Development of a model to estimate annual supply potentials and available amounts of logging residues from profitable sub-compartments in Tochigi prefecture, Japan using forest management records

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Abstract:
In this study, the annual supply potentials and available amounts of logging residues from profitable sub-compartments for all cities and towns in the Tochigi prefecture were estimated using forest management records. Three factories in Sano city, Kanuma city, and Nasu-shiobara city in the Tochigi prefecture were assumed as destinations for the raw materials, and forest operation systems were set based on forestry cooperatives. Annual available amounts of logging residues from profitable sub-compartments were estimated as 581 tons, based on the price of logging residues in this area: 3000 yen/ton. If a feed-in tariff (FIT) is established, the price of logging residues would be 10 000 yen/ton and the annual available amounts of logging residues from profitable sub-compartments would be 134 198 tons/year, which is almost equal to the demands of this area. 1 euro = 110 yen on 02.15.2011.

Keywords: annual supply potential, annual available amount, logging residues, forest management records, forest operation system

1 Introduction

In the Tochigi prefecture, there are facilities such as biomass power plants, chip production factories, and pellet plants which need woody biomass resources. These resources are mainly supplied by sawmill residues and construction waste woods. However, there are worries about the adequacy of supplies of these materials because the number of entrepreneurs who have set up biomass power plants as a measure against climate change has increased. Therefore, unused materials such as logging residues must be used in near the future. In addition, the area of Tochigi prefecture measures 640 785 ha, out of which about 54.5% is covered by forests (Tochigi Prefectural Government, 2009). About a half of these forests are man-made (44.9%), and their volume is 42 255 000 m^3 (62.4%). Because of delays in thinning, which was a serious problem for these man-made 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 2010). As a result, thinning operations were conducted on 2 663 ha in 2009, but almost all the thinning operations conducted were pre-commercial. Therefore, a large amount of thinned woods were left in the forests.

Iuchi (2004) and Kamimura et al. (2009) have developed techniques to estimate the supply potential of woody biomass, including logging residues, sawmill residues, and construction waste woods, in terms of the energy in the region as a unit of cities and towns. Yoshioka et al. (2005) and Kinoshita et al. (2009) have developed techniques to estimate the harvesting volumes and costs of logging residues in the region as units of sub-compartments, which were the conventional forest management units in Japan, whereas Yagi et al. (2007) and Yamamoto et al. (2010) have developed techniques that express them as units of kilometers of mesh or cities and towns. Aruga et al. (2006a) have developed a technique to estimate the harvesting volumes and costs of both timber and logging residues in the region as units of sub-compartments. Furthermore, Yamaguchi et al. (2010) have developed a technique to estimate the harvesting volumes and costs of logging residues considering the economic balances estimated from revenues and costs of both timber and logging residues in the region as a unit of sub-compartments, whereas Kinoshita et al. (2010) have developed a technique to express them as a unit of cities and towns. Moreover, Aruga et al. (2006b) have developed a technique to optimize forest biomass resource allocation to multiple plants in the region as a unit of sub-compartments, whereas Ranta (2005) and Möller et al. (2007) have developed a technique to express it at a national level.

In this study, the annual supply potentials and available amount of logging residues **from profitable sub-compartments** for all cities and towns in the Tochigi prefecture were estimated by considering three factories, in Sano city, Kanuma city, and Nasu-shiobara city, in the Tochigi prefecture as different locations. A previous study (Yamaguchi et al., 2010) estimated the volumes and costs for the whole city of Sano, but this study estimates volumes and costs using forest management records. This could enable the estimation of volumes and costs based on actual forest operations in the area.

2 Study Site and Materials

The study site is a man-made forest of Japanese cedar (Sugi) and cypress (Hinoki) where thinning operations were conducted in 2008 according to forest management records in 19 cities and towns out of 27 cities and towns (Figure 1). The area of the study site was 5 100 ha, which is 4.5% of the man-made forest, which measures 113 947 ha according to the forest registration data of the Tochigi prefecture. Three factories, in Sano city, Kanuma city, and Nasu-shiobara city, in the Tochigi prefecture were assumed as destinations **for the raw materials**. The annual demand for logging residues at the biomass power plant in Sano city is 6 000 tons (Yamaguchi et al. 2009), the annual production of chips at the chip production factory in Kanuma city is 12 000 m^3 (Shimotsuke news paper 2009), and the annual demand for raw materials at the pellet plant is 3 000 tons.

The forest registration data (stand ages, tree species, stocks, etc.), GIS data (information on roads and sub-compartment layers), and forest management records (locations and rate of thinning operations) of the Tochigi Prefectural Government were used for the study, and 50-m-grid digital elevation models (DEM) from the Geographical Survey Institute were also used. The data obtained from the Tochigi Prefectural Government were converted into 50-m-grid raster data for consistency with the DEM data.

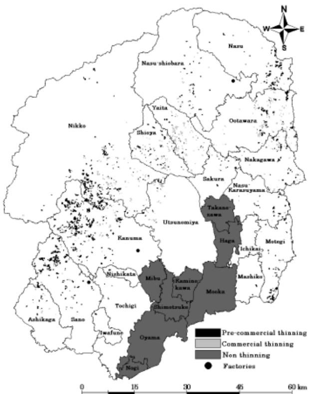

Figure 1: Distribution map of factories and the sub-compartments where pre-commercial and commercial thinning operations were conducted (the points were magnified ten times to make them easy to see)

3 Methods

In this study, the annual supply potentials and the available amount of logging residues from profitable sub-compartments have been estimated. The model estimated volumes in the following order: 1) selection of those sub-compartments from the forest management records where pre-commercial and commercial thinning operations were conducted; 2) estimation of annual supply potential of logging residues based on the thinning and extraction rates; 3) estimation of forwarding and transporting distances, and inclinations of operation sites; 4) estimation of total expenses; 5) estimation of income; 6) estimation of economic balances; and 7) estimation of annual available amounts of logging residues from profitable sub-compartments.

3.1 Estimating Annual Supply Potentials of Logging Residues

First, the sub-compartments where pre-commercial and commercial thinning operations were conducted were selected from the forest management records of 2008. Figure 2 shows the frequency distribution of the sub-compartments where pre-commercial and commercial thinning operations were conducted. Pre-commercial thinning operations were conducted even in the 60-year-old or older forests. Pre-commercial thinning operations constituted about 72% of the total thinning operations conducted. Utsunomiya and Yaita were the only cities where the percentage of commercial thinning in the total thinning operation exceeded 50%. These percentages were 82% and 76%, respectively.

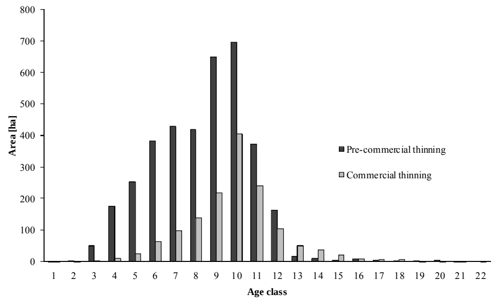

Figure 2: Frequency distribution by age class of sub-compartments where pre-commercial and commercial thinning operations were conducted

The extracting rates (*Er*), which is the ratio of the extracted volumes to the felled tree volumes (stocks of stems), were assumed to be 123% and 124% for Japanese cedar and Japanese cypress, respectively, considering branch extractions, because the biomass enlarged factor (BEF), which is the ratio of the entire tree volume above the ground, including branches, to the stocks of stems, were 1.23 and 1.24 for Japanese cedar and Japanese cypress, respectively (Greenhouse Gas Inventory Office of Japan 2006). The logging residues rate (*Lr*) is the ratio of logging residues to be transported to the factories to the total felled and extracted whole tree volume, whereas the timber rate (*Tr*) is the ratio of timbers to be transported to log markets to the total felled and extracted whole tree volumes. The logging residues rate (*Lr*) and the timber rate (*Tr*) are 90% and 10% of the stocks, respectively, in pre-commercial thinning operations, whereas both are 50% in commercial thinning operations. Table 1 shows each ratio to the whole tree volumes above the ground, including branches.

Table 1: Ratios to whole tree volumes above ground, including branches

		Pre-commercial thinning		Commercial thinning		Clear cutting
		Japanese cedar	Japanese cypress	Japanese cedar	Japanese cypress	Japanese cedar and Japanese
Extracting rate [*Er*]		123.0%	124.0%	123.0%	124.0%	123.5%
Logging residue rate [*Lr*]	Stem	73.2%	72.5%	40.7%	40.3%	20.2%
	Branch	18.7%	19.4%	18.7%	19.4%	19.0%
	Total	91.9%	91.9%	59.3%	59.7%	39.3%
Timber rate [*Tr*]		8.1%	8.1%	40.7%	40.3%	60.7%

Then, the annual supply potentials of the timber and logging residues were estimated using the following expressions.

$$H = S \times Cr \times Er$$
$$HL = H \times Lr \times Gr \quad (1)$$

H is the whole tree volume, *S* is the stock of the stems of a sub-compartment in the forest registration data, and *Cr* is the thinning ratio of each sub-compartment in the forest management records. If there is no record, *Cr* is assumed to be the average value of the thinning rate in each subsidiary enterprise (Table 2). *Gr* is the volume density, which is assumed to be 0.68 tons/m^3 based on the Mikamo Forest Owners' Association survey results (2008).

Table 2: Average of thinning rate, *Cr*, in each subsidiary enterprise

Subsidiary enterprise	Thinning rate [%]
Forestation	24
Erosion control	28
Protection forest management	29
Prefectural forest	29
New tax	29

3.2 Estimating Forwarding Distances, Transporting Distances, and Inclinations of Operation Sites

Forwarding distances were estimated as average distances from the landings to all grids within the sub-compartments. Landings were set within grids in such a manner as to minimize their distances from the roads, the centers of gravity in the sub-compartment, and the nearest factory. Transporting distances from the landings to the factories were calculated using the shortest path algorithm, i.e., the Dijkstra method. Inclinations of operation sites were estimated using the logging distances and differences in the elevation values from the landings to all the grids in a sub-compartment.

Logging residues were assumed to be transported to the nearest large-scale factories in Sano city or Kanuma city from all the cities and towns except for Nasu-shiobara city, Ootawara city, and Nasu town, whose logging residues were transported to a small-scale factory in Nasu-shiobara city. Two destinations for logging residues from Tochigi city, Nishikata town, Kanuma city, and Nikko city were selected by the sub-compartments. Logging residues from Nasu-shiobara city, Ootawara city, and Nasu town were assumed to be transported sequentially to the small-scale factory in Nasu-shiobara city from the sub-compartments, starting with the lowest harvesting costs until 3 000 tons of logging residues, which is the annual demand of the factory. The remaining residues in these municipalities were assumed to be transported to the nearest large-scale factory in Sano city or Kanuma city.

3.3 Estimating Total Expenses

The forest operation systems were determined based on forestry cooperatives. The forest operation systems were classified into five types (Table 3). These are (1) the whole-tree logging system with bunching by a grapple-loader and processing by a processer, (2) the cut-to-length (CTL) system with yarding by a swing-yarder, (3) the CTL system with bunching by a grapple-loader and forwarding by a forwarder, (4) the CTL system with only bunching by a grapple-loader, and (5) the whole-tree logging system with bunching by a grapple-loader and processing by a chainsaw. These were determined based on interviews with forestry cooperatives. Table 3 shows the forest operation systems for forestry cooperatives and only the processes inside the bold lines are considered for logging residue harvesting.

The forest operation systems for the sub-compartments of forestry cooperatives that have two kinds of harvesting systems were selected by considering the inclinations of the sub-compartments based on the ratio of the area by referring to interviews with forestry cooperatives (Table 4). The forest operation systems selected for steep sub-compartments were of types (2), the CTL system with yarding by a swing-yarder, and (5) the whole-tree logging system with bunching by a grapple-loader and processing by a chainsaw. Furthermore, bunching by a grapple-loader included two methods, i.e., one using a winch and the other without using a winch. Whether a winch should be used or not was determined from the inclinations of the sub-compartments. The forest operation systems in 20% of the sub-compartments with the steepest inclinations used a winch, as found by referring to the interviews with forestry cooperatives.

The machine size was set by referring to site surveys and interviews for forestry cooperatives. Table 5 shows the machine sizes of the forwarder, swing-yarder, and grapple-loader that were used for estimating harvesting costs. The loading capacities of the small and medium forwarders were 2.50 m^3 (1.70 tons) and 3.50 m^3 (2.38 tons), respectively. The bucket capacities of the base machine for small and medium swing-yarders were 0.25 m^3 and 0.45 m^3, and for small and medium grapple-loaders were 0.15 m^3 and 0.25 m^3, respectively.

After the forest operation system and machine size were selected, the direct expenses of harvesting the logging residues were estimated. The estimated direct expenses are shown in Table 6. The direct expenses included labor and machinery expenses (maintenance, management, depreciation, and fuel and oil expenses). However, the direct expenses of harvesting logging residues did not include the setting and removal expenses for yarding and spur road establishment expenses because these were assumed to be part of the direct expenses of timber harvesting. In the sub-compartments contacting the road grids and whose areas were small (0.25 ha), only piling by a grapple-loader and transporting by an 8-ton truck were assumed to be necessary. In Table 6, *Ly* denotes the swing-yarder's yarding distance, which was assumed to be 50 m, and *Ls* denotes the grapple-loader's bunching distance, which was assumed to be 10 m for small sizes and 15 m for medium sizes. The direct expenses in Table 6 were determined on the assumption that the productivity of logging residue harvesting reduced the productivity of timber harvesting by 48%, based on Mikamo Forest Owners' Association survey results (2008).

Table 3: Forest operation systems

	(1)	(2)	(3)	(4)	(5)
Forest operation system	Felling by Chainsaw ↓ Bunching by Grapple-loader ↓ Processing by Processer ↓ **Forwarding by Forwarder** **↓** **Transporting by 8-ton Truck**	Felling by Chainsaw ↓ Processing by Chainsaw ↓ **Yarding by Swing-yarder** **↓** **Forwarding by Forwarder** **↓** **Transporting by 8-ton Truck**	Felling by Chainsaw ↓ Processing by Chainsaw ↓ **Bunching by Grapple-loader** **↓** **Forwarding by Forwarder** **↓** **Transporting by 8-ton Truck**	Felling by Chainsaw ↓ Processing by Chainsaw ↓ **Bunching by Grapple-loader** **↓** **Transporting by 8-ton Truck**	Felling by Chainsaw ↓ Bunching by Grapple-loader ↓ Processing by Chainsaw ↓ **Forwarding by Forwarder** **↓** **Transporting by 8-ton Truck**
Forestry cooperative	Nikko-chiku Kanuma-shi Awano Mikamo Nasu-minami	Nikko-chiku Kanuma-shi Awano Mikamo	Nasu-shiobara-shi Ootawara Takahara Haga-chiku	Kuriyama	Utsunomiya-shi Nasu-machi Takahara

Processes inside the bold lines are considered for logging residue harvesting.

Table 4: Forest operation systems determined by inclinations

Forestry cooperative	Kanuma-shi		Nikko-chiku		Awano		Takahara		Mikamo	
Inclinations	Gradual	Steep	Gradual	Steep	Gradual	Steep	Gradual	Steep	Gradual	Steep
Forest operation system	①	②	①	②	①	②	③	⑤	①	②
Area [%]	50	50	60	40	50	50	70	30	50	50

Table 5: Machine size for each territory of each forestry cooperative

Forestry cooperative	Territory	Forwarder	Swing-yarder	Grapple-loader
Nasu-shiobara-shi	Nasu-shiobara (formerly Kuroiso, formerly Nishinasuno)	Small	-	Small
Kuriyama	Nikko (formerly Kuriyama)	-	-	Medium
Utsunomiya-shi	Utsunomiya	Small	-	-
Kanuma-shi	Kanuma (formerly Kanuma)	Small	Small	-
Nikko-chiku	Nikko	Small	Medium	-
Awano	Kanuma (formerly Awano), Nishikata	Small	Small	-
Ootawara	Ootawara	Small	-	Medium
Nasu-machi	Nasu	Small	-	-
Takahara	Nasu-shiobara (formerly Shiobara), Yaita, Shioya, Sakura	Medium	-	Small
Mikamo	Sano, Ashikaga, Tochigi, Iwafune	Small	Small	-
Nasu-minami	Nakagawa, Nasu-karasuyama	Small	-	-
Haga-chiku	Motegi, Ichikai, Mashiko	Medium	-	Small

Table 6: Direct expenses of harvesting logging residues

Machine and operation	Size	Direction	Expenses [yen/m^3]	Note
Forwarding by forwarder	Medium		$1.011Lf + 866$	Japan Forest Technology Association (2010)
	Small		$1.348Lf + 808$	
Yarding by swing-yarder	Medium	Downhill	$16.193 \times \{(1/1.26e^{-0.003\theta} + 1/1.26e^{-0.272-0.014\theta}) \times Ly + 208.9\}$	Japan Forest Technology Association (2010), SAWAGUCHI (1996)
		Uphill	$16.193 \times \{(1/1.26e^{-0.00345\theta} + 1/1.26e^{-0.272-0.0504\theta}) \times Ly + 208.9\}$	
	Small	Downhill	$13.563 \times \{(1/1.26e^{-0.003\theta} + 1/1.26e^{-0.272-0.014\theta}) \times Ly + 208.9\}$	
		Uphill	$13.563 \times \{(1/1.26e^{-0.00345\theta} + 1/1.26e^{-0.272-0.0504\theta}) \times Ly + 208.9\}$	
Bunching by grapple-loader [Using winch]	Medium	Downhill	$15.13 \times \{(1/1.26e^{-0.035\theta} + 1/1.26e^{-0.205-0.053\theta}) \times Ls + 44.36\}$	Japan Forest Technology Association (2010)
		Uphill	$15.13 \times \{(1/1.26e^{-0.0308\theta} + 1/1.26e^{-0.205-0.04187\theta}) \times Ls + 44.36\}$	
	Small	Downhill	$18.96 \times \{(1/1.26e^{-0.057\theta} + 1/1.26e^{-0.2-0.078\theta}) \times Ls + 41.51\}$	
		Uphill	$18.96 \times \{(1/1.26e^{-0.0536\theta} + 1/1.26e^{-0.2-0.064\theta}) \times Ls + 41.51\}$	
Bunching by grapple-loader [Using grapple]	Medium		3 002	
	Small		2 265	
Piling by grapple-loader			270	ZENKOKU RINGYO KAIRYO FUKYU KYOKAI (2001)
Transporting by 8-ton truck			$0.076Lt + 778$	SAWAGUCHI (1996)
Landing-establishment			$165.224H \times Lr + 7\,211$	ZENKOKU RINGYO KAIRYO FUKYU KYOKAI (2001)

Lf denotes forwarding distance (m), Ly denotes yarding distance (m), Ls denotes bunching distance (m), Lt denotes transporting distance (m), θ denotes operation site inclination (°), $H \times Lr$ denotes harvesting volume (m^3).

3.4 Estimating Annual Available Amounts of Logging Residues from Profitable Sub-compartments

Three types of unit prices were assumed for the logging residues: 3 000 yen/ton was estimated from the unit prices of pulpwood, 6,000 yen/ton with additional subsidies (Japanese Forestry Investigation Committee 2011a), and 10,000 yen/ton if feed-in tariffs (FIT) were introduced in Japan (Japanese Forestry Investigation Committee 2011b). After the logging residue unit prices were set, the incomes from logging residues were calculated and the annual available amounts of logging residues from profitable sub-compartments were estimated.

3.5 Revising Annual Supply Potentials and Available Amounts of Logging Residues from Profitable Sub-compartments

In this estimation, the number of sub-compartments has been decreased compared to the number of sub-compartments in the forest management records because small sub-compartments of less than 0.25 ha were missed during the conversion into 50-m-grid raster data, and some sub-compartments were missing in the links from the forest management records to the sub-compartment layers on the GIS as a result of more detailed divisions of the sub-compartments. Furthermore, there was no record of clear cutting, for which no subsidy was paid, in the forest management records since the forest management records obtained from the Tochigi Prefectural Government were generated from subsidy records. Therefore, it was impossible to estimate the annual supply potentials and available amounts of logging residues from clear cutting operations of sub-compartments using the method mentioned above. Therefore, correction factors were made from the ratio of all the annual supply potentials of logging residues estimated from the forest management records and estimated from the annual supply of timbers for all the cities and towns to the annual supply potentials of logging residues estimated using the method mentioned above. Then, annual supply potentials and available amounts of logging residues including those from the sub-compartments that were missed during the data recording, and where clear cutting operations were conducted, were estimated using correction factors although this method did not reflect the harvesting expenses of all sub-compartments.

4 Results and Discussion

The estimated annual supply potentials of logging residues are shown in Figure 3. The minimum, maximum, and average annual supply potentials of logging residues from the sub-compartments were 5 tons, 3,853 tons, and 78 tons, respectively. Figure 4 shows the distribution maps for the direct expenses of harvesting logging residues. Table 7 shows the annual supply potentials and available amounts of logging residues from the profitable sub-compartments in cities and towns. When the unit price of logging residues was 3,000 yen/ton, the annual available amounts of logging residues from profitable sub-compartments was 595 tons. When the unit price of logging residues was 6,000 yen/ton, the annual available amounts of logging residues from the profitable sub-compartments in Nasu-shiobara city, Ootawara city, and Nasu town could cover the annual demands of the small-scale factory in Nasu-shiobara city. The annual available amounts of logging residues from the profitable sub-compartments in the whole Tochigi prefecture area could also satisfy the annual demands of the two large-scale factories in Sano city and Kanuma city. Furthermore, when the unit price of logging residues was 10,000 yen/ton, the annual available amounts of logging residues from the profitable sub-compartments could meet the annual woody biomass demands of the large-scale factory in Sano city, which is 100,000 tons (Yamaguchi et al. 2009), alone, without additional sawmill residues and construction waste woods. Therefore, it was found that the introduction of the FIT had a large impact.

For each city and town, when the unit price of logging residues was 6,000 yen/ton, there were only three regions around the large-scale factory in Sano city where the ratio of the annual available amounts of logging residues from profitable sub-compartments to the annual supply potentials exceeded 40%: Sano city, Ashikaga city, and Iwafune town. On the other hand, the ratio in Kanuma city, where another large-scale factory is located that has a harvesting system similar to that of Sano city, did not exceeded 40%; it reached only 37%. This is because Kanuma city is larger than Sano city and the average transporting distance in Kanuma city (20.3 km) is longer than that in Sano city (15.8 km). The direct expenses of harvesting logging residues were low and the ratios were high in Utsunomiya city and Nishikata town because whole-tree logging system (1) or (5) in Table 3 was used. Direct expenses of harvesting logging residues in the whole-tree logging system consisted of the expenses of only forwarding by a forwarder and transporting by an 8-ton truck.

When the unit price of logging residues was 10,000 yen/ton, the regions where the ratio exceeded 60% were Utsunomiya city, Nasu-karasuyama city, Shioya town, and Nakagawa town. Though large-scale factories were located in Sano city and Kanuma city, their ratios were low because the direct expenses of harvesting logging residues in the CTL system with yarding by a swing-yarder, (2) in Table 3, were high. The whole-tree logging system is more profitable than the CTL system for harvesting logging residues.

The ratio was high in Shioya town because the number of sub-compartments that were allocated for the whole-tree logging system, (5) in Table 3, was greater than the number allocated for the CTL system, (3) in Table 3, in the Takahara Forest Owners' Association's territory. The ratios in Nakagawa town and Nasu-karasuyama city exceeded 90%, in spite of the long average transporting distances to the factories in Sano city and Kanuma city (55.9 km), as a result of use of the whole-tree logging system. However, the ratios in Nasu town, Nasu-shiobara city, and Ootawara city were small in spite of the whole-tree logging system, as a result of the longer average transporting distances of 64.9 km.

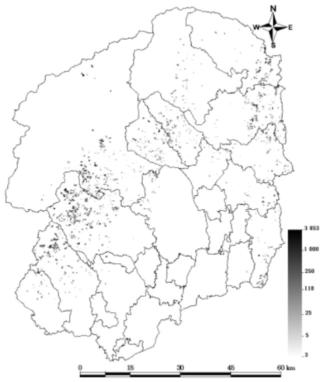

Figure 3: Annual supply potentials (tons) of logging residues from sub-compartments (the points were magnified ten times to make them easy to see)

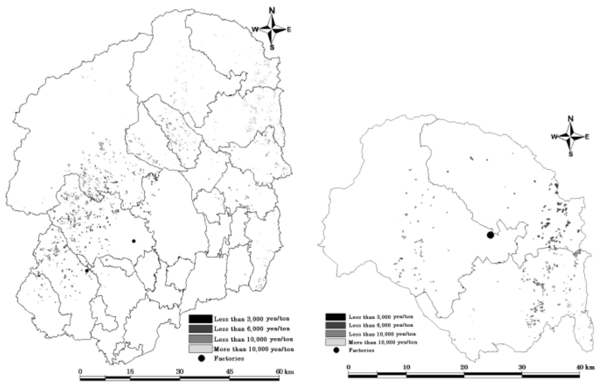

Figure 4: Distribution maps of the direct harvesting expenses for logging residues transported to the two large-scale factories (left) in Sano city or Kanuma city and a small-scale factory (right) in Nasu-shiobara city (the points were magnified ten times to make them easy to see)

Table 7: Annual supply potentials and available amounts of logging residues from profitable sub-compartments

Unit price of logging residues		3 000 yen/ton		6 000 yen/ton		10 000 yen/ton		Factories
Municipals	Annual supply potentials [tons]	Annual available amounts [tons]	Ratio [%]	Annual available amounts [tons]	Ratio [%]	Annual available amounts [tons]	Ratio [%]	
Utsunomiya	6 547.04	95.46	1.46	5 129.25	78.34	6 545.04	99.97	In Kanuma city
Ashikaga	3 762.44	0.00	0.00	1 544.87	41.06	2 058.01	54.70	In Sano city
Tochigi	184.96	0.00	0.00	69.74	37.70	69.74	37.70	In Sano city
Sano	44 654.92	92.66	0.21	21 744.60	48.69	22 371.26	50.10	In Sano city
Kanuma	81 908.04	124.53	0.15	12 973.78	15.84	14 929.45	18.23	In Sano city
		180.19	0.22	17 606.08	21.49	24 802.58	30.28	In Kanuma city
Subtotal	81 908.04	304.72	0.37	30 579.86	37.33	39 732.04	48.51	
Nikko	66 567.92	0.00	0.00	0.77	0.001	67.91	0.10	In Sano city
		1.39	0.002	9 604.18	14.43	24 141.79	36.27	In Kanuma city
Subtotal	66 567.92	1.39	0.002	9 604.94	14.43	24 209.70	36.37	
Ootawara	32 546.84	0.00	0.00	0.00	0.00	214.07	0.66	In Kanuma city
		71.94	0.22	836.09	2.57	836.09	2.57	In Nasu-shiobara city
Subtotal	32 546.84	71.94	0.22	836.09	2.57	1 050.16	3.23	
Yaita	12 404.56	0.00	0.00	154.09	1.24	6 161.07	49.67	In Kanuma city
Nasu-shiobara	4 867.44	0.00	0.00	0.00	0.00	544.80	11.19	In Kanuma city
		28.80	0.59	215.94	4.44	215.94	4.44	In Nasu-shiobara city
Subtotal	4 867.44	28.80	0.59	215.94	4.44	760.75	15.63	
Sakura	1 958.4	0.00	0.00	0.00	0.00	437.82	22.36	In Kanuma city
Nasu-karasuyama	5 301.28	0.00	0.00	8.92	0.17	5 284.67	99.69	In Kanuma city
Nishikata	1 250.52	0.00	0.00	741.75	59.32	741.75	59.32	In Kanuma city
Mashiko	187.68	0.00	0.00	15.09	8.04	15.09	8.04	In Kanuma city
Motegi	10 093.24	0.00	0.00	0.00	0.00	1 958.38	19.40	In Kanuma city
Ichikai	153.00	0.00	0.00	51.53	33.68	51.53	33.68	In Kanuma city
Iwafune	85.00	0.00	0.00	36.87	43.37	45.27	53.26	In Sano city
Shioya	16 966.00	0.00	0.00	729.77	4.30	11 040.90	65.08	In Kanuma city
Nasu	30 197.44	0.00	0.00	2 118.42	7.02	2 118.42	7.02	In Nasu-shiobara city
Nakagawa	16 531.48	0.00	0.00	0.00	0.00	14 010.70	84.75	In Kanuma city
Total	336 168.2	594.98	0.18	73 581.73	21.89	138 662.30	41.25	

5 Conclusions

In this study, a new model was developed to estimate the annual supply potentials and available amounts of logging residues from profitable sub-compartments, by considering the forest operation systems and machine sizes with reference to interviews with forestry cooperatives. Volumes and costs were estimated based on actual forest operations in the Tochigi prefecture using GIS and forest management records for 2008. The results showed that when the unit price of logging residues was 6,000 yen/ton, the annual available amounts of logging residues from the profitable sub-compartments could cover the annual demands of the three facilities that we used for this study. The whole-tree logging system is more profitable than the CTL system for harvesting logging residues. However, in the regions where the average transporting distance exceeded 60 km, this method was not profitable, even at a 10,000 yen/ton unit price for the logging residues. Therefore, the establishment and location of a terminal for trans-shipment from trucks with a loading capacity of 8 ton, which are widely used in forestry sites in Japan, to a truck-trailer with a loading capacity of 20 ton, which is the maximum loading capacity in Japan, should be considered in future studies to reduce transportation costs. Although here the model is only used to estimate the supply potentials and available amounts of logging residues for a single fiscal year, the supply potentials and available amounts for several years should be analyzed using forest management records of other fiscal years in order to determine the tendency of supply potentials and available amounts of logging residues, and to project future supply potentials and available amounts of logging residues.

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*Approximate translations by the authors.