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Analysis of the effects of using large drones to expand woody biomass supply potential in hilly and mountainous areas#

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ABSTRACT

In recent years, rapid increase of woody biomass power plants creates huge demand for fuelwood. Further expanding the use of forest residues requires cost reduction of collecting them to meet the demand. On the other hand, large drones with a payload capacity of 200 kg or more have been developed. They have a possibility to expand the forest area where timber can be economically logged using drones, thereby supply of fuelwood can increase. In this study, we present conditions in the forest where drone logging should be used, including steep terrain and long distances from roads, followed by evaluating economic efficiency of forestry operation under the conditions. The results show that the drone logging can be used economically in most of the sub-compartments with the conditions. Amount of forest residues available can increase more than 60% by applying drone logging. The energy obtained the residues covers 29% of the electricity demand in the study area. The results suggest drone logging system can contribute significantly to decarbonization of the region.

Keywords: woody biomass, forest residues, renewable energy, GIS, drone logging

1. INTRODUCTION

The Sixth Basic Energy Plan, approved by the Cabinet in October 2021, aims to maximize the introduction of renewable energy by utilizing policies such as FIT and FIP to achieve the goals of carbon neutrality by 2050 and a renewable energy ratio of 36%-38% in FY2030 (Agency for Natural Resources and Energy, 2024). Biomass power generation and heat utilization have various values as a regionally distributed, locally produced and locally consumed energy source, while they have problems such as limited biomass resources available for energy use and expensive power generation costs. Therefore, it is necessary to expand the stable supply of biomass fuels and reduce the cost of power generation on the premise of ensuring sustainability (Agency for Natural Resources and Energy, 2021).

In recent years, woody biomass power plants have been developed in various regions, and as of the end of September 2023, 55 facilities with an output of 2,000 kW or more and 83 facilities with an output of less than 2,000 kW have been certified under the FIT/FIP system for power generation facilities using biomass mainly derived from thinned wood and others. This rapid progress of woody biomass power generation has caused a rapid increase in the demand for fuelwood (Forestry Agency, 2024).

Because most of the wood left over from sawmills and construction waste has already been utilized, further utilization of forest residues, including branches and strips, is required to meet the increasing demand for fuelwood. The labor and cost of collecting forest residues are problems, therefore an efficient system for collecting and processing forest residues is required, such as whole-tree logging, chipping near the site, etc.

In addition, forest areas that are difficult to work with vehicle-based machinery has been increased as logging areas have become more remote in recent years (Ito et al., 2023). Yamada et al. (2023) pointed out that in areas/years with high timber production, forest areas with gentle slopes and close proximity to roads tend to be preferentially logged, leaving only forest areas with low profitability in the future, which could lead to the collapse of continuous timber production.

On the other hand, drones have been utilized in forestry operations for transporting seedlings, spraying chemicals and so on. Large drones with a payload of 200 kg or more have been developed recently, and their utilizations in carrying from forest land to log yard can reduce labor for tree logging in forest areas with steep slopes or long hauling distances, especially for whole-tree logging, thereby expanding the area of forest land

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where trees can be economically logged. This has the potential to cause increase of the fuelwood supply from forest residues.

Yoshioka et al. (2005, 2011) estimated supply and collection cost of woody biomass generated in the process of forestry operation for each sub-compartment, which is typical forestry operation unit defined in local forest inventory, in mountainous area. Kinoshita et al. (2009) conducted the estimation in Yusuhara town, and Yamaguchi et al. (2014) in Tochigi prefecture. Battuvshin et al. (2020) added Fukushima, Ibaraki, and Gunma prefectures, which have wood exchange with Tochigi prefecture. In these studies, cost models were proposed based on work processes and types of forestry machinery used. Ohki et al. (in press) analyzed the productivity and cost of logging systems using a large drone with a payload capacity of 200 kg by simulation, and showed the possibility of cost advantages over other logging methods depending on forest conditions such as topography and distance to log yard. However, forest conditions where drone logging is effective, or amount of wood resources that can be obtained have rarely been analyzed.

In this study, we examine the specific conditions where drone logging should be utilized, such as steep terrain and long distances from roads, and evaluate the economics of forestry operations with the utilization of drone logging system. Based on the results, we analyze the increase of forest residues supply that can be economically obtained with whole-tree logging using large drone, and discuss the effect on local decarbonization when the residues are used as energy.

2. METHOD

2.1 Stady area and materials

The study area is Hokuto City, which is located in the northwestern part of Yamanashi Prefecture and is surrounded by some of the most prominent mountains in Japan, including Mt. Yatsugatake. The forest area in the city is 45,848 ha (76% forest, 34% planted forest), of which 30,614 ha are prefectural forest, 418 ha are public forest, 762 ha are property-owned forest, and 14,054 ha are privately owned forest. Species consist of cedar (1%), cypress (8%), red pine (20%), larch (61%), other conifers (4%), sawtooth oak, quercus serrata, and mizunara Oak (1%), and other broad-leaved trees (5%) (Hokuto City, 2022).

This study uses polygons of sub-compartments for GIS analysis and tree species information for each sub-compartment obtained from local forest inventory. The area of each sub-compartment is calculated from each polygon, since area data of considerable number of sub-compartments are lacking in the local forest inventory. In this study, the sub-compartment polygons assigned “KEYCODE” are targeted for analysis.

“Road Centerline 2020” provided by the Conservation GIS Consortium is used for road data. Elevation data is obtained from “5-meter Mesh Numerical Map (Elevation)” provided by the Japan Map Center. The average of the elevation data contained in the polygon of each sub-compartment is calculated. Road lines are converted to points at 5-meter intervals, and the nearest elevation data from each road point is used as the elevation value for each road point. The elevation data set of “5-meter Mesh Numerical Map (Elevation)” is converted to slope angle, and the slope angle of each sub-compartment is calculated as the average value of the slope angle data contained in each sub-compartment polygon. QGIS 3.26 is used for the above GIS data processing.

2.2 Applicable targets for drone logging and work system

The forest conditions where drone logging should be utilized are identified through interviews with forestry operators and administrative agencies in the study area, to investigate the progress of forestry operations and needs for drone logging.

Forestry operations have been conducted in forest with easy-to-work conditions, such as gentle slopes, dense road networks, and easy access to strip roads. Conventional forestry machinery is mainly used. Current logging machinery include forestry work vehicle and small wood yarder, whereas small long-reach grapple and swing yarder are listed as future implementation targets (Hokuto City, 2022). Advantages of flying overhead and not being constrained by topography lead to application of drone logging in steep terrain and areas far from roads. In addition, drone logging should be utilized for selective thinning instead of row thinning and logging operations in multi-storied forest operations because of the advantage of not damaging surrounding trees and understory vegetation during the operation.

Therefore, sub-compartments that meet the following “OR” conditions are set as a target for drone logging.

・Slope angle of 30 degrees or more
・Distance from roads of 200 m or more

Table.1 Number of plants, felled trees per hectare

Species	Number of plants	(Number before 1st thinning)	Number of felled trees			
			Thinning(1st)	Thinning(2nd)	Thinning(3rd)	Final felling
Cedar	3,000	(2,700)	700	600	400	1,000
Cypress	3,000	(2,700)	500	650	450	1,100
Red pine	4,000	(2,700)	800	700	450	750
Larch	3,000	(2,500)	850	570	400	680

Table.2 Age, DBH, height in thinning and final felling

	Species	Thinning(1st)	Thinning(2nd)	Thinning(3rd)	Final felling
Age	Cedar	16	24	32	40
	Cypress	18	27	36	45
	Red pine	17	22	29	40
	Larch	16	23	31	40
DBH [cm]	Cedar	11.7	15.5	19.5	23.6
	Cypress	12.1	15.2	18.7	22.1
	Red pine	10.4	13.6	18.2	24.2
	Larch	9.5	13.3	17.2	22.0
Height [m]	Cedar	9.7	13.4	16.6	19.3
	Cypress	9.0	12.7	15.6	17.4
	Red pine	9.0	11.5	14.5	18.0
	Larch	8.6	12.4	15.6	19.0

The first condition is set based on the interview result that rarely forestry operations has conducted in forest areas with slope angle of 30 degrees or more. The second condition is set based on the limit of yarding distance for swing yarder, which is planned to implement in future. Forest areas beyond the yarding distance for swing yarder without building a new strip road are targeted for drone logging.

Based on Ohki et al. (in press), we assume that operators with a chainsaw enter the forest area to fell trees, and then a logging drone carries a whole of felled tree to the log yard beside the nearest road, where log bucking is conducted using a processor. Thus, all unused wood including branches and strips is accumulated at the log yard. The transportation from the log yard is assumed to use a 4-ton truck.

2.3 Calculation of the supply potential

The amounts of wood resources generated during the entire harvest period is calculated for each sub-compartment of larch, red pine, cypress, and cedar, when thinning and final felling are conducted according to the technical guidelines of standard harvest period described in the Regional Forest Plan (Yamanashi Prefecture, 2022a). This is divided by the number of years of the harvest period to obtain the amounts of wood resources generated per year. The amounts of wood resources generated in each sub-compartment is calculated by multiplying the amount per unit area and the area of the sub-compartment. Table 1 shows the number of trees planted and thinned per unit area for each tree species, and Table 2 shows the forest age, DBH, and tree height for thinning and final felling.

The volume of generated wood resources is calculated from the DBH and tree height at the age of each thinning or final felling using the “Stem Volume Calculation Program” provided by the Forestry and Forest Products Research Institute (FFPRI). Assuming whole-tree logging, the biomass expansion factor obtained from the National Institute for Environmental Studies (2023) is multiplied by the stem volume to calculate the volume including branches and strips. The wood resources volume is converted to weight by multiplying the specific gravity for standing tree of each species, referring to Saito et al. (2021). The specific gravity for standing tree is set separately for stem and branches, referring to Ohki et al. (2024). Weight of stem is calculated using specific gravity for stem, and weight of upper biomass increment due to the biomass expansion factor is calculated using specific gravity for branches. Table 3 shows the biomass expansion factor and the specific gravity for the stem and branches of each tree species.

Next, the supply potential of log materials (for lumber, plywood and wood chips) and residues (for fuelwood) are estimated. The volume of log materials is calculated by multiplying stem volume by yield ratio, and the remainder is accounted for as residues. The volume of all branches is also accounted for as residues. The yield ratio value is set to 0.8 for final felling, referring to Moriguchi et al. (2016), and 0.1 for the first thinning and 0.5 for the second and third thinning, referring to Yamamoto et al. (2017).

Table.3 Biomass expansion factor and specific gravity

Species	Biomass expansion factor (BEF)		Specific gravity [t/m^3]	
	Age≦20	Age>20	Stem	Branches
Cedar	1.57	1.23	0.714	0.656
Cypress	1.55	1.24	0.856	0.753
Red pine	1.63	1.23	0.965	0.985
Larch	1.5	1.15	0.833	0.878

2.4 Calculation of the revenue

The revenue for each sub-compartment during the entire harvest period is calculated by multiplying the amounts of log materials and residues, obtained in 2.3, by the purchase price of logs and residues, respectively. The purchase price of log materials is calculated as a weighted average of market prices for each log materials, including lumber, plywood and wood chips, with their supplies ratio as weight based on the 2022 Lumber Supply and Demand Report (Ministry of Agriculture, Forestry and Fisheries, 2024). The purchase price is set for each species. As for plywood, however, only the price for cedar is obtained, therefore this price is used for other species as well. The purchase price for wood chips is based on the price of conifer logs for all species. The purchase price for residue is assumed to be the same as the log price for wood chips and is converted to a price per ton using the specific gravity by volume of the branches and strips. Table 4 shows the logs prices and supplies used in the calculation, and the set purchase prices of logs and residues by species.

In addition, subsidies for three thinning are added to revenue based on the subsidy program in the study area. The standard unit price for each thinned wood volume is considered, referring to the Yamanashi Prefecture Standard Unit Price List of Subsidized Afforestation Projects (Yamanashi Prefecture, 2022b). The subsidy amount is calculated based on the basic subsidy rate at 0.4, which is a general value, and the condition that the forest management plan has been formulated and all unemployment insurance and other insurance are in place.

2.5 Calculation of the cost

2.5.1 Sub-compartment factors for cost calculation

The log yard in each sub-compartment is assumed to be located by the side of forest road, and is set at the nearest road point from the center of gravity of each sub-compartment. The carrying distance by drone is assumed to be the straight-line distance between the center of gravity of the sub-compartments and the yard, including the elevation difference.

The destination of the timber delivered to the site was assumed to be the satellite yard of the Yamanashi Forestry Cooperative Association in Hokuto City. The transportation distances on the road are calculated by multiplying the straight-line distance from yards of each sub-compartment to the satellite yard by a detour coefficient. The detour coefficient is set to 1.5 based on Suzuki et al. (2017).

2.5.2 Calculation of operation cost

Specifications, operation processes and cost model for drone logging are referred to Ohki et al. (in press). A multi-rotor type drone with maximum takeoff weight (MTOW) of 600 kg and payload of 200 kg flies to the forest area with an empty load, lifts felled trees, flies to the yard for carrying the trees, and unloads at the yard, without landing. The drone continues to fly, repeating this process several times until the battery runs low, then lands in the yard to replace the battery. The logging cost varies by each sub-compartment because the productivity of drone logging depends on the carrying distance. Drone logging is assumed to be whole-tree logging. If the weight of a single tree is less than the payload weight, one or multiple loadable trees are carried. If not, the tree is cut in half or more to be loadable weight and carried multiple times. Ohki et al. (in press) presents two types of cost parameters of drone logging; one is the higher cost scenario based on current technologies and the other is the lower cost scenario based on future technologies around 2030. In this study, lower cost scenario is applied for drone logging cost calculation.

Felling, backing and loading cost are referred to Battuvshin et al. (2020). The felling cost is 1,032 JPY/m^3 for using chainsaws, and the backing cost is 976 JPY/m^3 for using processors (L). The cost of loading logs onto tracks by grapples (M) is 316 JPY/m^3. Transporting cost is calculated by cost model for 4-ton truck, referred to Kinoshita et al. (2009). However, the unit labor cost is set

Table.4 Market log prices and supplies amount, set purchase prices of logs and residues

Species	Market log prices [JPY/m^3]			Market supplies amount [1000 m^3]			Set purchase prices [JPY/m^3]	
	Lumber	Plywood	Chips	Lumber	Plywood	Chips	Logs	Residues
Cedar	17,600	15,700	7,000	8,900	2,895	1,443	16,029	10,677
Cypress	25,100	15,700	7,000	2,100	614	257	21,592	9,297
Red pine	16,000	15,700	7,000	85	228	246	11,917	7,110
Larch	16,100	15,700	7,000	947	742	243	14,802	7,974

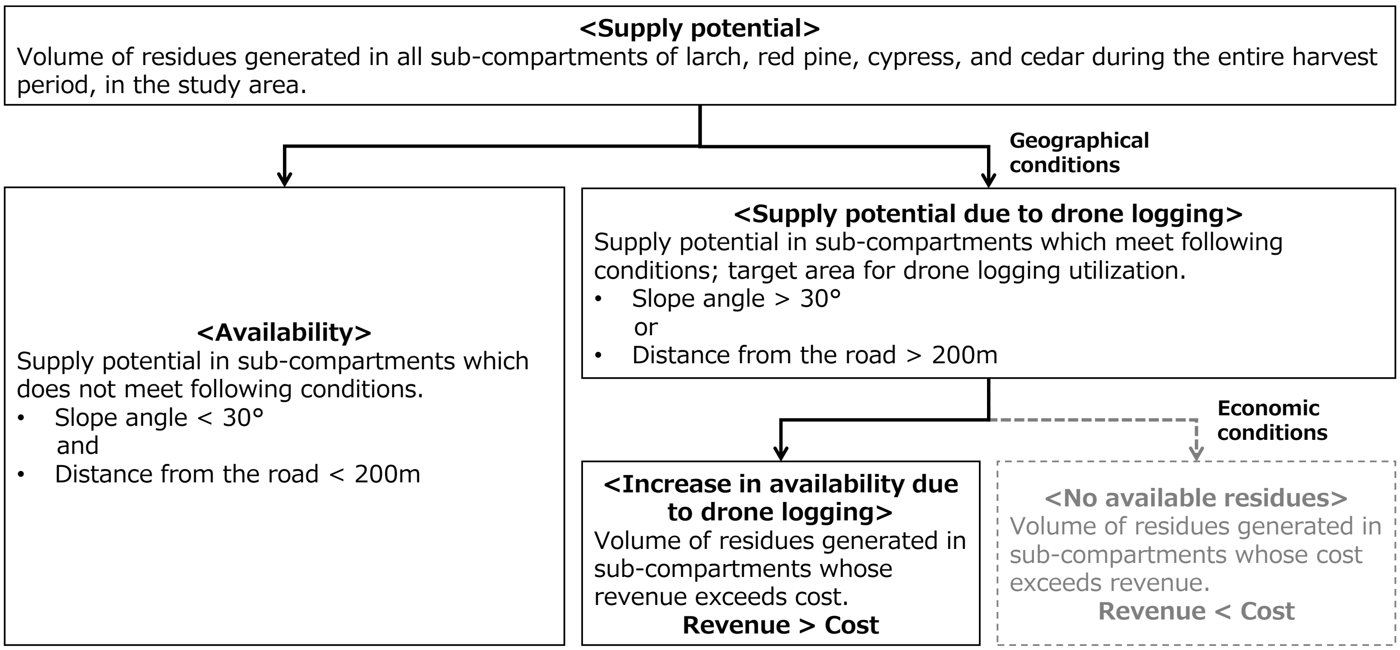

Fig.1 Concept of "Increase in availability due to drone logging" and definition of supply potential and availability.

at 22,200 JPY/day based on Yamanashi Prefecture (2022b).

The above costs for felling, backing, logging, loading, and transporting, unit cost per volume, are multiplied by the volume of wood resources, including stems and branches, generated in the three thinning and final felling to calculate the cost per sub-compartment for the entire harvesting period.

2.6 Estimation of residue availability

This study estimates the supply potential and availability of residues, especially the increase in amounts of residues by utilizing drone logging. "Supply potential" of residues is defined in section 2.3; the volume of residues generated in all sub-compartments of larch, red pine, cypress, and cedar during the entire harvest period.

In section 2.2, the conditions of sub-compartments where drone logging should be applied; specifically, slope angle of 30 degrees or more, or distance from roads of 200 m or more. Because these conditions are harsh for the forestry operation, utilizing drone logging can enable to carry wood resources from sub-compartments which meet these conditions. On the other hand, forestry operations can be progressed with current state in sub-compartments which does not meet these conditions, therefore residues can be carried from the sub-compartments. Thus, supply potential in sub-compartments which meet these conditions is defined as "supply potential due to drone logging", and supply potential in sub-compartments which does not meet these conditions is defined as "availability".

In the supply potential due to drone logging, the volume of residues carried economically is defined "increase in availability due to drone logging"; the volume of residues generated in sub-compartments whose revenue calculated in section 2.4 exceeds cost calculated in section 2.5.

Fig.1 shows the concept of "Increase in availability due to drone logging" and definition of supply potential and availability.

Table.5 Results of supply potential, supply potential due to drone logging, availability, and increase in availability due to drone logging

[m³/year]

Species	Supply potential	Supply potential due to drone logging	Availability	Increase in availability due to drone logging
Cedar	1,251	552	700	552
Cypress	6,215	2,258	3,956	2,258
Red pine	36,844	14,943	21,901	5,733
Larch	44,014	23,280	20,734	22,740
Total	88,325	41,033	47,291	31,284

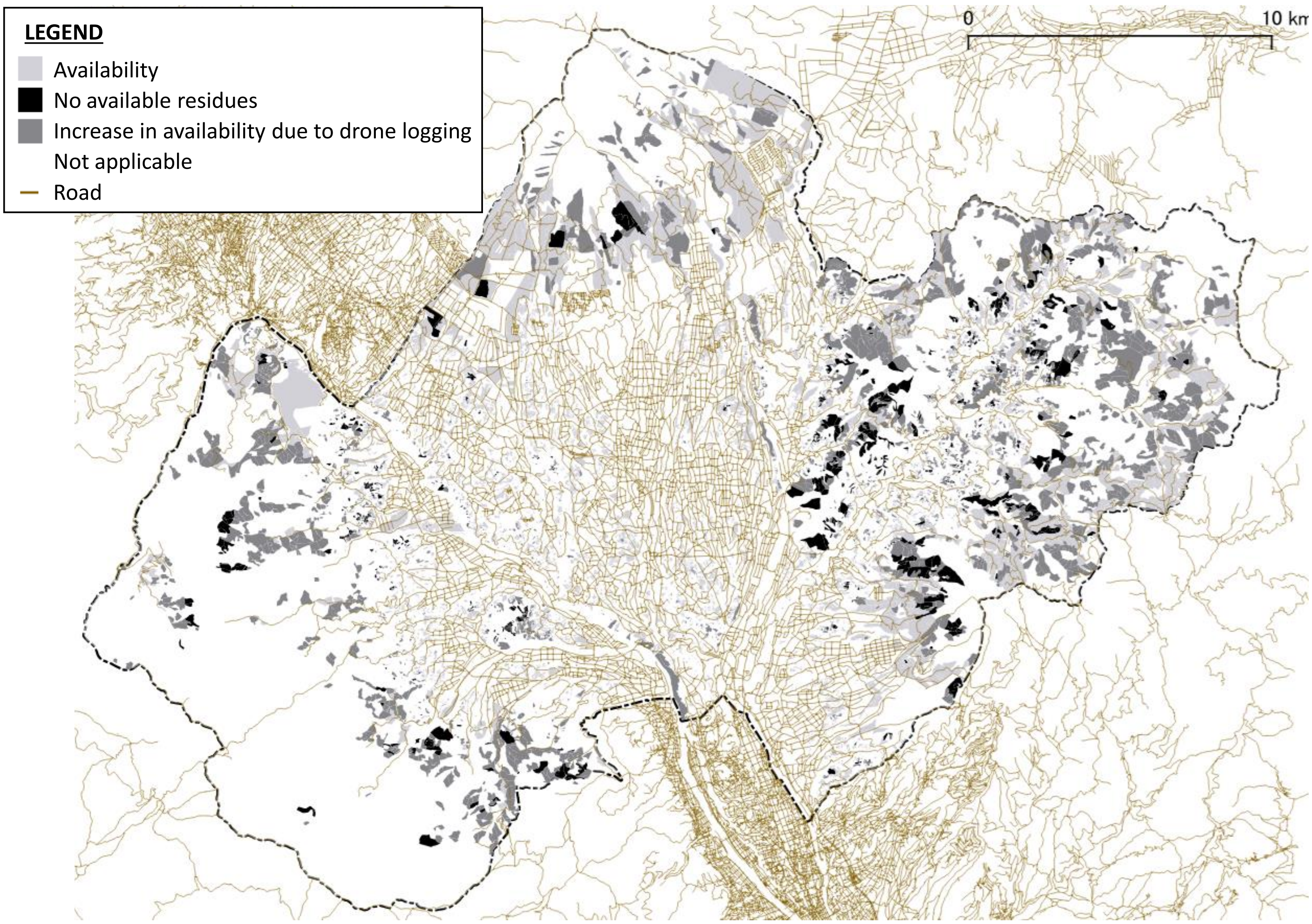

Fig.2 Distribution of sub-compartments which has supply potential and availability of residues

3. RESULTS AND DISCUSSION

Table 5 shows the results of supply potential, supply potential due to drone logging, availability, and increase in availability due to drone logging. Fig.2 shows the distribution of each sub-compartment.

The total supply potential of residues is 80,414 t/year, or 88,325 m^3/year in terms of volume by specific gravity of branches when standing. Supply potential due to drone logging, generated in sub-compartments with harsh conditions, is 41,033 m^3/year or 46.5% of total supply potential in terms of volume equivalent. The increase in availability due to drone logging is 31,284 m^3/year, or 35.4% of total supply potential and 76.2% of supply potential due to drone logging. These results suggest that drone logging can be economically applied to most sub-compartments with harsh conditions. The increase in availability due to drone logging is 66.2% of availability. This suggests drone logging can significantly contribute to increase of residues supply.

By species, residues are available in all cedar and cypress sub-compartments where drone logging should be utilized. The maximum carrying distances for the cedar and cypress sub-compartments are 685 m and 678 m, respectively. These ranges are relatively short, therefore no sub-compartments with significantly higher logging cost generate. In addition, the purchase price per ton of cedar and cypress residue are relatively high because their specific gravity of branches when standing is lower than that of larch and red pine.

For larch, residues are available in 97.7% of sub-compartments where drone logging should be utilized. Although the purchase price of larch is lower than that of cedar and cypress, the loading rate of the drone is relatively higher, which reduced the logging cost. The loading rate of the drone is not dependent on the species, and some operational ingenuities are needed. On the other hand, carrying distance of larch sub-compartments is relatively long. For more than 1,100m of carrying distance, the revenue is lower than the cost including drone logging in some of the sub-compartments.

In the case of red pine, residues in only 38.4% of sub-compartments where drone logging should be utilized can be available. This is because the purchase price of red pine is lower than that of other species for both logs and residues, resulting in lower revenue. Additionally, lower loading rate makes the logging cost high.

Next, we estimate the energy that can be supplied from the increase in availability due to drone logging, 31,284 m^3/year or residues. Based on the Hokuto City Renewable Energy Master Plan (Hokuto City, 2021), assuming the specific gravity of residue with a moisture content of 50% is 0.7, and the calorific value is 8.37 MJ/kg, the amounts of residues correspond to 183 TJ in terms of calorific value and 51 GWh in terms of electricity. According to the master plan, the annual electricity consumption of public facilities in Hokuto City is approximately 27 GWh, which can be fully covered by energy from the residues. The energy from the amounts of available residues originally is 277 TJ in terms of calorific value and 77 GWh in terms of electricity. Adding this value to the energy from the increase in available residues due to drone logging yields 460 TJ in terms of calorific value and 128 GWh in terms of electricity. This is equivalent to 9% of Hokuto City's energy consumption of 5,410 TJ and 29% of the electricity demand of 440 GJ in 2020.

The results suggest that the promotion of energy use from residues have an extremely large effect on the decarbonization of the city, especially for considering that future estimation of Hokuto City's energy consumption and electricity demand are on a downward trend.

4. CONCLUSION

In this study, we examine the specific conditions under which drone logging should be applied to forest area with steep terrain or long distances from roads, and evaluate the economic efficiency of forestry operations for utilizing drone logging. The results show that the drone logging can be used economically in most of the sub-compartments with slope angle of more than 30° or distance of more than 200 m from roads. In addition to the amount of residue available in the forest area with good working conditions, drone logging can increase the amount of available residue by more than 60%. As a result, the residues can cover 9% of energy consumption and 29% of electricity demand in the study area.

This estimation is based on the local forest inventory information and the ideal harvested amount shown in the regional forest plan. According to Hokuto City (2021), the amount of woody biomass available for energy use is estimated to be 7,838 m^3/year (in 2020), which is based on the actual thinning of private forests. This is only about 1/10 of the 78,575 m^3/year of residue estimated in this study. It is necessary not only to develop a drone logging system and promote its use, but also to look again at the potential of Hokuto City's abundant forest resources and establish a system for collecting residues and using them as energy while promoting forestry operation.

In this study, drone logging is applied to all of sub-compartments with harsh working conditions. Thus, comparing feasibilities between drone logging and other logging machinery is needed. Amount of money returned to the forest owner also should be considered in the estimation of increase in availability due to drone logging. In addition, comparing the energy supply from residues carried by drone and energy consumption of drone logging need further research.

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