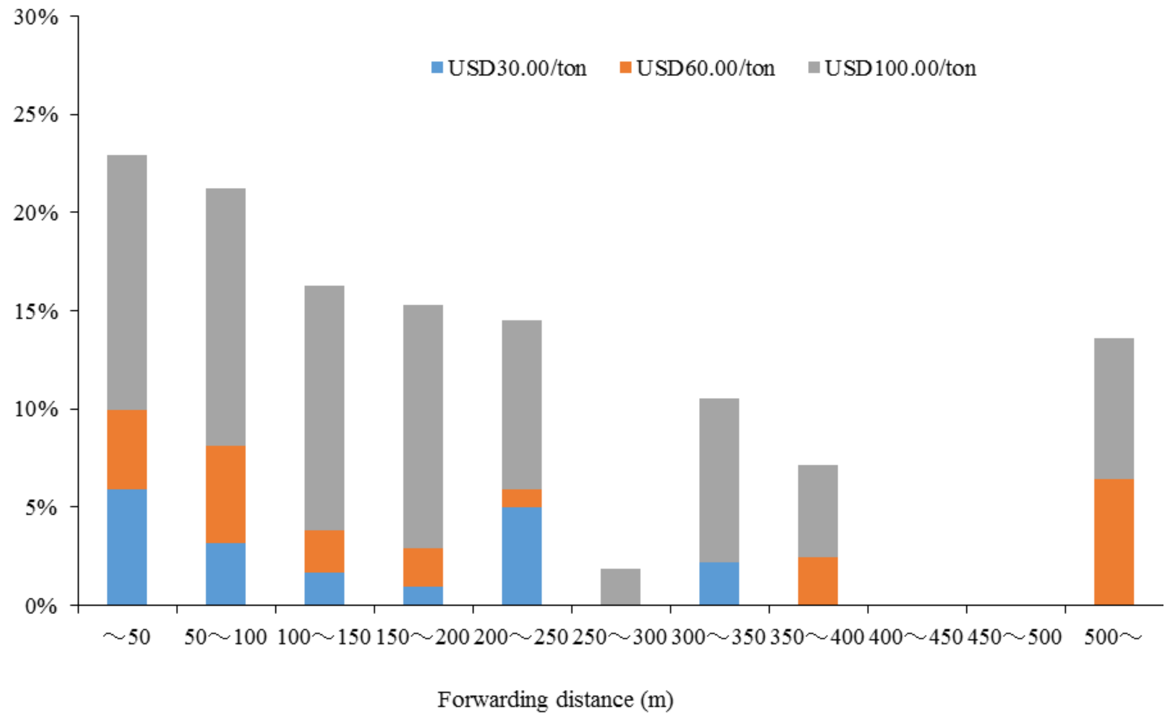

Figure 15. Rate of profitable aggregated stands, according to forwarding distance (with the price of Japanese cedar and other species being USD 100.00/m^3, that of Japanese cypress being USD 200.00/m^3, and with subsid

The RPAS was found to change in accordance with transportation distance (Figure 16, Figure 17). Aggregated stands were profitable until a 25-km and 35-km transportation distance was reached for timber and for logging residue with a USD 30.00/ton logging residue price, respectively. Profitable aggregated stands with a transportation distance exceeding 30 km for timber tended to have larger areas (i.e., about 40 ha).

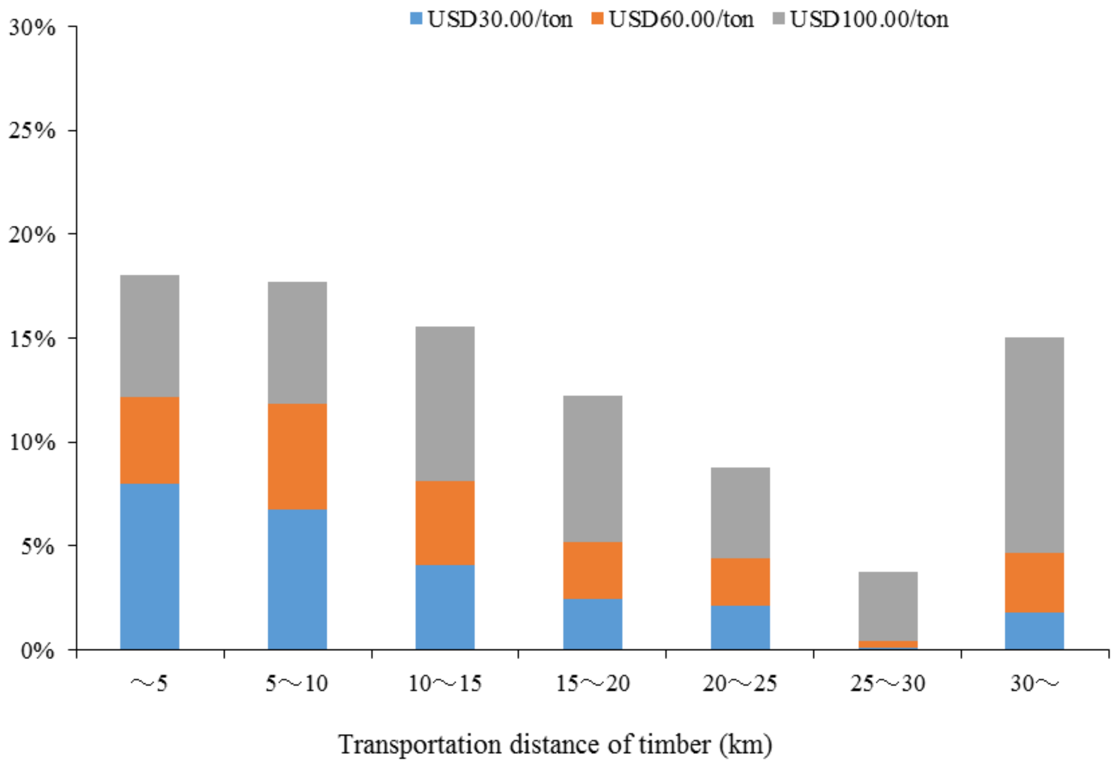

Figure 16. Rate of profitable aggregated stands, according to transportation distance of timber (with the price of Japanese cedar and other species being USD 100.00/m^3, that of Japanese cypress being USD 200.00/m^3, and with subsidy)

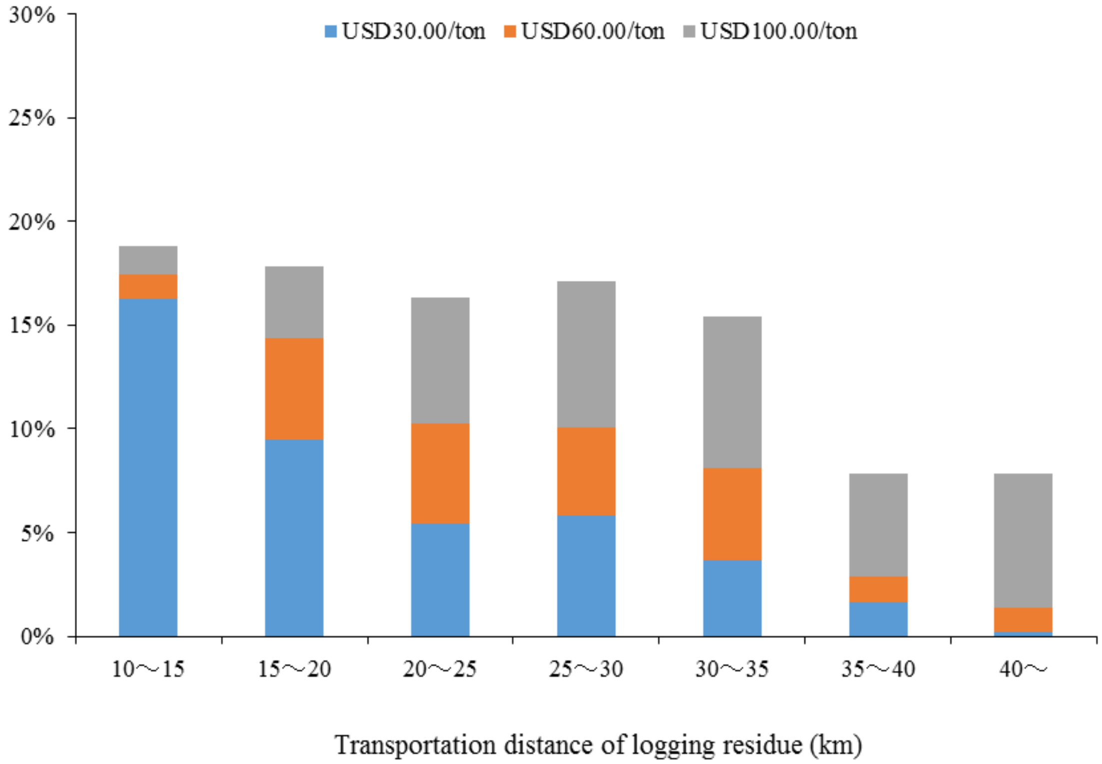

Figure 17. Rate of profitable aggregated stands, according to transportation distance of logging residue (with the price of Japanese cedar and other species being USD 100.00/m^3, that of Japanese cypress being USD 200.00/m^3, and with subsidy)

4. Conclusion

With the endpoint of helping to secure a steady supply of logging residue, this study projected the supply potential and availability of logging residue by using 2005–2011 forest management records and 2012–2016 forest management plans from the Takahara area of Tochigi prefecture, Japan. In the forest management plans, thinning methods (such as those of the precommercial or commercial variety) were not listed; therefore, the relationship between stand ages and commercial thinning operation rates were analyzed using forest management records, and commercial thinning rates were estimated with stand ages.

We then examined trends in the supply potential and availability of logging residue between 2005 and 2016. The supply potential of logging residue from precommercial thinning operations significantly increased between 2009 and 2010, because of a tax newly levied in April 2008; meanwhile, through the use of forest management plans, we projected a steady supply of logging residue. The supply potentials of timber and logging residue as per the forest management plans were lower than those as per the forest management records, because the latter included forest operations by logging companies other than the Takahara Forest Owners' Cooperative, and because forest management plans did not include precommercial thinning operations promoted by the new tax. Furthermore, the combination rates of the forest management records and plans with forest registration data and GIS data were 77% and 92%, respectively; therefore, the supply potentials could have been underestimated. These reductions should be considered when supply potentials and available amounts are used in energy facility plans.

Logging residue from precommercial thinning operations accounted for 46% of the supply potential; however, the available amounts of logging residue from precommercial thinning operations accounted for only 1%. Almost all available logging residue amounts were from final felling operations. In forest management plans, precommercial and commercial thinning operations are assumed to be conducted within the same subcompartments. Therefore, the profitability of subcompartments were improved through the use of commercial thinning operations, and the amounts of available logging residue from precommercial thinning operations were estimated in forest management plans, whereas no such data were estimated in forest management records.

The available logging residue amounts were increased for aggregated stands. In particular, in forest management records, the available logging residue amounts from precommercial thinning operations were estimated for aggregated stands, whereas no such figures were estimated for subcompartments. Yamaguchi et al. (2014b) found that nearly profitable subcompartments tended to be smaller than 4 ha, as almost all subcompartments were already smaller than 5 ha. By aggregating stands, areas larger than 6 ha each were increased in size, and those stands were made profitable even with the longer forwarding distances discussed in this study.

The available logging residue amounts were increased in line with both logging residue prices and timber prices. Therefore, the use of optimized bucking methods that generate the most profitable timber and logging residue sales would be important to increasing the available logging residue amounts. A new subsidy system initiated in 2011—by which subsidies were increased, according to extracted volumes—could help increase available logging residue amounts.

The Nakagawa biomass power generation plant established in 2014 consumes 50,000 tons of biomass per year, of which 70% is expected from logging residue. To maintain a steady supply of logging residue, a satellite yard was established in Yaita city. The Nakagawa biomass power generation plant bought logging residue at a satellite yard, at prices identical to those at the plant. The transportation distances of logging residue to a satellite yard have been significantly reduced, compared to those related to the chip production factory in Kanuma city and the pellet plant in Nasushiobara city. The reduction of such distances could also increase the available logging residue amounts.

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