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BIOMASS TRANSPORTATION COSTS BY ACTIVATING UPGRADED FOREST ROADS AND INTERMEDIATE LANDINGS

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Abstract: *The transportation cost of biomass for energy production using a mixed-standard road network was analysed. All of the wood products coming from spur roads need reloading operations at intermediate landings to enable the long transportation on primary roads after chipping. The timber coming from secondary roads, on the other hand, was better to be transported directly to the demand locations. The combination of primary and secondary roads was an effective practice in both timber and chip transportation. When harvesting logging residue for energy production, the cost was reduced by 4.7 EUR/solid m*^{3} *by upgrading spur roads to secondary roads. On primary roads, high moisture content of materials always affects the capacity of timber transportation and also affects chip transportation when exceeding 30%. It is strongly recommended to reduce the moisture content as much as possible prior to transportation.*

Key words: *biomass; transportation cost; moisture content; primary road; secondary road; ridge road; spur road; linear programming.*

1. Introduction

Primary roads are important since transportation on such roads is significant both, in terms of total energy consumption and cost within a biomass supply chain [4]. The modification and adaptation of the forest road network require more time [3], and it is strongly recommended to harvest, for the moment, the forest located in the area having a good road infrastructure. We arranged forest road standards as Table 1 to be more practical based on the national forest road network strategy [15].

In Japan, there was a governmental project to construct primary roads on the ridge of mountains for about 50 years since 1956 until 2008. It improved the accessibility to inner-mountainous regions, and enabled the harvesting operations on both sides of the road.

Such primary roads were built on 3,300 km all over Japan [5]. From our observation carried on 3 routes from 2014 to 2016, it was found that such roads were well maintained and provided easy access to the forest alongside.

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Forest road standards in Japan Table 1

Class	Primary	Secondary	Spur
Period	Permanent	Permanent	Temporary
Width [m]	4-5	3.5	2.5-3
Design speed (km/hr)	20-40	15	Not designed
Openness	For everyone	Only for forestry	Only for forestry

The secondary forest road network has been subsidised for several years and its use is gradually increased while its management, such as its cost-effective construction methods and water control techniques, is still developing [11] and [17]. It fully improves the transportation efficiency in the forest compared to the conventional spur roads. Although it was indicated that the expansion of the primary road network is crucial to reduce the harvesting cost [15], the combination of secondary and primary roads is one of the best current practices in Japan.

The use of wood for energy purposes is a hot topic in Japan as well as in other countries [7]. After coming into effect of the Feed-in Tariff law (2014), many power plants with the average capacity of 5 MW have been established and a steady supply of forest biomass is an urgent issue. Comminution of forest biomass by mobile chippers is an indispensable practice to reduce the bulk density of the material while the chippers equipped with medium-sized engines are cost effective [18]. Such chippers, however, cannot be transported on secondary and spur roads due to their size.

In this study, we analysed the wood chip supply system characterized by chipping at intermediate landings located alongside the primary forest roads. Although it has been shown that the direct transportation of timber was cheaper than the wood chips recovered from logging residue chipped at intermediate landings [8], it is necessary to include the effect of road condition on the transportation cost. The drying function of storing was also proved to be effective in the attempt to reduce the transportation cost to produce fuel [1], and it was indicated that this function would have an effect on the CO_2 emissions associated with the wood chip supply [9]. Therefore, we have taken the effect of moisture content into consideration.

2. Objectives

The goal of this study was to evaluate the transportation cost of dried forest biomass on the existing mountain ridge roads. At the same time, it can be shown that such an inter-regional road network can support a steadier production since it enables the access to several suppliers. The currency used in this study was converted from Japanese Yen (JPY) to Euro (EUR) using the rate of 123.08 JPY/EUR as of June 8th, 2017.

3. Material and Methods

3.1. Study Area, Systems and Simulation Scenarios

The study area was chosen for a forest where a primary road having 70.1 km in length is located in a part of a mountain ridge of Miyazaki Prefecture, Kyushu Island, Japan. The local tree species was assumed to be Sugi (*Cryptomeria japonica* L.f. (D. Don)), which is the dominant species in this region. The density of air-dried Sugi is 0.38 t/solid m^3 at the wet-based moisture content of 15%. The harvesting area was set within 1 km from the primary road and included 8,882 ha of private forest land (Fig. 1).

By using the random point function in GIS, 120 harvesting sites of 1 ha clear-cut were randomly produced within the studied area and used in the simulation that considered the function of the primary road and intermediate landings. About 61 solid m^3/ha was assumed to be produced as logging residue after clear-cuts in the region and the annual amount volume of residue was estimated at 7,320 solid m^3. Twenty intermediate landings were set evenly at the roadside of the primary road. The construction of landings was assumed to be costless since they were set on a part of the road. There were three biomass power plants in different directions. The average transportation time from all of the intermediate landings to the demand points no. 1, 2 and 3 was of 3.0, 2.3 and 2.8 hours, respectively. The closest demand point was point no. 2 and the furthest was the point no. 1. The function of OD cost matrix in Network Analysis Extension of ESRI ArcGIS 10.3.1 was used to calculate the shortest transportation time from intermediate landings to power plants.

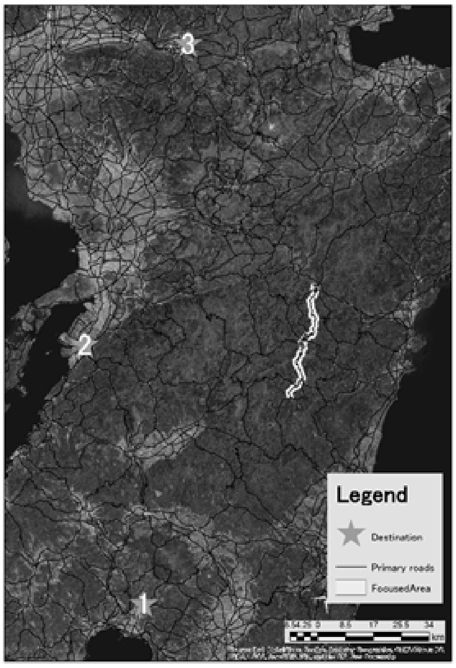

Fig. 1. *The map of primary roads and demand points*

The analysis was characterised by the road condition from a harvesting site to the primary road via secondary or spur roads and the condition of the material was either logging residues or timber. There were four scenarios dealing with both of materials by chipping operation at intermediate landings - Scenarios (1) to (4) - and two scenarios dealing with timber by re-loading at intermediate landings - Scenarios (5) and (6). Each scenario was compared to the direct transportation of the materials from landings in forest. The material type and condition of roads were: (1) logging residues via spur roads; (2) logging residues via secondary roads; (3) and (5), timber via spur roads; and (4) and (6), timber via secondary roads. The payload size of trucks was assumed to be of 4-, 10- and 20-tonne on spur, secondary and primary roads, respectively (Table 2). Among the 20-t trucks, there is another type with bigger capacity of 50 loose m^3 in volume and 13-t in weight. The influence of moisture content to this truck was also analysed to see its future availability. The chipped material was assumed to be directly loaded onto chip trailers.

To make a contrast, the transportation costs were compared for a production that was evenly delivered to the three power plants and for all the production delivered to the closest demand point (no. 2). By comparing these two sourcing types, the advantage of the inter-regional accessibility of the ridge primary road would be emphasized.

3.2. Linear Programming Model

The transportation cost in the studied area C (EUR/solid m^3) was optimized by solving the following linear programming (LP) model:

minimize

$$C = \sum_{i,j,k}^{n,m,l} (x_{ik}C_{ik} + x_{kj}C_{kj} + x_{ij}C_{ij}),$$

subject to

$$\sum_k^l x_{ik} + \sum_j^m x_{ij} \le V_i,$$

$$\sum_i^n x_{ik} - \sum_j^m x_{kj} = 0,$$

$$\sum_k^l x_{kj} + \sum_j^m x_{ij} = d_j,$$

Trucks on each road standard Table 2

Class	Spur	Secondary	Primary
Truck type	4-t	10-t	20-t
Engine output [PS]	137	186	235
Fixed cost [EUR/hr]	11.0	17.8	41.7
Fuel cost [EUR/hr]	6.3	8.6	10.8
Wage [EUR/hr]	20.3	20.3	20.3
Volume capacity Vt^* [loose m^3]	8	20	40
Weight capacity Vw^* [tonnes]	3.55	9.0	11.0

where:

x_{ik}, x_{kj}, and x_{ij} were the volume of material/product transported from the harvesting site i to the intermediate landing k, the intermediate landing k to the demand j, and directly from the landing i to the demand j, respectively (solid m^3);

n, m, l – the numbers of harvesting sites, intermediate landings, and demands in the model area, respectively;

V_i – the volume of forest products from the landing i (solid m^3/landing);

d_j – the demand size at the demand j (solid m^3).

In this model, the volume of forest products V_i was set to 61 solid m^3 based on the data from the model area.

The costs of truck transportations, C_{ik}, C_{kj} and C_{ij} (EUR/solid m^3) were calculated by following equations:

$$C_{ik} = Ct_{ik}(2t_{ik} + tl_{ik} + tu_{ik})/Vt_{ik}$$

$$C_{kj} = \frac{Ct_{kj}(2t_{kj} + Vt_{kj}/p + tu_{kj})}{Vt_{kj}},$$

$$C_{ij} = Ct_{ij}(2t_{ij} + tl_{ij} + tu_{ij})/Vt_{ij},$$

where:

Ct was the hourly cost of truck (EUR/hr);

t – the transportation time (hours);

tl – the time for loading (hours);

tu – the time for unloading (hours);

p – the productivity of mobile chipper (loose m^3/hour);

V_t – the loaded volume (solid m^3).

The loading time of logging residue was assumed to be 0.33 hours on spur roads, and 0.66 hours on secondary roads. The time for unloading of logging residues and wood chips was assumed to be 0.33 hours. For timber loading and unloading, the efficiency was assumed to be 20.405 solid m^3/hour [14]. The used chipper was a medium-sized chipper equipped with a 353-kW engine mounted on a truck, MUS-MAX WT8-XL manufactured by MUS-MAX Landmaschinenbau Urch KG, Austria. The productivity p was assumed to be of 66.3 loose m^3/hour [16]. The relocation cost of chipper was not considered for such a short distance between the landings.

Moisture content of the truck load was taken into account in the equations to investigate its influence on the transportation cost. The capacity of the truck Vt was limited when the weight exceeded the capacity of a truck because of high moisture content of the load. The transported volume Vt (Solid m^3) was decided by the following equations:

$$Vt = Vw^* d_u,$$

(when $Vt^* \cdot dt^{od}/(1-u) \geq Vw^*$),

$$Vt = Vt^* \cdot dt^{od} \cdot d_u/(1-u)$$

(when $Vt^* \cdot dt^{od}/(1-u) < Vw^*$), where:

Vt^* was the volume capacity of a truck (loose m^3);

dt^{od} – the density of the load per loose m^3 in oven-dry tonne (tonne/loose m^3);

u – the moisture content of the load;

Vw^* - the weight capacity of a truck (tonnes);

d_u – the density of Sugi per solid m^3 with the moisture content of u (tonne/solid m^3).

The density of the logging residue was of 0.135 oven-dry tonne/loose m^3, for wood chips it was of 0.201 oven-dry tonne/loose m^3 [6] and for timber it was of 0.254 oven-dry tonne/loose m^3.

The effect of moisture content on the truck capacity was analysed in the range of 15 - 50%.

4. Results and Discussions

The effect of moisture content on transportation capacity is shown in Fig. 2. The moisture content affected the capacity of chip transportation on the primary roads when exceeding 30% with 11-t capacity and 22% with 13-t capacity. The capacity of timber transportation on primary roads were always affected by the moisture content. The usage of 13-t capacity of trucks had high possibility of transportation cost reduction if the load was dried enough. Also, the capacity of timber transportation on spur and secondary roads decreased when reaching a moisture content of 44%. For logging residue transportation, the moisture content of load did not have any effect on the capacities because logging residue was assumed to be too bulky. Transportation capacity for timber increased as the moisture content decreased.

Regardless of moisture content, there were no cases in which the biomass was directly transported from the harvesting site i to the demand j in scenarios (1), (2), (3) and (5), and vice versa in scenarios (4) and (6) (Fig. 3). All of the products coming from spur roads required reloading at intermediate landings due to the lower transportation capacity on spur roads. It was recommended for the timber coming from secondary roads to be transported directly to the demand points.

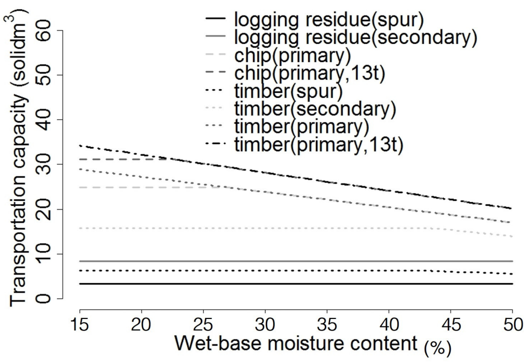

Fig. 2. *Effect of moisture content on transportation capacity on each road*

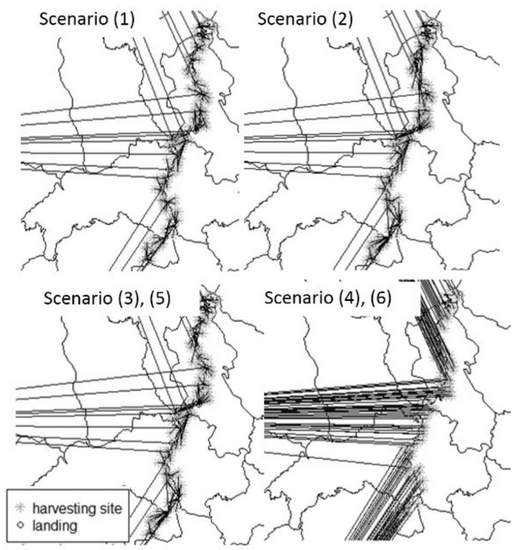

Fig. 3. *The allocation of biomass in each scenario*

The average costs are shown in Fig. 4. The total cost was the cheapest in scenarios (4) and (6) of direct timber transportation from harvesting sites to the demand points via secondary roads. The combination of primary and secondary roads was effective in chip transportation. The costs ranged from 18.6 EUR/solid m^3 to 28.0 EUR/solid m^3 (Table 3).

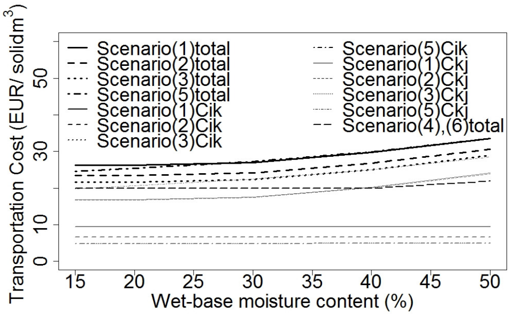

Fig. 4. *Average costs according to the moisture content*

Comparing scenarios with spur roads to those with secondary roads, the transportation costs were reduced by 4.7 EUR/solid m^3 on average by upgrading spur roads to secondary roads. It would be reasonable for spur roads to be upgraded to secondary roads. In Scenario (5), timber transportation via spur roads had the second highest cost. Reloading at intermediate landings increased the operation time and the cost despite the largest timber transportation capacity on primary roads. It was also interesting that there were no big differences between the costs whether the demand points were distributed or concentrated in the area, under the same condition. This could be the advantage of the inter-regional primary road. Therefore, the primary roads benefit the biomass transportation for energy, and the combination of the secondary roads is further effective. Biomass drying is strongly recommended since it makes the difference in the transportation costs especially in case of long transportation on primary roads. Additional arrangements are required to reduce the moisture content of logging residue at the roadside for Sugi species [10], but the natural drying of the whole trees up to a moisture content of 30% could be reached by air-drying for 3 to 6 months in the harvesting site [12]. Therefore, the drying of the whole trees in the harvesting site is a practical solution to reduce the transportation costs. The primary road cannot demonstrate its ability unless the materials are dried well.

Table 3

Total transportation costs (EUR/solid m^3) of each scenario at their most economical moisture content

Scenario	Demand	C_{ik}	C_{kj}	C_{ij}	Total
(1) - MC(30)	No. 2	9.4	16.3	–	25.7
	No. 1,2 and 3	9.4	17.6	–	28.0
(2) - MC(30)	No. 2	6.6	14.7	–	21.3
	No. 1,2 and 3	6.6	16.8	–	23.5
(3) - MC(30)	No. 2	4.8	16.1	–	20.9
	No. 1,2 and 3	4.8	17.5	–	22.3
(4), (6) - MC(40)	No. 2	–	–	18.6	18.6
	No. 1,2 and 3	–	–	20.0	20.0
(4) - MC(30)	No. 2	4.8	21.2	–	26.0
	No. 1,2 and 3	4.8	22.5		27.3

MC(x) meant the wet-base moisture content of x %.

There were several limitations in our model. The transportation costs were calculated based on the hourly cost without any delays caused by organisational problems especially such as the interaction between mobile chippers and transportation. In practice, truck scheduling optimisation such as "Fast Truck" [2] would be useful to reduce delays and get close to the optimised cost shown in our study. The construction cost of spur roads should be included in scenarios (1), (3) and (5) because they are a temporary used infrastructure, while the construction cost of primary and secondary roads can be ignored from the operational cost due to their longer life span [13].

5. Conclusions

High standard forest roads are necessary for transporting forest biomass and to enable the access for several demands. The reduction of moisture content is important for chip transportation on primary road and timber transportation. To establish a biomass supply chain, a road network of high standard is indispensable as pointed out [3]. Primary roads developed on mountain ridge bring benefits in the utilization of forests located in mountainous regions. There are such primary roads constructed all over Japan and the activation of those roads will help to create an inter-regional supply of wood products for keeping the diversity of the accessible demand points. Secondary roads support the effective use of primary roads when extracting logging residues for energy and they can also act as the main infrastructure when harvesting timber.

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