博士論文

Studies on Harvesting and Supply Chain Management of Wood Chip for Energy

(木質バイオマスの収集集荷作業システムとサプライチェーンマネジメントに関する研究)

吉田美佳

Contents

1 Introduction

1.1 General background of woody bioenergy utilization for energy in Japan

Forest resources are one of the main natural resources produced in Japan. The forested land accounts for 68.6 % of Japanese land (The World Bank 2015). Japan has the 18th largest percentage of forested area for total land. The country with the largest share of forested area for total land is Republic of Suriname in Africa of 94.6%, followed by Federated States of Micronesia in Pacific Ocean of 91.7 % and Republic of Seychelles in Indian Ocean of 88.5 %. Among the developed countries, Republic of Finland has the largest percentage of 72.9 % followed by Kingdom of Sweden of 69.2 % and Japan. From these facts, it is true that Japan is one of the countries with rich forest resources. Japan is responsible for the globe to realize sustainable forest management in an advanced way. The wood use as a renewable energy resource is a global trend because of the main concerns such as the rising of energy demand and the awareness of climate change, the scarce of fossil fuel, the environmental dilemma caused by fossil and nuclear energy systems (Wolfsmayr and Rauch 2014), and rural area management by creating sustainable job opportunity from local resources (Shabani et al. 2014).

European Union (EU) sets a specific target of renewable energy utilization that purposes enlarging the share of renewable energy to 20 % of total energy (European Commission 2013). Fig. 1.1 shows the share of solid biofuels excluding charcoal for total energy consumption. While there was a variance among countries, the share of solid biofuels was definitely increasing in EU countries. They also start to use liquid biofuels, and the share of renewable energy of 28 European countries was 15 % of total energy in 2013 (European Commission 2013).

North America is also promoting the use of renewable energy resources. In US, the total consumption of woody bioenergy was 2,214 quadrillion Btu (A quadrillion Btu equals to 1015 Btu which means 1.055 ×1018 J) in 2014 (US Energy information Administration 2015). While the share of renewable energy sources to total energy was 12.0 %, woody bioenergy had the biggest share among renewable resources and shared 2.8 % of total energy consumption (US Energy Information Administration 2015). In Canada, 16.9 %

of primary energy supply was provided from renewable resources. Energy from biomass resources is the third most important form of renewable energy after hydro and wind powers (Government of Canada 2014). The interest for woody bioenergy exists and they think about the economical way to supply and to consume woody bioenergy (Government of Canada 2015). The unique point in Canadian woody bioenergy utilization is wood pellets. They export 85 % of pellet production, which is equivalent to 1.3 million tonnes and less than 1 % of Canadian forest sector exports by value, to European countries. Their contribution to reduce fossil fuels is, therefore, appeared to the share of woody bioenergy in EU (Government of Canada 2015).

Among advanced countries in renewable energy utilization, such as Nordic and Central European countries, wood materials have already become the most dominant resource and the countries in North America are also thinking about the use of woody bioenergy and starting to use. Compared to these facts, the trend of woody bioenergy in Japan is the great matter of attention. Fig. 1.2 shows the changes of energy consumption in Japan from 1965 to 2012 (Agency for Natural Resources and Energy 2014). With the background of economic growth, the energy consumption is getting larger and larger. In 2012, only 7.9 % of the total energy consumption was derived from non-fossil energy resources and the energy from renewable resources accounted only 4.0 % of the total energy consumption (Agency for Natural Resources and Energy 2014). Compared with the above countries, it is clear that the wood use as an energy resource is not advanced in Japan while there is a high potential of woody bioenergy compared to other domestic natural resources.

The energy use of woody bioenergy is originally not a novel topic for Japanese forestry. Woody bioenergy had been utilized as firewood and charcoal in daily life until around 1960's. Figs. 1.3 and 1.4 show the change of firewood and charcoal production amount, and these have been diminished after 1960 mainly because of the change of Japanese lifestyle by oil energy (Forestry Agency 2015a). Besides the rise of oil energy, the rehabilitation from Second World War required coniferous forest, and artificial planted coniferous forests increased (Fig. 1.5). Such transition from deciduous to coniferous forests made forestry operations more labour intensive and professional work, and it meant forestry industries modern industrialized.

Apart from such situations, energy use of woody bioenergy had been promoted in 1980's motivated by the two oil crises in 1970's, which were worldwide issues. The movement ended along with the decrease of oil price, and all woody bioenergy attracted attention from all over the world again in the context of contribution for global warming. The latter movement promoted thinning to save greenhouse gas (GHG) emission. Under the Kyoto Protocol, which was an international treaty about the reduction of GHG emission and adopted in 1997, four forestry activities: afforestation; reforestation; deforestation; and forest management; were counted as works with GHG emission/removal. Japan set a domestic target for GHG removal by forest management and supported thinning operation financially.

Consequently, during the period from 2007 to 2011, 2.76 million ha of planted forest had been thinned. The volume of carbon sequestrated in 2011 was equivalent to 4.0 % of overall GHG emission in the base year of 1990 (Forestry Agency 2013). Compared to the national emission reduction commitment target of 6 % of overall GHG emission in the base year during 2008 to 2012, 3.8 % of GHG removal has achieved by forestry (Forestry Agency 2015a) so that forestry has played an important role in a domestic GHG removal activity. However, it can be said that Japanese rich forest resources have slept yet without showing the potential of GHG removal, and the use of forest resources should be promoted sustainably to contribute for global warming in universal standard. Yet Japanese governmental strategy has recommended several times of thinning without clear cut, clear cutting is more economical (Toyama et al. 2012) and required for sustainable forestry because the aging structure of plantation forest (Forestry Agency 2015a). Timber price decreases steadily (Fig. 1.6) and innovation in production systems is urgently required (Yoshioka 2011).

Cut to length system using harvesters and forwarders have been introduced as an efficient system. Branches, tops and low quality timbers have been, however, accumulated and abandoned at forest sites or landings as logging residues because of their economical infeasibility (Yoshioka et al. 2000) although Japanese government has provided financial support for thinning to local government according to Thinning Promotion Special Law (Forestry Agency 2014). The amount of logging residues is, consequently, estimated at 20 millions solid m^3 annually (Forestry Agency 2015a) and the use of these logging residues for energy is expected to bring extra profit for forest owners and contractors.

The efficient system to collect and use these logging residues is a big issue in the context of the economy of forest industries besides the ecological context of reducing GHG emission. This new market of woody material as an energy resource has a big meaning for industries under the current timber market where the product prices keep decreasing (Nakama et al. 2011). It was reported that only 276 companies (8 %) produced over 10,000 solid m^3 annually in 2010 and they were supposed to produce about 55 % of annual material production — 6.03 million solid m^3 — in Japan in 2010 (Forestry Agency 2015a) and they were supposed to become the main stakeholders of Japanese forestry. About the half of the annual production was, however, from a lot of small scale forest owners or entrepreneurs. It was not possible to ignore the system for small scale forestry while the economy of such forestry seemed more severe than those of large scale ones. Studies on economy of woody bioenergy utilization as an energy resource both for large and small scale forestry are strongly required.

1.2 Previous studies of woody bioenergy utilization for energy

The aspect of supply chain management (SCM) is indispensable to flow it smoothly because woody bioenergy utilization can be regarded as a product flow from forests to markets. As the use of woody biomass energy becomes common, reviewing researches are now available from the aspect of harvesting, volume estimation, energy conversion (e.g. An et al. (2011), Wolfsmayr and Rauch (2014)). The highlighted studies were, therefore, presented from below. Firstly the basic idea of SCM was introduced. Then, studies about the collection of logging residues and its processing were summarized.

1.2.1 Basic idea of supply chain management

SCM includes several key issues such as: logistical management; total system costing; holistic approach; and total production management (Pulkki 2001), and they were classified into two broad decision categories: strategic and operational levels; and four major decision areas: location, production, inventory, and transportation (Ganeshan and Harrison 1995). Decision categories were defined from the aspect of time span, and sometimes added a tactical level between strategic and operational levels (An et al. 2011). Strategic levels are made over a longer time horizon than operational decisions which are over a day-to-day basis and operational decisions are made for efficient management in the product flow of strategically planned supply chain (Ganeshan and Harrison 1995). For SCM analysis, it is important to take time span into account.

Supply chains of wood materials for fuel were characterized by types of assortment at the end of supply chain, for instance: logging residues; low quality logs; stumps and roots; bundles; chips; and bark; and these characteristic affected decisions in above four areas. Because logging residues can be collected during timber harvesting operation at the same time and save collection cost for logging residues, there was an economical advantage when using logging residue as a resource (Barua and Bonilha 2013). For realizing this advantage, whole tree harvesting (WTH) systems have become popular (Hytönen and Moilanen 2014).

Logging residues are bulky form as wood material for energy. For instance, their bulk density was reported as only 120 to 150 kg/m^3, while it should be about 250 to 280 kg/m^3 for realizing full payload of trucks in the US context (Angus-Hankin et al. 1995). In a Finnish study, it was summarized that the solid volume content of logging residue was 0.15 to 0.20 while that of chip was 0.36 to 0.46 (Ranta and Rinne 2006). In a Japanese study, it was reported that the density of branches was 0.06 dry tonnes/m^3 and increasing around 0.1 dry tonnes/m^3 by the chopping operation using a scissor grapple (Yoshida et al. 2011).

Comminution increases the bulk density of logging residues and it is also indispensable before using wood material as energy (Wolfsmayr and Rauch 2014). Supply chains with comminution process have been, therefore, studied on its economical performance. It is found that the allocation of comminution process is crucial for the whole supply system (Laitila 2008) and chip supply chains can be categorized into four chains by the location of comminution such as: terrain comminution; roadside comminution; terminal comminution; and comminution at plant (Kärhä 2011). The most common supply chain among eight European countries (Czech Republic, Finland, France, Hungary, Poland, Slovakia, Spain, and the UK) was the chip supply chain using roadside comminution by a truck mounted chipper and a separated truck trailer (Asikainen et al. 2008). In Austria, approximately two third of the volume for fuel was from roadside comminution (Rauch and Gronalt 2011). In American and Canadian contexts, while it was not specially recommended, comminution at harvesting site was expressed as densification of in-woods residues for efficient transportation, and the use of grinders was mentioned as well as mobile chippers

(Jackson et al. 2010). Chip supply by roadside comminution can be considered as one of the main supply chains of logging residues.

In the chip supply chain using roadside comminution, the economical effect of interaction between comminution operation and transportation was pointed out (Asikainen 1998). Generally produced chip was directory loaded into a container or a truck bin to avoid the contamination of ground materials which degrade the quality of chip. The interaction caused waiting time on both a comminution machine and a truck. A study simulated this effect on the supply cost by using stochastic simulation taking the conditions of road surface into account (Zamora-Cristales et al. 2013) and another study simulated the effect between the chip harvester and a bin forwarder (Talbot and Suadicani 2005). From these studies, for economical production it was important how to keep the comminution machine working, which differed by not only the system design itself but also by the transportation distance.

The price of chip is classified according to quality, and differed by site. According to a report about chip price from 2011 to 2014 among nine European countries (Austria, Croatia, Germany, Greece, Ireland, Italy, Romania, Slovenia, and Spain), the chip price of popular quality was 56.3 EUR/t in Croatia while 136.2 EUR/t in Ireland followed by 132.0 EUR/t in Austria in the first half of 2014 (Biomass Trade and Logistics Centres 2014). It was also reported that the price of chip from logging residues varied from 60 EUR/t to 140 EUR/t in Germany in 2010 (Kumazaki 2011). It was difficult to predict the future trend of Japanese chip market from these data so that it was necessary to keep up the research about price.

1.2.2 Whole tree harvesting systems

Even categorized as WTH systems, there is a big difference between vehicle systems and cable systems. In Finland, vehicle systems with a single or multi grip harvester head are popular, and a lot of studies about their productivity and economical efficiency were performed (Laitila et al. 2010). On the other hand, cable-yarding systems are popular and still indispensable in Japan because of the steep terrain conditions of mountainous forests where the vehicle systems could not be available (Sakai and Kamiizaka 1980). Recently, whole tree harvesting systems by cable systems mainly using swing or tower yarders are recommended again for Japanese forestry (Forestry Agency 2015a).

Tower yarder systems are widely used in Central Europe (Leo et al. 2014) such as Austria, where holds the Alps mountainous area and covered with dense road network of 45 m/ha (Ghaffariyan et al. 2010), Switzerland and Italy, where also hold the Alps mountainous area. In Norway, on the contrary, swing yarders which are mounted on excavators as undercarriage are found to be suitable for their shallow and unstable boreal forest land with trees of small volume (Talbot et al. 2015).

These two systems are certainly economical on appropriate harvesting while the new structure of systems combining tower yarder and winching systems has been suggested regarding the mature of planted forest (Suzuki et al. 2015). On the other hand, tower yarder systems seem to have the difficulty of introducing into forests because of Japanese narrow forest and public road network and the restrictions on total vehicle weight basically up to 20 tonnes and height up to 3.8 m by the road traffic law. It will take a time to overcome such the problems in social structure. Swing yarder systems are easier to introduce and actually introduced more than tower yarders (Forestry Agency 2015a) because it is a conventional excavator based machines. The economical harvesting area of swing yarders was, however, as short as that of winching systems and the advantage of swing yarders was suspected (Yamada et al. 2010). Winching system is simple and the studies about it have not been updated while the state-of-art machines are introduced in 2010. It is necessary to update the basic data and to clarify the advantage of innovative machines.

1.2.3 Roadside comminution

Mobile machines are necessary for the roadside comminution system and a lot of studies about the machines have been conducted. From technical aspect, there is the comparison of productivities between drum and disk chippers (Spinelli et al. 2013), the analysis of the effect on productivity from piece size and material type (Assirelli et al. 2013), and the damage of blade wear during operation and its effect on productivity and chip size distribution (Nati et al. 2010, Spinelli et al. 2014). The idealistic situation for the most economical operation became obvious — the sharp knives, and the larger material and screen size. There are also a lot of studies comparing machines and systems in practice and the difference among systems could be seen (Table 1.1). These are indeed important for evaluating the machine ability but it is difficult to find an appropriate machine only from the information about productivity and calculated costs. The criteria for choosing a machine should be clarified by the initial investment of machine and the business scale of entrepreneur.

1.2.4 Transportation

Because transportation process included the problems related to road network, it included more wider range of topics on not only the comparison among systems but also optimization problems, volume estimation, network analysis, facility allocation problems and scheduling problems. The basic purpose through the studies was to minimize the supply cost while satisfying the demand. To reduce the transportation cost over long distances, the use of railway (Karttunen et al. 2013) and water ways (Karttunen et al. 2012) were researched. The economical advantage of such transportation was significant especially when transporting exceeded over 100 km transportation. To secure the supply satisfying the demand, material flow optimization should be developed by analyzing the cost including storage allocation problem (Eriksson and Björheden 1989, Kanzian et al. 2009). These studies included the use or change of infrastructures, and the positive effect on the economy was clarified. Contrary to these studies on tactical level, the result of system comparison between comminution and transportation processes on the operational level showed that there was flexibility in the machine combination while the larger trucks were basically more economical (Zamora-Cristales et al. 2015). Methodologies from operational research using geographic information will be useful and powerful for solve the problems in transportation process.

In Japan, the basic geographical data obtained by light detection and ranging (LiDAR) and geological structure map are used in the field about automatic road construction (Saito et al. 2013, Son et al. 2014) and the estimation of stock volume is also done by using geographic information system (GIS) (Kamimura et al. 2012). The minimization of transportation cost has been tried in the timber transportation process (Shirasawa et al. 2013). The study for transportation of wood chip for energy has considering geographic information not yet completely studied and it is urgently required.

1.3 Problem definition and objective of this study

Problems in the supply chain of wood chip for energy are roughly divided into the problem in harvesting and in supply chain management. It is necessary to establish efficient harvesting systems to collect lower quality timbers and the bulky part of tree which have been abandoned after harvesting. Whole tree harvesting is regarded as a useful method, and the advantage of simple winching system using the state-of-art machine is an interesting topic to classify the whole tree harvesting systems. Managing supply chain means optimizing the supply flow and minimizing the supply cost. In the supply chain of wood chip for energy, optimizing comminution and transportation processes is the target and the theory should be established and applied in actual areas. The objective of this study is to illustrate an economical chip supply chain using mobile chippers at landings in forest based on the analysis of harvesting, comminution and transportation processes.

This study is consisted of five parts of analysis. In the chapter 2, a winch harvesting system using powerful tractor was investigated its productivity both on flat and steep terrain conditions to clarify its ability, and the new winching method which would save fuel consumption was suggested. In the chapter 3, five different mobile chippers were investigated on its productivity by using stochastic simulation model to evaluate their objective productivity. In the chapter 4, the way of rational chipper choice according to business scale was shown by using regression analysis between the costs and the engine power of chipper. In the chapter 5, the total costs for chip supply was calculated for districts in a region and compared each other to those when using timbers as chip material in a model area. The allocation of mobile chippers was also analyzed to see the effect of interaction between chipping and transportation processes and transportation distance in a system. In the chapter 6, the key for the successful establishment of chip supply chain was tried to be found by analyzing an advanced supply chain model in Denmark. The summary of these five analyses and forward for the future were in the last chapter 7.

Table 1.1: Comminution cost data obtained from previous studies

Country	Material	Productivity	2),3)Comminution cost	Reference
EU	Logs	100 loose m^3/hr	193	Francescato et al. (2008)
EU	Logging residues	55 loose m^3/hr	359	Francescato et al. (2008)
EU	Full tree	60 loose m^3/hr	331	Francescato et al. (2008)
Italy	Logging residues	1)n.a	498	Valente et al. (2014)
Norway	Bundled logging residues	1)n.a	193	Valente et al. (2014)
Finland	Logging residues	55.0 loose m^3/hr	193	Asikainen and Pulkkinen (1998)
Finland	Logging residues	23.0 loose m^3/hr	162	Asikainen and Pulkkinen (1998)
Finland	Logging residues	50 to 60 loose m^3/hr	278	Asikainen and Pulkkinen (1998)
Spain	Logging residues	56.2 loose m^3/hr	634	Tolosana et al. (2011)
Spain	Logging residues	33.8 loose m^3/hr	610	Tolosana et al. (2011)
US	Logging residues	36.7 Dry-t/hr	290	Harrill and Han (2010)

Japan	Logging residues	[1]n.a	441	Moriguchi et al. (2004)
Japan	Logging residues	17.28 loose m^3/hr	1,985	Yoshioka et al. (2002)
Japan	Logging residues	883.3 kg/hr	419	Yoshioka et al. (2006)

[1] The abbreviation "n.a" meant "not available".

[2] The currency ratio was 138.048 YEN/EUR, 119.388 YEN/USD, and 0.151 USD/FIM. FIM meant "Finnish markka".

[3] The units were converted by coefficients of 2.8 loose m^3/solid m3, 0.25 t/loose m3, 3.6 GJ/MWh, and 2.6 GJ/loose m^3.

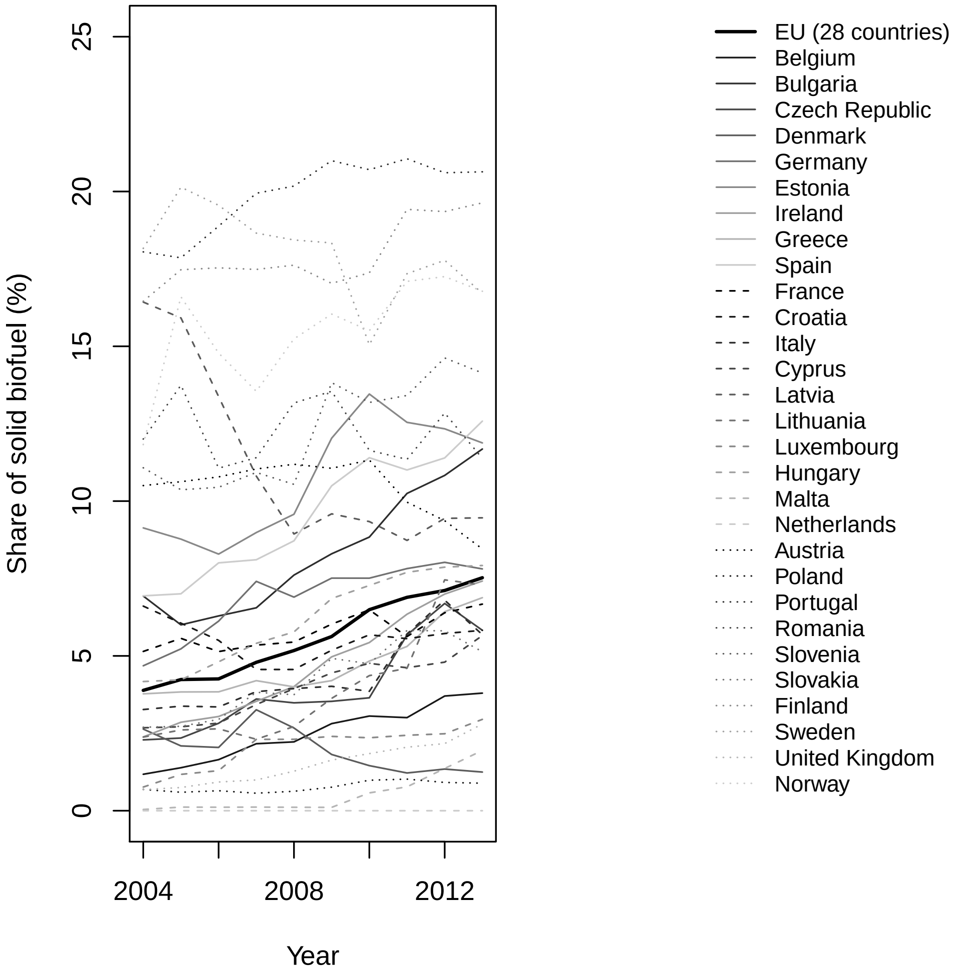


Fig. 1.1: Share of solid biofuels in 28 European countries

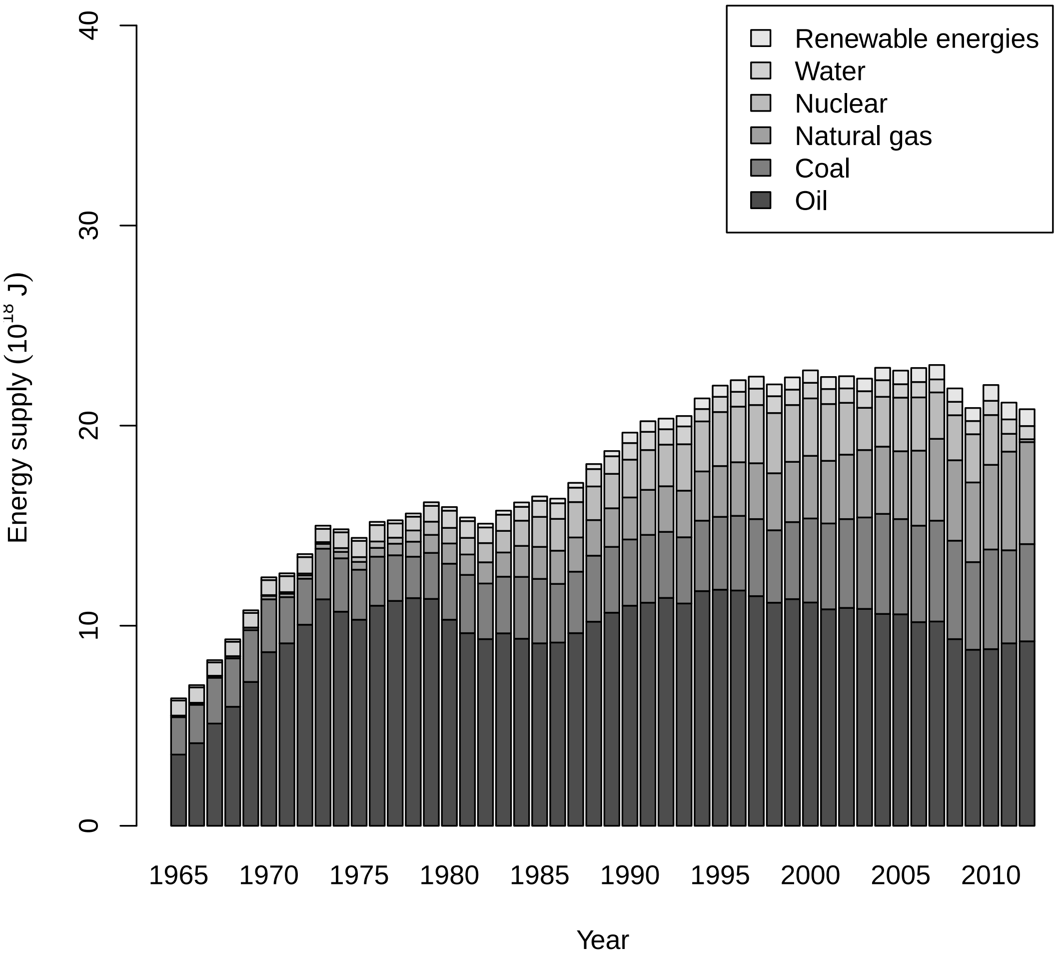


Fig. 1.2: Energy consumption in Japan from 1965 to 2012

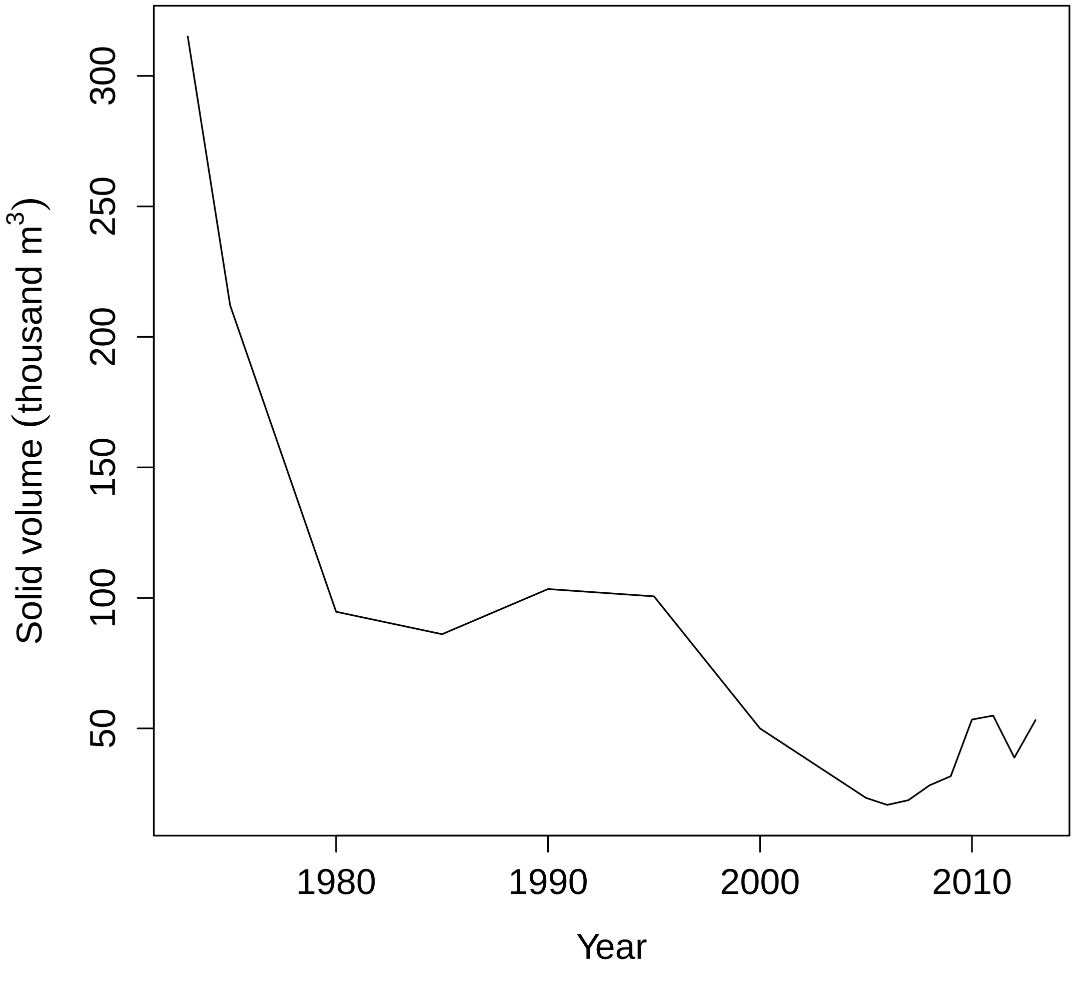


Fig. 1.3: Fire wood production in Japan

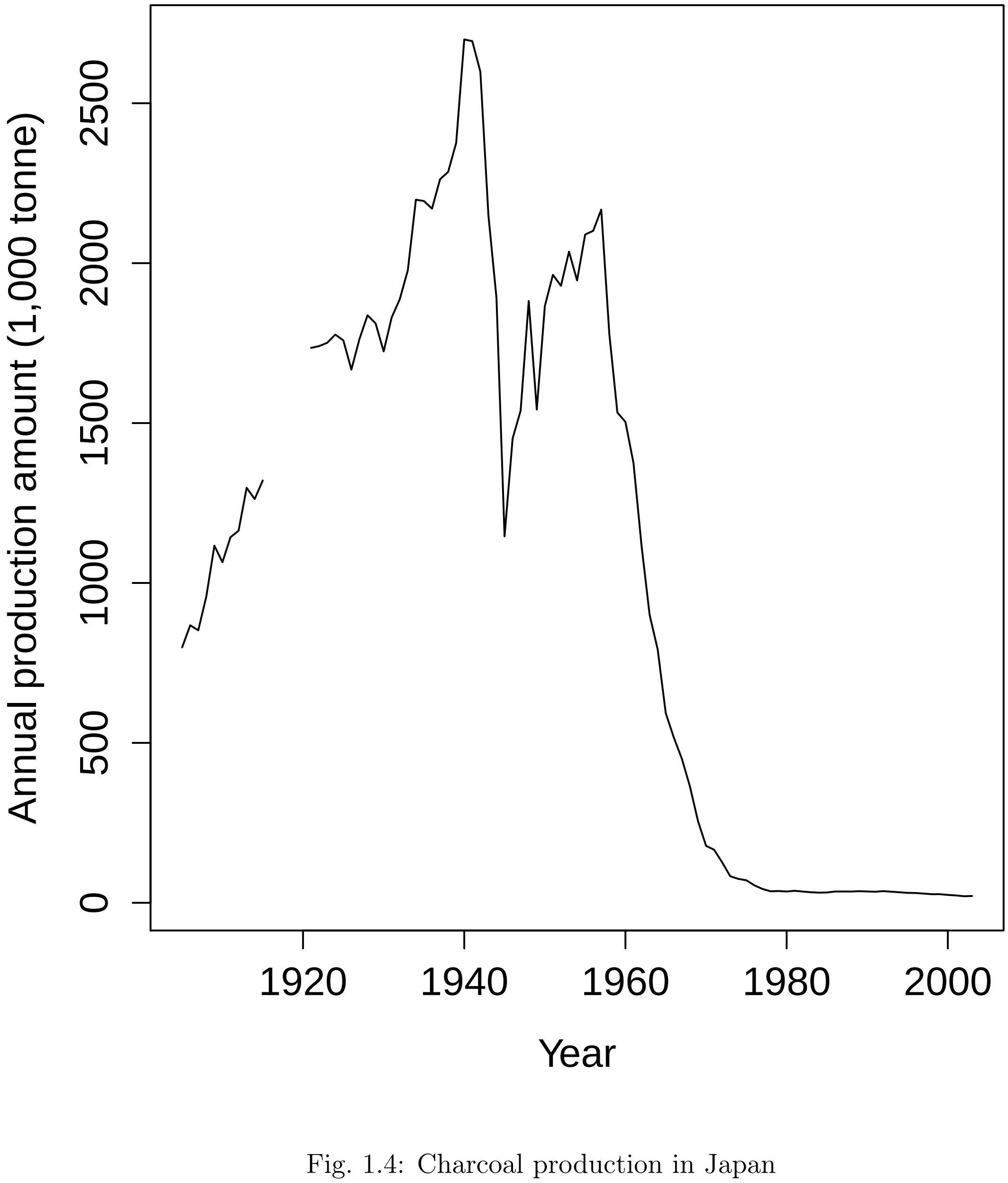


Fig. 1.4: Charcoal production in Japan

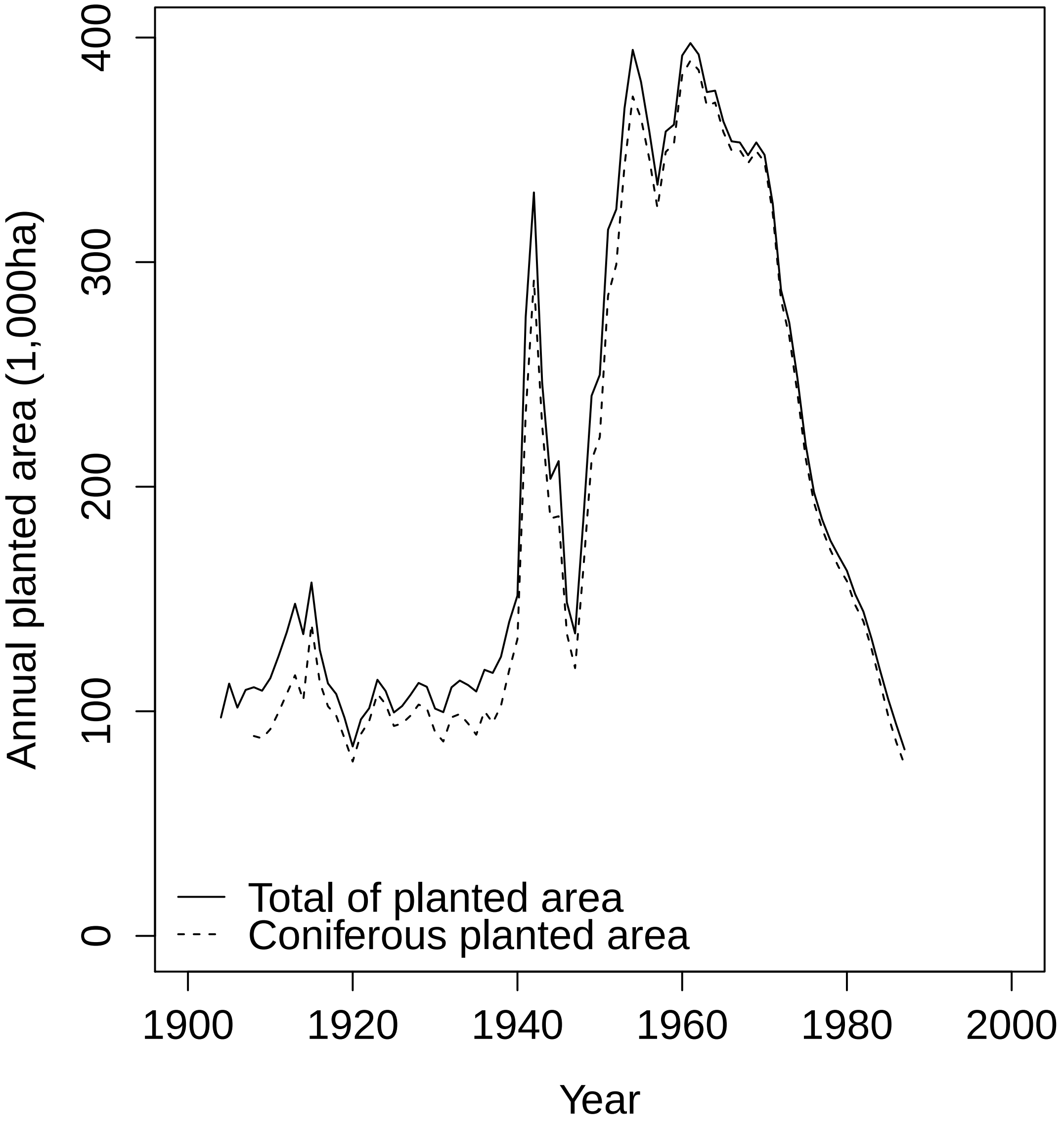


Fig. 1.5: Transition of planted area

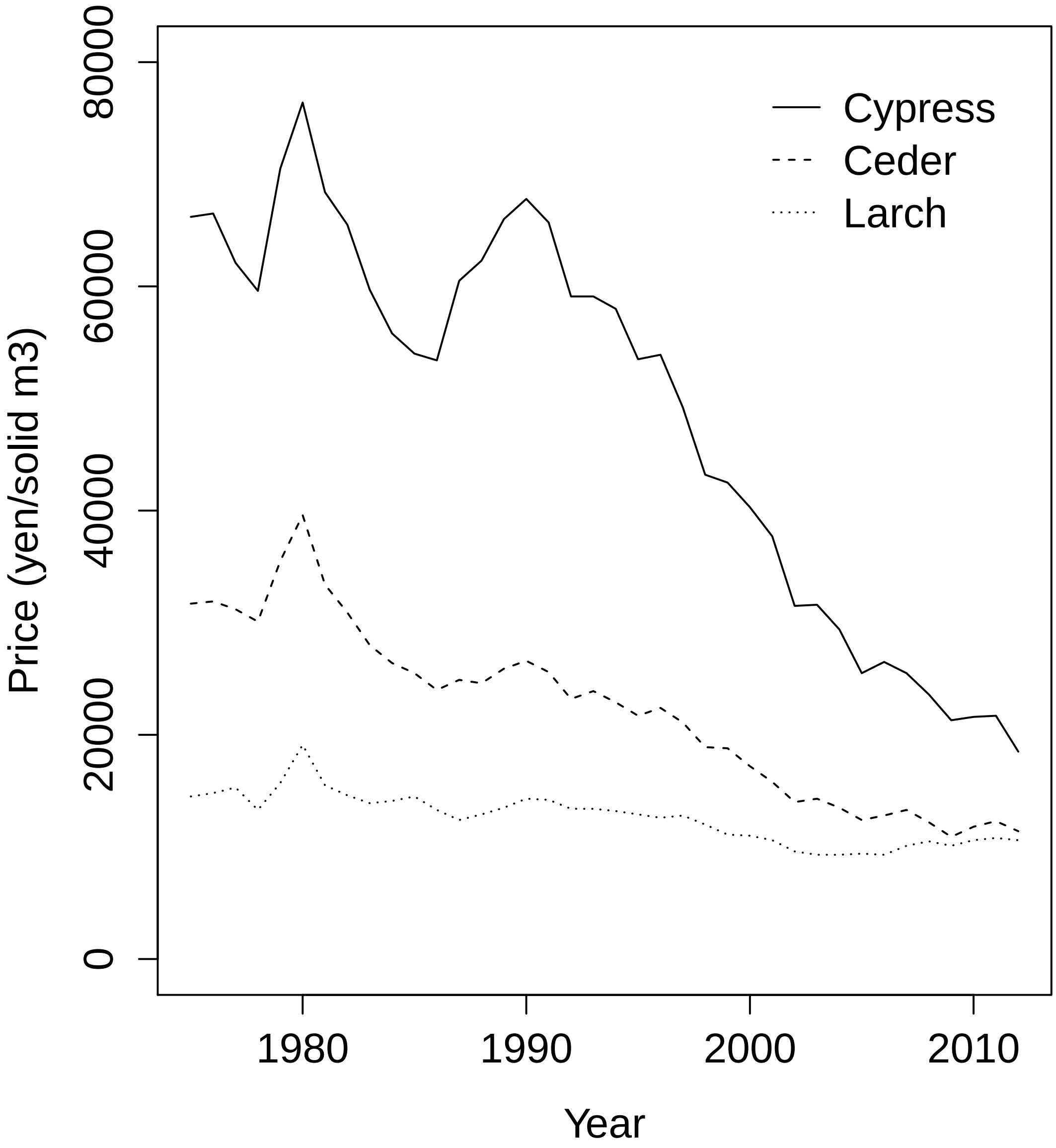


Fig. 1.6: Timber prices of main product

2 Winch harvesting on flat and steep terrain areas and improvement of its methodology

2.1 Introduction

Feed in tariff (FIT) law came to effect on July 1st, 2012, in Japan and the price of electric energy from unused wood materials was set at 32 JPY/kWh (0.3 USD/kWh, 1 USD=101.6 yen, 2014/5/09) which was decided on the basis of the high logging cost and intended to motivate to harvest unused wood materials. In this context, whole tree harvesting methods using cable systems had been reflected. A previous work that studied the relationship between material prices and production cost of line thinning emphasized that fully utilization of felled trees was necessary to reduce production cost (Yoshino et al. 2010). Whole tree harvesting method is suitable for fully utilization of felled trees because the method keeps the recovery rate at an operation site (Laitila et al. 2010), and logging residue from whole tree harvesting can be a by-product of conventional timber harvesting, which covers the extraction cost of these residues (Stampfer and Kanzian 2006). Economical profit from fuel utilization of unused wood materials such as tree tops and slashes is expected.

On-ground winch harvesting is a basic system among the cable systems. It is applicable to uphill and downhill harvesting on flat and steep slopes. Wheel tractors with a winch-attachment were tried to introduce in 2010 on both flat and steep slope areas in Japan while the major winch equipment had been winch attachments on excavators, called ”swing yarder”. It was pointed out that the high production and energy/fuel costs associated with mechanical harvesting of forest biomass were the major factors that could impede the use of forest biomass for energy (Pan et al. 2008). Tractors have multi functions with various kinds of attachments and will reduce the harvesting cost by using in many ways efficiently (Johansson 1997). Therefore, the winch system on a wheel tractor is expected to realize lower harvesting cost especially in young forest stands. Moreover, such multi functional characteristic seems to be appropriate to small scale operational site because it has not enough operational area to keep working on a single operation.

It is important to know the appropriate time standards for proper arrangement of tender procedures and for rational planning of operations (Sowa and Szewczyk 2013). As well as studies on the time standards, the effect of slope conditions to the harvesting productivity and the winch harvesting procedure itself are also an important topic to study for above purposes. In this study, we analysed two winching procedures that were observed during actual thinning operations with a winch attachment on a tractor on flat and steep slopes. Winch harvesting productivity and operator's walking speed on flat and steep terrain situations were analysed based on results of time studies, and two ideas of winching procedure from the aspect of load or fuel reduction were evaluated.

2.2 Materials and methods

2.2.1 Materials

Two typical different thinning sites, sites A and B, were investigated. Site A was located at a forest in Tsurui Village, Hokkaido Island whose terrain was moderate flat. The surface of skidding corridors was covered with bamboo grass and logging residue (Fig. 2.1). On-ground winch harvesting was practiced by the tractor, Fendt Werner Wario714 (96 kW), with Schlang & Reichrt remote controlled double winches. One of the winch drums was equipped with wire rope. Its diameter was 14 mm and the weight was 0.704 kg/m. The other, which was used during this investigation, was equipped with textile rope. Its diameter was 14 mm and the weight was 0.1 kg/m. The maximum rope length was 90 m for both drums. The tractive force of two winches was both 8.2 tonnes. Trees were previously felled and delimbed by chainsaw. Tree species was larch (*Larix kaempferi*) which was easy to delimb because of less branches. The average volume of harvested trees was 0.28 m^3. An operator harvested logs from a forest land to the spur road side by the remote controlled winch in tree length condition. The experienced year of the operator was two and half years, and mainly engaged in tractor operation for two years.

Site B was located at a forest on a steep terrain in Kami City, Shikoku Island where the average slope was 35 degrees. The forest surface was black soil. The tree species was Japanese cedar (*Cryptomeria japonica*) and the average volume of harvested trees was 0.50 m^3. On-ground uphill winch harvesting was practiced by the tractor, John Deere 6930 (114 kW), equipped with Schlang & Reichrt 's remote controlled double winches as same as site A. One of the two winch ropes was wire rope with 10 mm in diameter and the other was textile rope with 10 mm in diameter. The maximum rope length was 90 m. An experienced operator harvested logs from forest to forest roadside in whole tree condition.

At site A, felled trees were scattered because of selection thinning, whereas felled trees were concentrated in a line at site B. In this way, the felling situations and the harvesting procedures were different between sites A and B. For convenience, the harvesting procedure at sites A and B were named as ”Procedure A” and ”Procedure B”, respectively, not depending on terrain conditions.

2.2.2 Observation method

Time of winch harvesting was measured by stopwatching to calculate productivities. Work elements of winch harvesting were classified into 6 elements: releasing, pulling the winch rope to logs; attaching, attaching felled trees to the winch rope; reeling, reeling the winch rope; detaching, detaching winch rope at roadside from logs; stop, all operational stops of winch due to search logs and ways and others; and delay, all delays due to mechanical, personal and organizational causes. Operations were also recorded by a video camera. At site A, the positions of worker and tractor were recorded by GPS logger with the interval of every second to measure skidding distances because felled trees were scattered and it was difficult to measure distance during operation. Skidding distances were calculated from the data of latitude, longitude and altitude referred as straight line. At site B, it was possible to observe operation by eyesight because felled trees were concentrated along a line and the understory vegetation was sparse. Skidding distances were measured by a laser range finder. Other components needed for analysis were obtained by interview. The velocities of releasing and reeling operations were calculated from operation time and skidding distance. Average time of attaching and detaching operations and stop were also calculated. The data obtained from these observations were used in the following analysis.

2.2.3 Productivity calculation method

Cycle time and the productivity of winch harvesting, Cy (sec) and P (m^3/h), were derived theoretically from equations (1) and (2), respectively, according to the maximum skidding distance based on the equation by (Sakai and Kamiizaka 1985):

$$Cy = D(1/v_1 + 1/v_2) + iT_a + T_d + T_s \tag{1}$$

where D was the maximum winch skidding distance (m); v_1, the velocity of reeling (m/sec); v_2, the velocity of releasing (m/sec); i, the number of attaching operation in a cycle (i times/cycle); T_a, the time for attaching operation (sec); T_d, the time for detaching operation (sec); and T_s was the time for stop (sec):

$$P = 3600jV/C_y \tag{2}$$

$$i, j \leq 3$$

where j was the number of harvested trees in a cycle (trees/cycle); and V , the average tree volume (m^3/tree). Productivities of both procedures on actual sites were calculated and also simulated to compare when the average volume of trees V was set equal as 0.2 m^3 here as a representation of a young forest. The combinations of i and j were expressed as (i, j), and it was assumed that three trees could be harvested in a cycle at the maximum from the observation. Thus, the possible combinations of (i, j) were, (3,3), (2,2), and (1,1) for Procedure A, and (3,3), (2,3), (1,3), (1,2), (2,2) and (1,1) for Procedure B. The average of reeling and releasing velocities, and the average time of attaching, detaching, and stop were used in this calculation.

2.3 Results

The examples of GPS data were shown in Fig. 2.2 The average of Horizontal Dilution of Precision (HDOP) was 0.922, so that the GPS data was considered enough accurate for the analysis. The situations of Procedures A and B could be schematically illustrated as shown in Fig. 2.3 from this GPS data. In Procedure A, logs scattered around a skidding corridor were one-by-one attached to winch rope during reeling operations. On the contrary, a couple of logs could be bundled by a sling rope and attached at one time in Procedure B. When harvesting in these typical situations where 9 logs located at locations 1 to 3, the numbers of harvested trees and cycles were the same between Procedures A and B as discussed later.

At site A, the observed 17 cycles among total 18 cycles of winch harvesting operation time during 1.3 hours were used to analyze velocity because there was an error of GPS. The average winch skidding distance was 28 m. Average releasing and reeling velocities that were calculated from the time including walking accompanied with logs were 0.53 m/sec (n=17, SD=0.20, max=1.05, min=0.20) and 0.43 m/sec (n=17, SD=0.17, max=0.78, min=0.04), respectively. The average time for attaching operation and detaching operation were 18 sec (n=53, SD=13, max=67, min=2), and 19 sec (n=18, SD=14, max=51, min=6), respectively. Forty-nine trees were hauled. The average number of attaching operation in a cycle was 2.94 times, and 2.72 trees were harvested in a cycle. The reason why the number of harvested trees less than that of attaching operations was that attaching operations failed sometimes. The actual harvesting productivity of Procedure A at site A was 13.5 m^3/h for the average tree volume 0.28 m^3.

At site B, total observed winch harvesting operation time was 42 minutes. Skidding distances of all 9 cycles were measured and the average distance was 18 m. In releasing, data of 8 cycles were used to calculate the average releasing velocity because there was an extra operation and it was difficult to separate from releasing operation in a cycle. Data of 7 cycles were used to calculate the average reeling velocity because of the same reason as above. The average releasing and reeling velocities were calculated including walking time were 0.67 m/sec (n=8, SD=0.34, max=1.16, min=0.22) and 0.26 m/sec (n=7, SD=0.14, max=0.48, min=0.09), respectively. The average time for attaching operation and detaching operation were 18 sec (n=11, SD=12, max=49, min=6), and 16 sec (n=9, SD=10, max=31, min=5), respectively. Eighteen trees were hauled. The average numbers of attaching operation in a cycle and harvested trees in a cycle were 1.22 times and 2 trees, respectively. The actual harvesting productivity of Procedure B at site B was 17.4 m^3/h for the average tree volume 0.5 m^3.

Differences in velocities and time consumptions between sites A and B were checked by t-test, and there was a significant difference in reeling velocity ($p<0.05$) while there were no differences in releasing velocity and the time consumptions of attaching, detaching, and stop ($p>0.05$) although the experience of operators was much different. Using obtained data in Table 2.1, the productivity P on each site were simulated as shown in Fig. 2.4. It was resulted that the operation was the most productive at both sites A and B when j was 3. The productivity decreased rapidly within the short skidding distance. As a matter of course, the productivity of Procedure B decreased as increasing the number of attaching i, although the reduction was slight. Comparing the Procedures A (3, 3), B (3,3) and B (1,3) as shown in Fig. 2.5, it was recognized that the procedures with the maximum harvested volume could achieve at the high productivity in a short skidding distance even in a young stands with the average tree volume of 0.2 m^3. The difference between the productivities was larger between the productivities of Procedure A (3,3) and Procedure B (1,3) rather than between Procedure A (3,3) and Procedure B (3,3). Multiple attaching operations are inevitable for Procedure A so that such productivity reduction caused by multiple attaching operations should be taken into account when comparing Procedure A to Procedure B with single attaching operation.

2.4 Discussion

Only in the reeling velocity, there was a significant difference between sites A and B in spite of similar engine horse powers. On the other hand, in a similar study of Imatomi (1997) that experimented releasing and reeling velocities on paved roads with four different terrain conditions, both velocities were affected by terrain conditions. This difference seemed to be caused by the difference of skidding corridor conditions of two studies. The skidding corridors were covered with bamboo grass and logging residue at site A, and with slippery black soil at site B. The actual releasing velocity including operator 's walking might be affected not only by slopes but also by the condition of understory vegetation and surface soil.

The reeling acceleration a (ms^{-2}), and winching power p (kg) of a winch drum can be defined as the following equations (4) and (5) (Sakai and Kamiizaka 1985):

$$a = 2\pi Rr/\eta \tag{3}$$

where R, effective diameter of winch drum (m); r, acceleration of the engine rotation (s^{-2});

and η, the speed reduction ratio, and:

$$p = W(\eta \cos\theta + \sin\theta) + dw \tag{4}$$

where W, the weight of harvested logs (kg); η, the coefficient of friction between soil and logs; θ, the degree of slope (where downhill skidding uses minus); d, the skidding distance (m); and w, the weight of rope (kgm^{-1}). The mechanical work of winch harvesting $F(N)$ was calculated by the following equation (5):

$$F = ap \tag{5}$$

From equations (3) to (5), it is understandable that the mechanical work of winch harvesting becomes heavier as the load increasing. Additionally, the effective diameter of winch drum decreases as the extension of skidding distance, so that it is necessary to maintain the reeling speed by accelerating the engine rotation. Fuel consumption, therefore, increases as attaching logs and extending skidding distance during a cycle. When harvesting in the sample situation of Fig. 3, the mechanical work of Procedure A will be lighter than that of Procedure B because the full load occurs when harvested from only location 1 with Procedure A while that occurs from further points as locations 2 and 3 with Procedure B. The procedure A is preferable in operation site B because it will be possible to reduce fuel consumption with keeping higher productivity.

From the result of productivity simulation, the most effective factor on productivity was the harvested volume in a cycle in both of the procedures. Therefore, to increase on-ground winch harvesting productivity, increasing the harvested volume in a cycle is effective even if the number of attaching operations in a cycle increases. The method like Procedure A was naturally thought out to keep productivity by increasing the number of attaching trees in a cycle gradually within the selection thinning condition.

The productivities of actual operations were higher than those of simulations because the volume of trees was larger than that in the simulations. It indicates that keeping productivity becomes easier as increasing volume of trees. This fact was also supported by the result that the productivity in late thinning sites was higher than those in early thinning sites when the maximum skidding distance was fixed at 50 m (Sowa and Szewczyk 2013). The upturn of winch harvesting productivities was rapid within 30 m of the maximum of skidding distance so that such short skidding distance is appropriate for efficient winch harvesting. For harvesting with longer distance, a mini tower yarder attachment for tractors is simple system (Spinelli et al. 2010). Its productivity was not so varied as extending skidding distance compared with on-ground winch harvesting. Harvesting productivity will be improved by using such different attachments properly according to the maximum harvesting distance from forest road.

2.5 Conclusion

The numbers of harvested logs is the most effective factor for productivity of winch harvesting. The productivity was also affected by the soil and ground conditions in actual operations as well as geographical terrain condition. However, the difference in productivity between on sites A and B was slight within the skidding distance of 30 m when the number of attaching operation was the same. The important point is that winch harvesting may realize the high productivity even in a young forest within short skidding distance and increasing the harvested volume in a cycle.

The number of test was insufficient and more investigations should be necessary for accurate productivity estimation. However, we proposed a new idea of winch harvesting method which would relate to the selection of felling method. Because the mechanical work will become heavier as increasing the harvested volume in a cycle and as extending the skidding distance, Procedure A whose characteristic is one-by-one attaching operations will reduce fuel consumption of winch harvesting. Procedure A will, therefore, benefit the economy and ecology of winch harvesting especially with longer skidding distance from the aspect of saving its fuel consumption although the skidding distance is usually short in the actual logging operation.

It is said that reducing log weight by natural drying is important for transporting bioenergy because the moisture in a wood material makes waste use of transportation energy and reduces the calorific value as raw material for bioenergy (Talbot and Suadicani 2006). Harvesting planning including drying whole trees in forest after felling should be considered, which will totally bring economic and ecological benefit to winch harvesting.

Table 2.1: Averages of winch harvesting efficiencies

Site	Site A	Site B
Releasing velocity v_1 (m/sec)	0.53	0.67
Reeling velocity v_2 (m/sec)	0.43	0.26
Time for attaching T_a (sec)	18	18
Time for detaching T_d (sec)	22	16
Time for stop T_s (sec)	68	57

Fig. 2.1: Skidding operation on site A

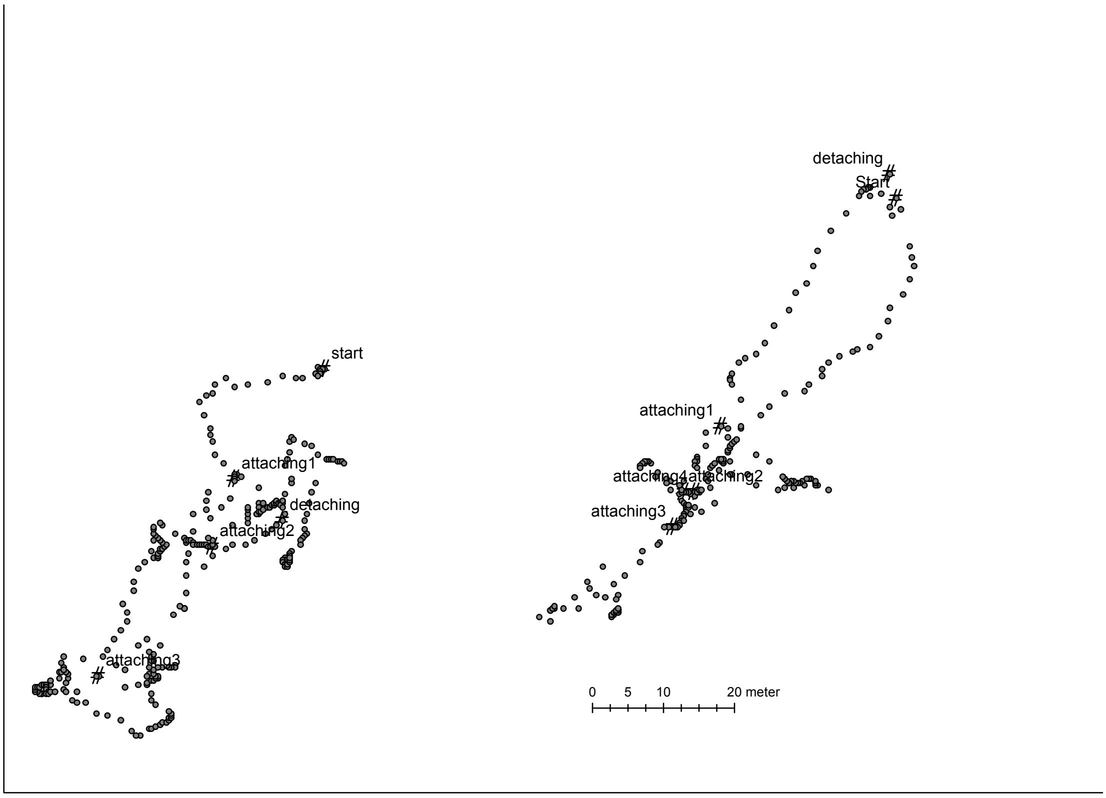
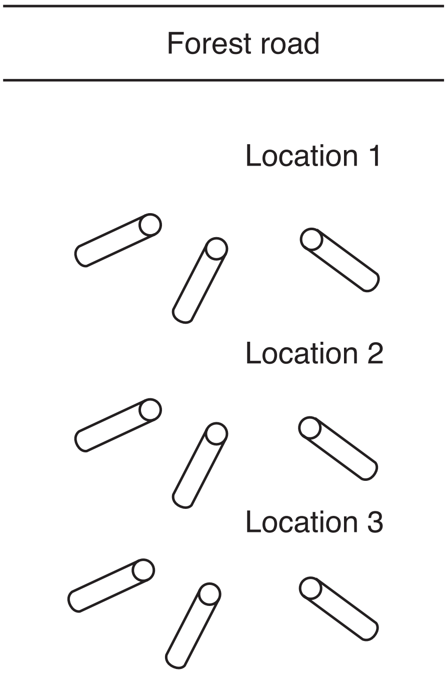


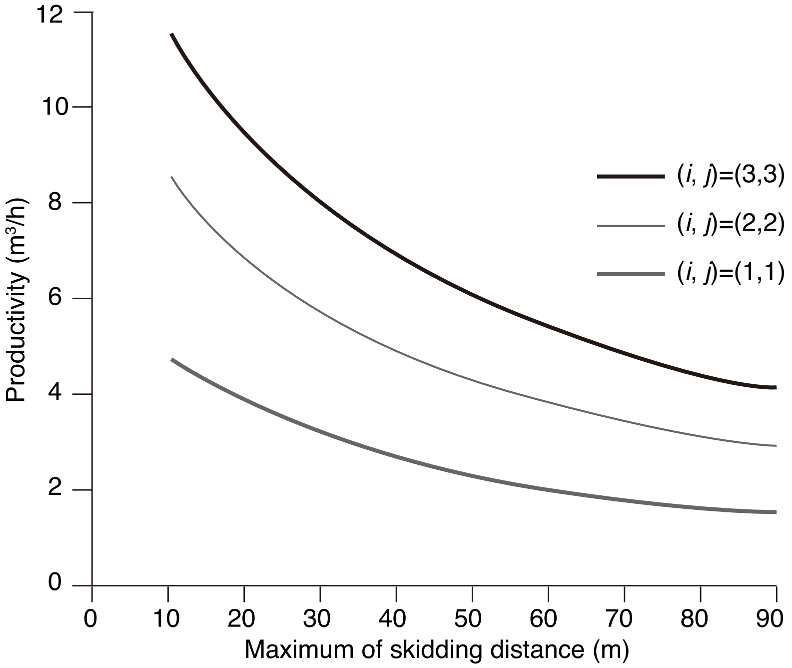
Fig. 2.2: Two examples of GPS track data in skidding operation on site A

(a) Site A

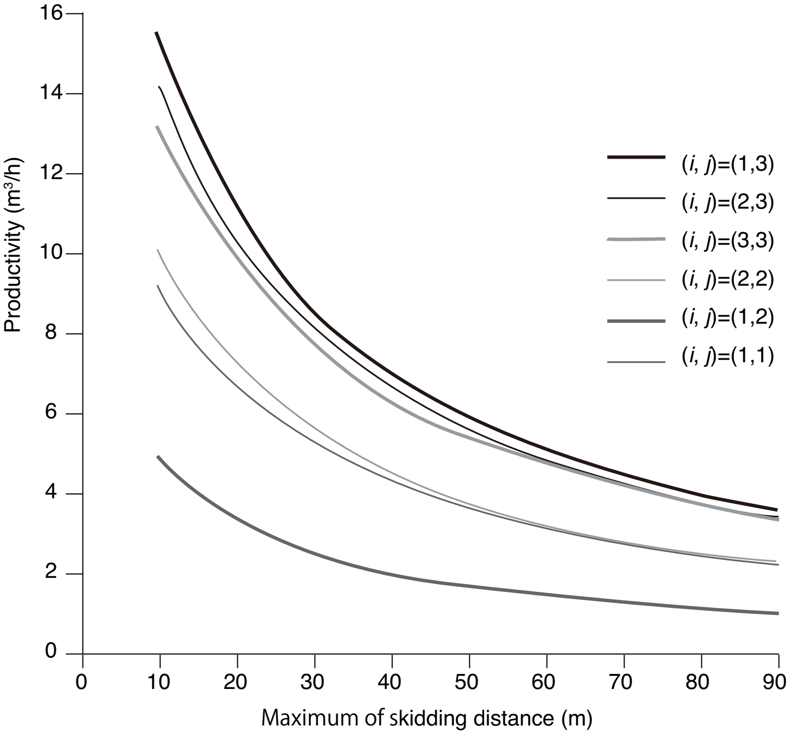


(b) Site B

Fig. 2.3: Skidding situation



(a) Site A



(b) Site B

Fig. 2.4: Harvesting productivity for (the number of attaching operation in a cycle, i, the number of harvested trees in a cycle, j)

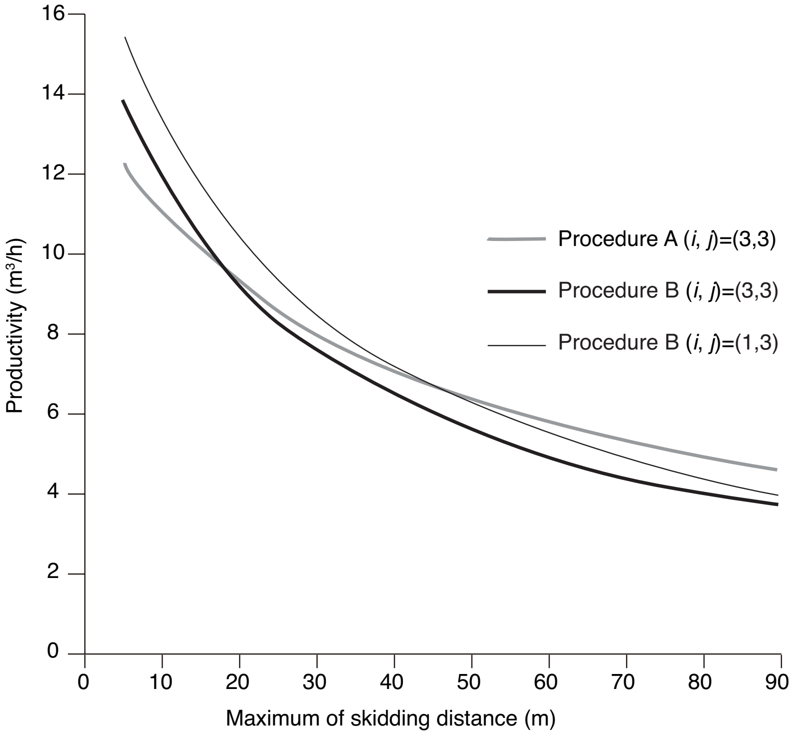


Fig. 2.5: Comparison of productivity among Procedures A and B when (the number of attaching operation in a cycle, i, the number of harvested trees in a cycle, j) was (3,3)

3 Evaluation of chipping productivity with five different mobile chipping types at different forest sites by a stochastic model

3.1 Introduction

Japanese forestry has suffered in part by low profitability of timber selling; the low price of timber materials; and conclusively, the lower timber quality of harvested trees due to poor management of planted stock in the planted forests, which accounted a quarter of Japan's land (Forestry Agency 2015a). The wood use as a renewable energy resource is a global trend and wood demand as an energy resource enables the use of such lower quality timbers and logging residues, which were left at harvesting site. Therefore, it is expected to bring additional profit for forest companies or forestland owners while improving forest health and quality.

While there are conventional chip supply chains for pulp industries using a fixed chipper at factory site and storage, some mobile chippers were introduced in Japan to produce wood chips at mountain forest roadside with the expectation for chip production at lower cost. One of the emerging issues in sustainable chip supply chains for energy use with such mobile chippers is estimating the productivity of chipping operation because work conditions of mobile chippers are less unified than chipping by a fixed chipper and the productivity should be varied. At the same time, the supply chain for chipping at forest roadside for immediate production of chips requires immediate transportation and logistics to storage or a factory. Therefore, the importance of chipping productivity estimation on mobile chippers has been gradually recognized for optimized transportation scheduling by stakeholders.

It is well known that the productivity of wood chipping is mainly affected by the total solid volume of a piece of material. The relationship can be expressed in various ways, such as chipping time per ton/volume for average piece size (Spinelli and Hartsough 2001, Assirelli et al. 2013); productivity for load size of a loader (Röser et al. 2012); productivity for piece size under a multi-linear regression analysis (Ghaffariyan et al. 2013); and productivity for butt-end diameter of logs (Yoshida and Sakai 2014b). These previous estimation models were generally analyzed by linear regression to estimate a productivity of a chipper for the average of material sizes in a forest area. On the other hand, productivity usually differs according to the timing of observations in that the feed-to-chip process changes hourly to daily. Furthermore, it is common that there are differences between estimated and actual productivities across chipper machines (e.g. Spinelli and Magagnotti (2010), Ghaffariyan et al. (2013)). As the material supply and the product delivery are scheduled under the typical productivity, unexpected variances of chipping productivity sometimes drastically lower or erode profit in its supply chain. Therefore, average values of productivity and its variances will show not only the typical productivity of a chipper that is required for profitable and sustainable forestry but also the variance of chipping productivity that further influences the ongoing production.

The variance of chipping productivity seems to be derived from fluctuations in feeding time of a piece of material to a chipper. Compared to other forestry operations such as timber harvesting, chipping operation has less complex operations (Röser et al. 2012), and operator's effect could be regarded as, therefore, secondary and minute to overall production (Spinelli and Magagnotti 2010). Thus, the variance may be derived from the accumulating of uncertainty of handling the materials and the machinery over time and unique to every iteration of producing a volume of wood chips.

The aim of this study is to estimate the variance of chipping productivity by using a stochastic simulation model for objective evaluation of chipper performance. Stochastic simulation method was selected to analyze difference over time of a productive system to estimate productivity. Five different types of mobile chippers were analyzed and their productivities were compared to show the robustness of this method.

3.2 Material and methods

3.2.1 Time observation and machine selection

To obtain real data at forest chipping site, time observations recorded by stop watch were conducted nearby the five mobile chippers during operations. The observed productive chipping system factors were divided into two main elements: feeding chipper and operational delay. A cycle of feeding operation was defined as the time between the start of a grapple loader movement on the prepared material pile and the time releasing materials from the grapple onto the feeder of the chipper. During this operation, chip was produced at the chipper and chipping time was included in feeding time because feeding and chipping can not be separated because of the interaction between a chipper and a grapple loader (Röser et al. 2012). The operational delay was time of extra operations that included cleaning the landing site; preparing logs from piles; and removal of a stuck logs in the feeder, which randomly occurred and varied according to operational situations. All operational delays less than 15 minutes were taken into consideration in the productivity calculation, which were used as one of the criteria to classify delays (Samset 1990). All of the observed delays were below the minimum criteria in this study and, therefore, included. The time of errors caused by observation interference between the operators and investigators were excluded.

To derive productivity, the common formula for chipping productivity P (loose m^3/hr) can be shown as below:

$$P = d \sum_{i=1}^{n} V_i / h \tag{6}$$

where; d is the density coefficient for converting solid volume to chip volume (loose m^3/solid m^3); n, the total number of feeding operations in a production period; V_i, the material solid volume in each i time of feeding operation (solid m^3); and h is the gross working time of a chipping operation (hr). The variance in chipping productivity can be considered to be caused by a gross working time h that consisted of the time for feeding operations and delays. Five different types of mobile chippers: TP250 mobile turnable (expressed as TP250); YM-400C; Farmi 380; CBI chip max 484VR (expressed as CBI); and MUS-MAX WT8-XL (expressed as MUS-MAX), were analyzed in this study. TP250 was the smallest chipper in its size with engine power of 53.7 kW, and chosen for its smallness. This chipper was designed for manual loading and vehicle traction, and a wheel loader was used to assist its loading operation. The knives were equipped on a disk. YM-400C and Farmi 380 had similar engine power of 150 kW and 140 kW, respectively, and knives were also equipped on a disk. YM-400C was an independent machine mounted on four-wheeled vehicle equipped with a feeding assistant belt conveyor. Farmi 380 was one of the attachments connected to the tractor power take off (PTO). It had a feeding assistant chain conveyor and an integrated grapple loader. Because of their relatively smaller size and mobility, these three chippers were useful for Japanese small-scale forestry from forest site along narrow roads towards mill destinations. MUS-MAX was a truck mounted chipper with a feeding assistant belt conveyor, knives on a drum cutter, and an integrated grapple loader. It had an engine with 353 kW power, and could be regarded as a middle class chipper. It was chosen for its integrated chipping and driving abilities, and for its engine power. CBI was the representative largest chipper both in size and engine power. It had a self engine of 570.7 kW power, a feeding assistant belt conveyor, and knives on a drum cutter.

At a feeding operation, plural pieces of material were fed in the investigations except for YM-400C. Although YM-400C had an enough feeder dimension for plural pieces, only a piece of material was fed because materials were stuck when plural pieces were fed. The investigations were located in different places of Japan. These sites were at paved landings except for Farmi 380, whose location was a storage landing near to forest. The sample size of investigation on CBI was insufficient because of the lack of material and limited observation time. However, this data was also used in this study to see the effect on productivity.

3.2.2 Material size measurement

The number of logs of each feeding operation were observed and recorded by a video camera. The number of materials that could be obtained was verified from pictures. The material size was measured during actual investigations by different methods because of limitations in investigations. The materials were logs in 4 m lengths in the investigations of TP 250 and YM-400C, whose top and butt-end diameters and lengths were measured for the volume calculation by Smalian's formula. The materials were short logs in 2 m lengths in the investigation of Farmi 380, where 124 logs were randomly chosen and measured its top-end diameter to estimate the material size distribution. It was possible to regard such short logs as column-shaped timber, and, therefore, the volume was calculated by squared diameter method from top-end diameters. The observation time was limited in the investigations of CBI, and only the total weight of material logs was measured as 7.3 wet-tonnes before chipping. Therefore, the average volume of a piece of material was calculated by using the weight density coefficient of 0.6 wet-tonne/solid m^3 when regarding the wet-based moisture content was 0.5 whose oven-dry weight was 0.3 oven-dry tonne (Greenhouse Gas Inventory Office of Japan et al. 2015) and the number of material logs. The number of fed logs at a feeding operation was regarded as the material distribution in the model simulation of CBI. The materials were logs in 4 m lengths in the investigation of MUS-MAX, whose top-end diameters were previously classified in 2 cm increment by the operation contractor, for the calculation of volume by using a volume table used in practice. The unit "loose m^3" meant a cubic meter of chip volume.

3.2.3 Simulation method

The probability distributions of feeding time and material size were assumed to follow a log-normal distribution because all of the figures were positive number and theoretically could be infinite. To obtain appropriate location μ and scale σ parameters, feeding time, and material size data, these parameters were re-sampled by bootstrapping 2,000 repetitions on TP250, YM-400C, Farmi 380 and MUS-MAX, and by 4,000 repetitions on CBI because of its small original sample size. The normality of generated parameters was tested by Shapiro-Wilk normality test to judge the adaptability of mean values, as representation. By using these obtained parameters, chipping productivity at j time of repetitions P_j (loose m^3/hr) was expressed by using two independent probability distributions, as the formula (2):

$$P_j = (1-\alpha)d \sum_{M,F \in \mathbb{D}} f(M)/g(F) \tag{7}$$

where α was the operational delay time ratio observed in actual operations; $\mathbb{D}$, the data set of trials indicating the number of operation cycles F and materials M; $f(M)$, the probability distribution of material size at a feeding operation; and $g(F)$ was the probability distribution of feeding operations. These denominator and numerator were independent. The density coefficient d was set at 2.8 loose m^3/solid m^3 here (Serup et al. 1999). The ratio α was substituted by the ratio obtained from actual investigations. R-language was used for all of the analysis and simulation. The chipper machine details, investigation details, and simulation constraints were summarized in Table 3.1.

3.3 Results

Fig. 3.1 showed the histograms and fitted probability distributions for the time of feeding operation and material size on each chipper. The fitted distribution of material size on CBI had more of a peaked distribution than its histogram, and that of MUS-MAX had a gentler peak compared to its histogram, while the others were generally well-fitted to log-normal distribution. The location and scale parameters and p-values by Shapiro-Wilk normality test on these parameters were shown in Table 3.2. Some of the p-values were not significant, and they could not be regarded as normal distributions; therefore, it should be considered whether the mean value could be the representation of parameters. However, these were distributions with a greater peak, and values were concentrated around their median values which were almost the same as the mean values. The median values were, therefore, applied as both location and scale parameters as representation of the parameter for probability distribution.

The estimated productivity distributions were shown in Table 3.3. Productivities could be estimated with certain variance, and objectively evaluated. The productivities from actual observations were within each two-sided confidential interval (p=0.05) except for CBI, and, therefore, the obtained productivity distributions generally seemed to be reliable. All of the productivity distributions were positively skewed, and the median values were available at the productivity most frequently observed, which was almost the same as mean values, too. The productivity distributions of TP250 and YM-400C were similar to each other despite their differences in machine size and engine power. Comparing the estimated productivities of YM-400C and Farmi 380, that of Farmi 380 was higher while the machine size and engine power were similar to each other.

The productivity of MUS-MAX was higher than other three smaller chippers with the relatively lower operational delay time ratio. Moreover, CBI showed the highest productivity. The productivity of chippers except for CBI and MUS-MAX concentrated in a narrow variance with about 4 loose m^3/hr difference in two-sided confidential interval. The estimated productivity of large sized machine MUS-MAX, which had bigger mechanical power potential, was also varied only in 10 loose m^3/hr differences in the two-sided confidential interval. The productivity of MUS-MAX was also concentrated, as well as that of other three smaller chippers. On the contrary, the productivity of CBI, whose engine power was about double to 10 times larger than those of others, varied in more than 100 loose m^3/hr difference in the two-sided confidential interval. This large difference should be a problem in production scheduling and investment.There was a necessity of improvement on the operation.

3.4 Discussion

3.4.1 Suggestions for productivity improvement

The operational delay time ratios of chippers were different, and it implied the possibility of productivity improvement because delay had a big influence on chipping operation (Spinelli and Visser 2009). The productivity of YM-400C was similar to that of smaller chipper, TP250, but would be improved when the operational delay time reduced to the ratio that TP250 had. Only a log could be fed at one feeding operation for YM-400C due to mechanical reasons; therefore, reducing operational delays was the only way to decrease the operational delay time ratio. Otherwise, increasing the average volume of material was another possibility.

Farmi 380 also had a larger operational delay time ratio that could impact its productivity. In the operation, material piles were located behind the entrance of feeder Therefore, its operational delay could have had the possibility to decrease or be improved by locating the pile in front of the feeder. The other three chippers, TP250, CBI and MUS-MAX showed the smaller operational delay time ratios and especially the operations of bigger class chippers seemed efficient. Therefore, the productivity will be improved and sustainable only by preparing larger pieces of material. The size of TP250 was, however, small and manual feeding system restricted log sizes even if the operator used a wheel loader for feeding assistance. Hence, it has few possibilities of productivity improvement.

Conversely, MUS-MAX had a larger entrance; a feeding-assistant belt conveyor; and bigger engine power compared other chippers. The capacity seemed to be used at maximum because the chipper could have multiple logs fed at the same time of the feeding operation during the observation. This multiple log feeding could only be possible by extending the length of timber logs, which would improve chipping efficiency of the system. On the other hand, the largest machine, CBI, had greater amount of feeding space for more material onto the assistant conveyor during the observations. Furthermore, utilization of a grapple loader with larger grappling capacity would increase the volume at a feeding operation. In general, the appropriate use and setup of operation on site are important to fully show the performance of chipper, as well as what and how the system can improve on to increase its performance and efficiency.

3.4.2 Discussion on the model

The observed productivities were in the range of two-sided confidential intervals except for CBI and there were almost no difference between the mean and median values. Log-normal distribution was generally well-correlated to express feeding time and material size distributions because chipping operation was simple to form a supply chain and stable in its production. The location and scale parameters estimated from one dataset of an actual investigation could represent feeding time and material size distributions at an acceptable level by applying re-sampling method used in this study. For CBI, the probability distribution of the material size had a steeper slope and higher peak because of the small number of sample size, and it would be improved as increasing the sample size. For MUS-MAX, the probability distribution of the material size had a gentler peak due to its conventional method whereby using volume table with a wide diameter increment of 2 cm. For example, the volume of a log with the diameter of 17.9 cm was actually calculated as that of a log with the diameter of 16.0 cm. Therefore, the histogram was discrete and concentrated on some specific volumes. The volume of materials used in this study could be underestimated, causing differences between the histogram from actual data and the fitted distribution. But this underestimation was minor in absolute values and did not significantly affect the accuracy to estimate productivity. Nevertheless, for chip production, the measurement of material size should be precise to make sure the estimated chipping productivity.

The productivity variance expressed by two-sided confidential intervals seemed to be derived from the number of trials in a simulation represented by $\mathbb{D}$. Based on a common law known as the law of large number, the average of the results obtained from a larger number of trials should be close to the real mean. The trial numbers of CBI was smaller than others, and it resulted in the wider productivity variance of more than 100 loose m^3/hr difference in the two-sided confidential interval. A continuous operation with larger operation cycles and materials was, therefore, preferable to realize productivities in a narrow variance and to establish a stable chip supply chain based on a reliable chipping productivity because it neutralized the variance in chipping productivity. Furthermore, to stabilize chipping productivities, truck or storage capacities are important to mitigate the interaction between chipping and transportation operations.

For further development of this simulation method, it is necessary to have a large and accurate data pool of feeding time, material size distribution, and operational delay time obtained from practice. Recently, some grapple loaders have an automatic data collection system to find their actual productive time ratio and fuel consumption. Such technology is useful to have feeding and operational delay time automatically. Data sharing among researchers are also useful to increase the amount of verified data for objective comparison of chippers with an available database built.

3.4.3 Evaluation of five chippers and suggestion

Considering the produced chip transportation directory after chip production based on the relationship with truck capacities, MUS-MAX showed an ideal productivity suitable for today's 21st century Japanese forestry at site situation. Because the available capacity of typical large trucks is around 40 m^3 of semi-trailers/large trucks and chipping will take less than one hour by using MUS-MAX. The other three smaller chippers will take more time and suitable for the combination with smaller trucks, whereas all of truck capacities used in common seemed to be too small for CBI to show its potential. Therefore, for CBI, it is preferable to arrange a system with no interaction between chipping operation and chip transportation systems, called a hot system (Asikainen 1998). From Table 3.3, the productivity began to vary in an increasingly wider variance as the chipper size became larger; therefore, the condition of operation such as location and quality of material should be made in their best especially for large class chippers.

3.5 Conclusion

The variance of productivities for each chipper can be estimated from recorded observations, and it can be neutralized by increasing the number of cycles — feed-to-chips operational cycles. The typical productivities were represented by the median values of the productivity distribution, and these increasingly corresponded to their engine powers. Not only the typical productivity is achievable at median values but also the variance of productivity should be taken into account when choosing chippers.

This stochastic model applying log-normal distributions of feeding operations and material sizes was useful to estimate the variance of productivities—4 to more than 100 loose m^3/hr—possibly appeared at a certain level. To make this estimation more precise, accurate material size measurement is indispensable and required. It is also helpful for the development of this method to increase the amount of qualified data via an automatic data collection system at the site on the chipping machinery and the entire system, and also by data sharing of these comparable systems among researchers.

Table 3.1: Chipper machine details, investigation details, and simulation constraints

Chipper Machine Name	TP250 mobile turnable (Denmark)	YM-400C (South Korea)	Farmi 380 (Finland)	CBI chip max 484VR (USA)	MUS-MAX WT8-XL (Austria)
Chipping type	Disk (2 knives)	Disk (4 knives)	Disk (4 knives)	Drum (4 knives)	Drum (8 knives)
Mobility	Tracked	Self-propelled	Tractor attachment	Tracked	Truck mounted
Engine	Internal	Internal	External	Internal	Internal
Power (kW)	53.7	150	140	570.7	353
Feeder dimension	H 260 mm x W 350 mm	H 500 mm x W 400 mm	H 380 mm x W 420 mm	H 762 mm x W 1,219 mm	H 600 mm x W 640 mm
Feeding assistant equipment	No assistance	a belt conveyor	a chain conveyor	a belt conveyor	a belt conveyor
Discharger type	Blower	Blower	Blower	Blower	Blower
Material type used in the investigation	Sugi and hinoki logs of 4m in length	Sugi logs of 4m in length	Sugi short logs of 2m in length	Tree tops and short logs	Sugi and hinoki logs of 4m in length
Observation place	Paved landing	Paved landing	Unpaved landing next to forest road	Paved landing	Paved landing

Total time of investigations (hr)	1.07	1.5	0.81	0.086	1.01
Observed cycles of feeding operation (cycles)	25	115	63	13	88
Number of material logs (pieces)	80	115	464	111	569
Number of simulation cycles for feeding time function F	25	115	63	13	88
Number of simulation cycles for material size M	80	115	464	13	569
Representation of material size probability distribution $f(M)$	Log volume	Log volume	Diameter of a short log	The number of material logs at a feeding operation	Log volume

The number of repetitions i	2,000	2,000	2,000	4,000	2,000
Average material size (solid m^3)	0.08	0.08	0.02	0.09	0.05
Operational delay time ratio α	0.15	0.24	0.43	0	0.08
Productivity from the actual observation (m^3/hr)	18.7	18.3	22.6	338	68.2

Table 3.2: Parameters of log–normal distribution for material size and feeding time, and p–values of Shapiro-wilk normality test

Chipper	Probability distribution	Location parameter μ	Scale parameter σ
TP250	$f(M)$	Median=-2.59(Mean= -2.59±0.02, p–value=0.25)	Median=0.15 (Mean=0.15±0.01, p–value=0.10)
	$g(M)$	Median=4.70 (Mean=4.70±0.06, p–value=0.065)	Median= 0.27(Mean=0.27±0.04, p–value=0.32)
YM-400C	$f(M)$	Median=-2.63 (Mean=-2.63±0.05, p–value=0.74)	Median=0.48 (Mean=0.48±0.04, p–value=0.35)
	$g(M)$	Median=3.40 (Mean=3.39±0.03 , p–value=0.75)	Median= 0.32 (Mean=0.32±0.02, p–value=0.53)
Farmi 380	$f(M)$	Median=2.26 (Mean=2.26±0.02 , p–value=0.77)	Median=0.23 (Mean=0.23±0.01, p–value=0.47)
	$g(M)$	$^{1)}$Median=3.47 (Mean=3.47±0.04, p–value=0.014*)	Median= 0.30(Mean=0.30±0.03, p–value=0.25)
CBI	$f(M)$	$^{1)}$Median=2.08 (Mean=2.07±0.11, p–value=5.947e-05***)	$^{1)}$Median=0.38 (Mean=0.37±0.06, p–value< 2.2e-16***)

	$g(M)$	Median=3.12 (Mean=3.12±0.09, p–value=0.073)	1)Median=0.30 (Mean=0.30±0.06, p–value=3.667e-08***)
MUS-MAX	$f(M)$	Median = -3.06 (Mean = -3.061±0.0074, p–value=0.47)	Median = 0.18 (Mean=0.18±0.0051, p–value=0.55)
	$g(M)$	Median =3.12 (Mean = 3.611±0.041, p–value=0.33)	1)Median = 0.3827 (Mean =0.3832±0.042, p–value=0.00067***)

*p–value < 0.05

***p–value < 0.001

1) Distribution could not clarified its normality by normality test, but was possible to use median values as the representation

Table 3.3: Results of productivity estimation

Chipper	TP250	YM-400C	Farmi 380	CBI	MUS-MAX
Min (m^3/hr)	13.55	15.44	20.12	226.77	58.15
Median (m^3/hr)	17.01	18.40	23.72	278.44	66.33
Mean (m^3/hr)	17.04	18.41	23.72	270.09	66.37
Max (r/hr)	20.63	23.04	27.69	343.62	75.83
Two sided confidential interval (p =0.05)	15.25 to 19.12	16.42 to 20.51	21.84 to 25.79	250.98 to 309.65	60.94 to 71.90
Skewness	0.14	0.16	0.15	0.2	0.06
Kurtosis	0.002	0.11	0.11	0.1	-0.018

The term "m^3" means loose m^3 here

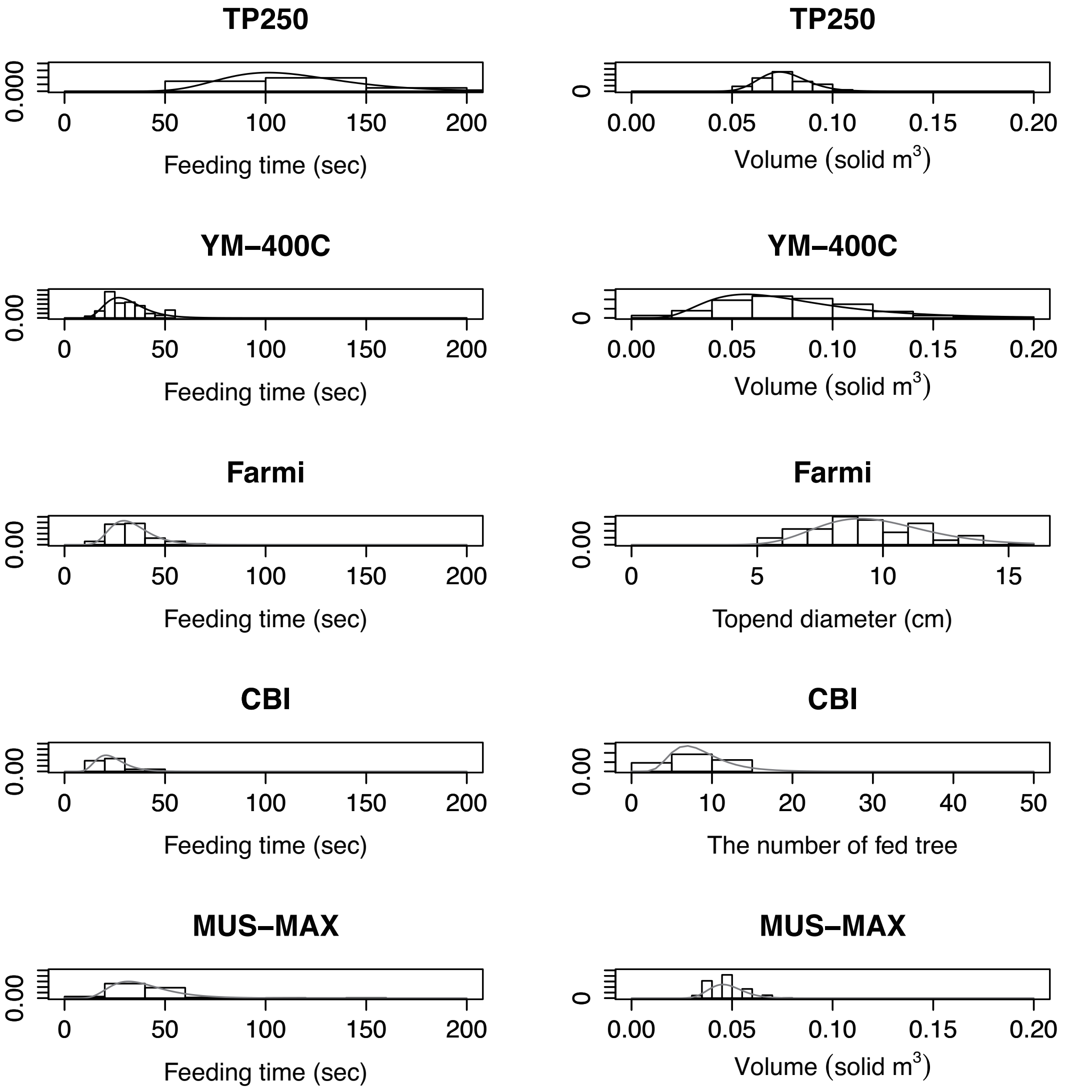


Fig. 3.1: Histograms and fitted probability distributions for the time of feeding operation and material size on each chipper. (Left) for the time of feeding operation. (Right) for the material size.

4 Rational choice of chipper size when considering the business scale of a supply chain in a region

4.1 Introduction

There are many wood resources that can be use for energy generation, and logging residues after timber harvesting are considered as one of the most economical (Barua and Bonilha 2013). In Japan, 20 million solid m^3 logging residues composed of low quality timbers, tree tops and branches are abandoned after logging because of their low quality and price (Forestry Agency 2015a). They are bulky and difficult to transport so that chipping at landings in the forest is necessary as a densification method. It is gradually becoming possible to choose a chipper from low to high investment cost and the opportunity to join the new market of bioenergy in Japan is increasing as the distributers increase the import of machines. The productivity of chipper is, however, in the strong relationship with its engine power (Spinelli and Hartsough 2001) and the initial investment might increase as the engine power increases while it is usually confidential (Nordfjell et al. 2010). The balance between the chippers initial investment and productivity must be clarified according to the annual business scale that is required to depreciate the initial investment of a chipper.

At the same time, more productive chippers require more material to stable and segueing operation. A larger collection area is necessary and it raises economical risk caused by higher transportation cost as same as when introducing a large power plant (Kumar et al. 2003). The forest road density in Japan is scarce (19 m/ha) compared to countries with more developed use of forest biomass for energy as Austria and Germany (89 m/ha). This fact limits the accessibility to the forest area despite the large stock (Forestry Agency 2014). It means that the cost efficiency of chip transportation is the main restriction for economical production because of the strong interaction between chipping and transportation processes (Asikainen 1998). Therefore, the trade-off relationship between chipping and transportation costs should be taken into account when choosing a mobile chipper for a region. The purpose of this study was to find the most economical chipper size, classified by its engine power, when considering transportation cost and annual bushiness scale of a chipper.

4.2 Materials and methods

4.2.1 Chipping cost

Five representative mobile chippers from small to large engine power that currently had been available in Japan were investigated on their productivities, cost factors, and fuel consumption. The chippers were, TP250 mobile turnable (TP250), YM-300C, Farmi 380, CBI chip max 484VR (CBI), and MUS-MAX WT8-XL (MUS-MAX). All chippers were imported to Japan, after long-term use overseas that had proved their performance, reliability, and stability. The details of them were summarized in Table 4.1 and the chippers were temporary categorized into three groups — small, middle and large — based on their engine power. Chipping cost C_i (JPY/loose m^3) was calculated for each chipper in relation to annual business scale by the following equations based on Miyata (1980):

$$C_i = C_{ci}/V_{an,i} \tag{8}$$

$$V_{an,i} = p_i q_i DH \tag{9}$$

$$\begin{aligned} C_{ci} = \sum_{i \in \mathbb{C}_i} \{ &(P_i(1-s))/N_i + P_i r\{(1-s)(N_i+1)/(2N)+s\} \\ &+ (m_i P_i(1-s_i))/N_i + f_p f_i (1+e) \cdot q_i DH + wDH\} \end{aligned} \tag{10}$$

where $C_{c,i}$ was the yearly cost of machineries in a supply chain $\mathbb{C}_i$ (JPY/yr); V_{an},i, the annual business scale of chip material in a supply chain $\mathbb{C}_i$ (loose m^3/yr); p_i, the productivity of chipper in a supply chain $\mathbb{C}_i$ (loose m^3/hr); q_i, the rate of productive machine hours (the rate of PMH); D, the yearly working days (days/yr); H, the daily working hours (hr/day); P_i, the initial investment of machines in a supply chain $\mathbb{C}_i$ (JPY); s, the salvage rate of machines ; N, the depreciation time of machines (yr); r, the rate of insurance, interest and tax; m, the maintenance rate of machines ; f_p, fuel price (JPY/L); f_i, the hourly fuel consumption in a supply chain $\mathbb{C}_i$ (L/hr); e, the lubricant rate to fuel cost; and w was hourly salary including social charges (JPY/hr). In equation (10), the chipper operator was assumed to be annually employed. The tax rate was changed to 0.08 based on the Japanese law, and the rate of insurance, interest and tax was together 0.23 here.

Lubricant rate e was set at 0.2 (Nihonrindokyokai 1982). The maintenance rate that was used were the mean of the rates presented in Miyata (1980), as the maintenance rate is seldom reported in studies. The hourly salary w was set at 2,500 JPY/hr (Shinrinsegyouplannerkyokai 2012). The cost factors for each machine were summarized in Table 4.2. Costs were calculated directly for each chipper. The relationship between chipping costs and engine power were analyzed by linear regression analysis.

4.2.2 Transportation cost

Iwate prefecture was used as a model area for the transportation cost to make the problem more realistic. Iwate prefecture is located in North East Japan, consisting of 33 cities, and 1.17 million ha of forest which occupied about 77 % of the prefecture land. Coniferous forest on private land — 336,592 ha — was considered as productive forest and its total stock was 105 million solid m^3 in trunk volume in 2011 (Iwate Prefecture 2012). One power plant with 5.8 MW of capacity has been running in this region since April, 2014 (39 °35'06.3"N, 141 °39'48.0"E) and was assumed as the end user in this study. The plant consumes 90,000 tonnes — 378,000 loose m^3 — of wood chip annually from forests in the area. The available amount of logging residues at landing j, V_j, (loose m^3) was calculated by the following equations:

$$V_j = d(u_1 + u_2)zV_{t,j} \tag{11}$$

where d was chip density coefficient (loose m^3/solid m^3); u_1, the residual rate of trunk volume; u_2, the rate of branches to trunk volume; z, the thinning rate of stock volume; and $V_{t,j}$ was the stock volume at the landing j (solid m^3). The chip density coefficient d was set at 2.8 loose m^3/solid m^3 (Serup et al. 1999). The residual rate u_1 was set to 0.4, which was obtained through interviews with forest entrepreneur in the Iwate area, and it was at a very similar level as the average residual rates for coniferous and broad leaved timbers presented by the Forestry Agency (2015b). The rate of branches u_2 was set to 0.23 (Greenhouse Gas Inventory Office of Japan et al. 2015). The thinning rate z was calculated base on the total volume that was thinned during 2011 from both public and private forests in Iwate prefecture, 707,322 solid m^3 (Iwate Prefecture 2012) and resulted in the rate z of 0.0067 as no more detailed data was available. Chip transportation cost from the landing j in a supply chain $\mathbb{C}_i$, TC_{ij} (JPY/loose m^3), was calculated by the following equations:

$$TC_{ij} = n_{ij}(C_t + wH)/(p_i H) + 0.035 f_p PS(1+e) \cdot (2t_j)/V \tag{12}$$

$$\begin{aligned} C_t = \{&(P_t(1-s_t))/N_t + P_t r_t\{((1-s_t)(N_t+1)/(2N_t) + s_t) \\ &+ (m_t P_t(1-s_t))/N_t\}/D \end{aligned} \tag{13}$$

$$n_{ij} = (2t_j + V/p_i + t_o)/(Vp_i) + 1 \tag{14}$$

where n_{ij} was the number of trucks at landing j when using chipper i which were required to keep the chipper i working; C_t, the daily depreciation cost of a truck (JPY/day); PS, the engine power of trucks (PS); t_j, the one-way driving time from landing j to the destination (hr); t_0, the time for unloading and other extra delays (hr); and V was the payload of the truck (loose m^3). The payload of trucks was assumed to be 10 tonnes and the volume V was assumed to be 20 loose m^3.

The data for trucks was obtained from the table of factors for construction equipment in 2013, the attached table no.2, machine code 03-031-011-110 (Ministry of Land, Infrastructure, Transport and Tourism 2014) and its applicability to forestry was validated by personal communication with a truck manufacturers. The truck price P_t was 12,600,000 JPY; the salvage rate s_t was 0.13; the depreciation time N_t was 10 years; the engine power of trucks PS were 334 PS; the rate of insurance, interest and tax r_t was 0.23, as same as for the chippers; and the maintenance rate m_t was 0.5. The time for unloading and other extra delays t_0 was estimated to 1.0 hour based on personal communication with manager at a power plant in another prefecture because the data of the model power plant could not be available. The second term of the equation (5) represented the fuel consumption according to the engine power (Nihonrindokyokai 1982). Furthermore, an extra truck was added to the number of trucks that was required to keep the chippers working at landing n_{ij} as buffer against unexpected delays, to make the estimations more realistic.

GIS data of the forest area with city borders and public roads were obtained in a ESRI shape files form from the National Land Numerical Information and the Geospatial Information Authority of Japan, respectively. These geodetic datum were JGD2000 Japan

Plane Rectangular CS X. Each forest area was categorized by the boundaries of the cities in Iwate prefecture, and one gravity point for each forest were regarded as a landing. This estimation means that there were 33 landings — i.e. the maximum value of j was 33. Public roads excluding highways were used to calculate transportation time. The one-way driving time from landing j, t_j, was calculated by using OD cost matrix analysis of Esri ArcMap 10.2.2 by minimizing the driving time. The average truck speed was assumed to be 50 km/h and 30 km/h on primary and secondary roads, respectively. Fig.4.1 showed the forest resources, road network and the location of the power plant — the destination — in the model area.

The average of transportation cost TC_i (JPY/loose m^3) was calculated by using linear optimization method to minimize the cost while satisfying the volume required to depreciate chippers:

$$C_{ti} = \min \sum_{j \in \mathbb{C}_i} x_{ij} TC_{ij} \tag{15}$$

subject to

$$\sum_{j \in \mathbb{C}_i} x_{ij} = V_{an,i} \tag{16}$$

$$V_{an,i} \leq \sum_{j \in \mathbb{C}_i} V_j \tag{17}$$

where x_{ij} was the volume of chips (loose m^3) collected from landing j by using chipper i. Transportation cost was also analyzed in relation to the engine power of chipper with regression analysis. The total cost for the supply system was the sum of chipping and transportation costs. All of the analyses were conducted by using R–language and the regression method was the least squares method.

4.3 Results

The shortest distance to the power plant from landing j were calculated for totally 31 landings, as two landings (no 15 and 30) were not connected to the public road network due to insufficient data about the road network. The average transportation distance was 86.7 km (SD=29.3, Max=135.3, Min=19.3) and the one-way transportation time were mainly distributed between 1.5 and 2.5 hr. Only five landings had the one-way transportation time below 1.5 hr (Fig. 4.2). These times meant that most trucks only could do one delivery per day, even with the most productive chipper.

The relationship of annual business scale and chipping cost was shown in Fig. 4.3. It was obvious that the chipping costs decreased with enlarged business scale, but there was a limit to the cost reduction for each chipper. It was impossible to achieve the chipping cost below 500 JPY/loose m^3 by using small chippers unless they worked nearly full time. On the other hand, small chippers could achieve the cost of around 500 JPY/loose m^3 with smaller annual business scale (8,300 –12,700 solid m^3) than larger chippers required. If such cost is economically acceptable, small chippers will be useful for forest owners with limited amount of material, while chipping of large amounts of material by middle or large sized chippers will be necessary if the market requires the chipping cost below 500 JPY/loose m^3.

When the rate of PMH was 0.75 for the chippers, the number of landings, annual business scale, transportation time, calculated costs based on the data of five machines and estimated costs based on the regression analysis were shown in Table 4.3. In this analysis, only the largest chipper needed to utilize material from landings over one hour drive away from the power plant. The chipping costs were analyzed with linear regression while the transportation costs were analyzed with linear regression, to estimate the total system cost. The regression line for the chipping costs C_c and for the transportation costs C_t were:

$$C_c = -0.838x + 676.221 \tag{18}$$

$$C_t = 0.0057x^2 - 4.465x + 1629.313 \tag{19}$$

where x was the engine power (kW). The adjusted R^2 were 0.914 and 0.625, respectively. The detailed results of the regression analysis are shown in Table 4.4. The transportation cost was minimized at a chipper engine power of 388 kW when using the regression functions, and the total cost, the sum of C_c and C_t, was minimized at a engine power of 461 kW (Fig. 4.4). From Table 4.3, the average of total cost for chippers with a small engine power estimated by the regression was 1,784 JPY/loose m^3, which was more than

600 JPY/loose m^3 higher than the average of the larger chippers which was around 1,150 JPY/loose m^3.

4.4 Discussion

The engine power had a strong negative relationship with the chipping cost. The regression line of the transportation cost looks well fitted and larger data pool would be useful for making future analysis more precise. It was found that the total cost had the minimum point and that there clearly was an optimal engine size for chippers although this point might change if the local road network situation is different.

Chippers with lower engine power have smaller business scale and lower productivity resulting longer loading time for the truck. This raised the transportation cost and would limit the initial investment of transportation system which could be depreciated. Innovations for saving the initial investment of transportation system are necessary. One cost-improving solution is to use containers with larger size as show in the study about a chip-harvester system (Talbot and Suadicani 2005). On the contrary, the increment of transportation cost when using the largest chipper was because of its larger business scale and the expansion of material collection area making the transportation distance longer. The use of trucks with larger payload would improve the efficiency over such long transportation distance, otherwise a production increment — increased logging operation — in a closer area would be more effective. In this case, both the cost effectiveness and ecological sustainability of the harvest should be kept in mind. The forwarding cost and chipper relocating costs should also be included in future estimates with more landings.

In this study, the landings were mainly located at remote places as shown in the calculations of transportation time (Fig. 4.2). The time for unloading and other extra delays seemed to occupy a significant portion of transportation cycle time and had a large impact on the transportation cost in this study. If the efficiency of the unloading was improved and landings were located closer to the end user, then the minimum point of transportation cost would move towards chippers with lower engine power.

Owing to the above trade-off between the chipping cost reduction and transportation cost increment, the total costs was minimized at a certain chipper engine power of 461 kW. Therefore, the use of MUS-MAX and CBI could be recommended among the five mobile chippers analyzed in this study. The advantage of small chippers was also clarified as a chipping cost around 600 JPY/loose m^3 that could be achieved at a small business scale while the total cost was over 600 JPY/loose m^3 higher than for larger chippers with larger business scale. If it is possible to support the gap in total costs, small chippers enables small scale forest entrepreneurs to join the new energy production market with a low initial investment (Yoshida and Sakai 2014a).

4.5 Conclusion

It was clarified that an engine power of 461 kW was the theoretically optimal engine power. The chipper with this engine size yielded a total system cost of about 1,150 JPY/loose m^3. The use of chippers with middle and large engine power was, therefore, recommended from the economic point of view in practice. On the other hand, chippers with smaller engine power would be useful for establishing a chip supply chain with a smaller business scale of 8,300 to 12,700 solid m^3 at the cost of about 1,780 JPY/loose m^3. Well-balanced chip supply chains could be established, by finding the best combination and allocation of small and large sized chippers.

Table 4.1: Chipper machine details, investigation details, and simulation constraints

Chipper Name	TP250 mobile turnable (Denmark)	YM-400C (South Korea)	Farmi 380 (Finland)	CBI chip max 484VR (USA)	MUS-MAX WT8-XL (Austria)
Size category	Small	Small	Small	Large	Middle
Manufacturer	Linddana A/S	Yulim machinery	Farmi Forest Oy	Continental Biomass Industries Inc.	Mus-Max Landmaschinenbau Urch KG
Chipping method	Disk (2 knives)	Disk (4 knives)	Disk (4 knives)	Drum (4 knives)	Drum (8 knives)
Mobility	Traction	Self-propelled	Tractor attachment	Traction	Track mounted
Engine	Internal	Internal	External	Internal	Internal
Power (kW)	53.7	150	140	570.7	353
Feeder dimension	H 260 mm x W 350 mm	H 500 mm x W 400 mm	H 380 mm x W 420 mm	H 762 mm x W 1,219 mm	H 600 mm x W 640 mm
Feeding method	Manual with mechanical assistance	Mechanical	Mechanical	Mechanical	Mechanical
Feeding machine	wheel loader	separated grapple loader	integrated grapple loader	separated grapple loader	integrated grapple loader

Discharger type	Blower	Blower	Blower	Blower	Brower

Table 4.2: Input values for calculating the chipping cost of the studied chippers

Chipper in supply chain $\mathbb{C}$	TP250	YM-400C	Farmi 380	CBI	MUS-MAX
Initial investment P_i (10,000 JPY)	1,872.5	1,170	2,903	10,700	5,500
Chipper price (10,000 JPY)	980	500	2,903	9,000	5,500
Grapple price (10,000 JPY)	892.5	670	0	1,700	0
Depreciation time N (yr) *	5	5	5	5	5
Salvage rate s **	0.1	0.1	0.1	0.1	0.1
Rate of productive machine hours q *	0.75	0.75	0.75	0.75	0.75
Annual working days D (day/yr) *	250	250	250	250	250

Daily working hours H (hr/day) *	8	8	8	8	8
Maintenance rate m^*	0.68	0.68	0.68	0.68	0.68
Interest, insurance and tax r *	0.23	0.23	0.23	0.23	0.23
Fuel price f_p (JPY/L)	125.7	125.7	125.7	125.7	125.7
Fuel consumption f_i (L/hr)	13.7****	30.9****	20.6	180.0****	13.5
Salary w (10,000 JPY/day)***	2	2	2	2	2
Productivity p_i (loose m^3/hr)	17.01	18.4	23.72	278.44	66.33

* from Miyata (1980)

** from Zenkokuringyoukairyouhukyukyoukai (2001)

*** from Shinrinsegyouplannerkyokai (2012)

**** It included the fuel consumption of a grapple loader uniformly assumed as 6.0 L/hr.

Table 4.3: Number of landings, transportation time, and calculated cost based on individual chippers and estimated costs based on the regression analysis when the utilization rate of 75 % is assumed

		TP250	Farmi380	YM-400C	MUS-MAX	CBI
	Engine power (kW)	53.7	140	150	353	570.7
	Annual business scale (solid m^3)	9,113	9,857	8,271	35,534	149,164
	Number of landing	1	1	1	2	8
One-way transportation time (hr)	Average	0.39	0.39	0.39	0.66	1.15
	SD	NA	NA	NA	0.38	0.4
	Min	NA	NA	NA	0.39	0.39
	Max	NA	NA	NA	0.93	1.55
Calculated cost (JPY/loose m^3)	Chipping	598	603	579	317	222
	Transportation	1,372	1,003	1,273	720	967
	System total	1,970	1,606	1,852	1,037	1,189
Estimated cost by regression analysis	Chipping	631	559	551	380	198
	Transportation	1,406	1,117	1,089	770	954

(JPY/loose m^3)	System total	2,037	1,676	1,639	1,150	1,152

Table 4.4: Least squared regression models for the chipping (C_c) and transportation (C_t) costs depending on chipper engine size

Regression line	Independent variable	Estimated coefficient	Std. Error	t-value	p-value
C_c	Intercept	676.2213	40.0573	16.8814	0.0005***
	x	-0.838	0.1273	-6.5844	0.0071**
C_t	Intercept	1629.31318	212.56949	7.66485	0.0166*
	x	-4.46529	1.83733	-2.43032	0.136
	x^2	0.00575	0.00283	2.0329	0.179

* p-value < 0.05

** p-value<0.01

*** p-value<0.001

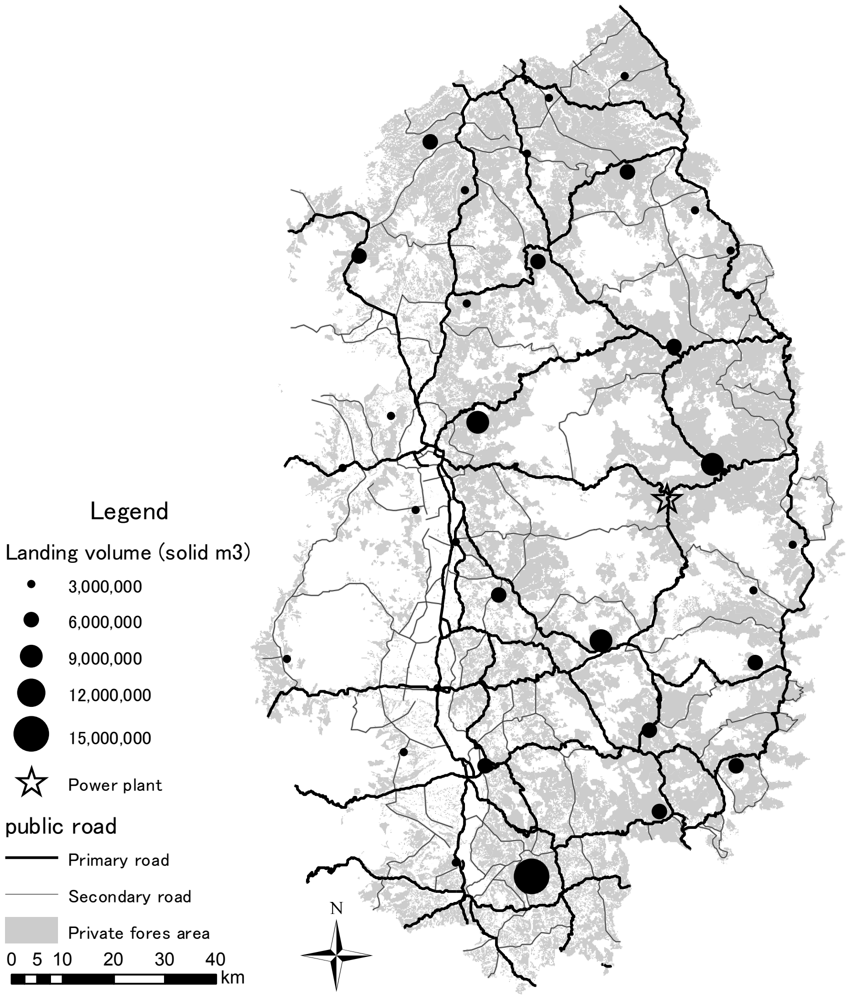


Fig. 4.1: Forest resources, road network and the location of the power plant in the model area

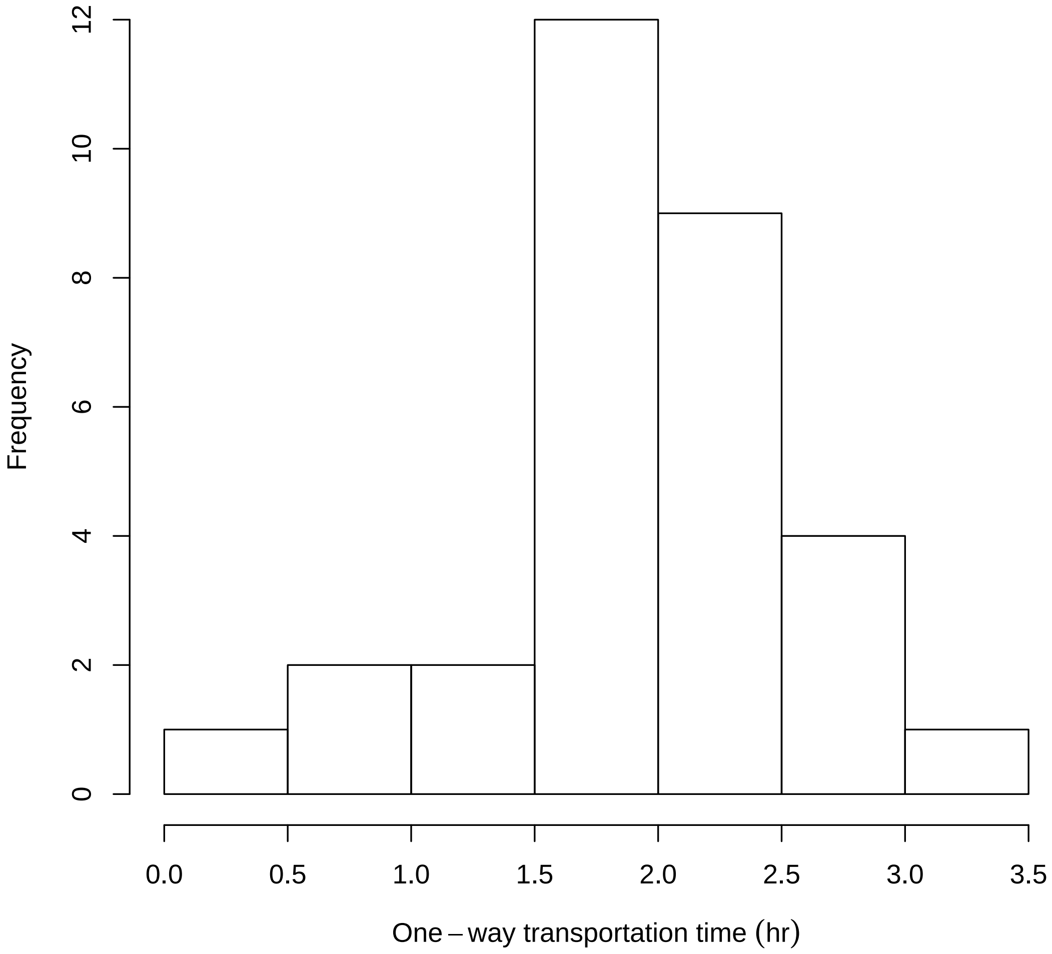


Fig. 4.2: Histogram of the one-way transportation time from landing to power plant on the model area

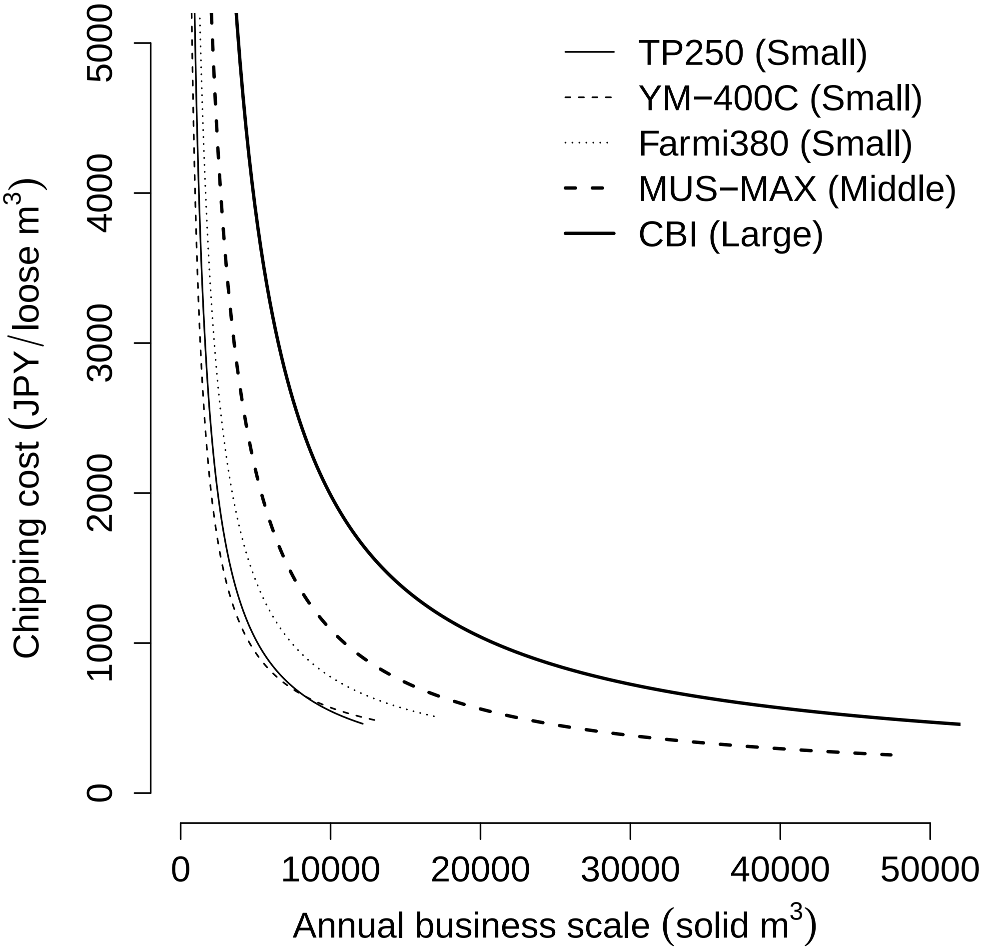


Fig. 4.3: Chipping costs depending on annual business scale for the studied chippers for 0-100% utilization rates

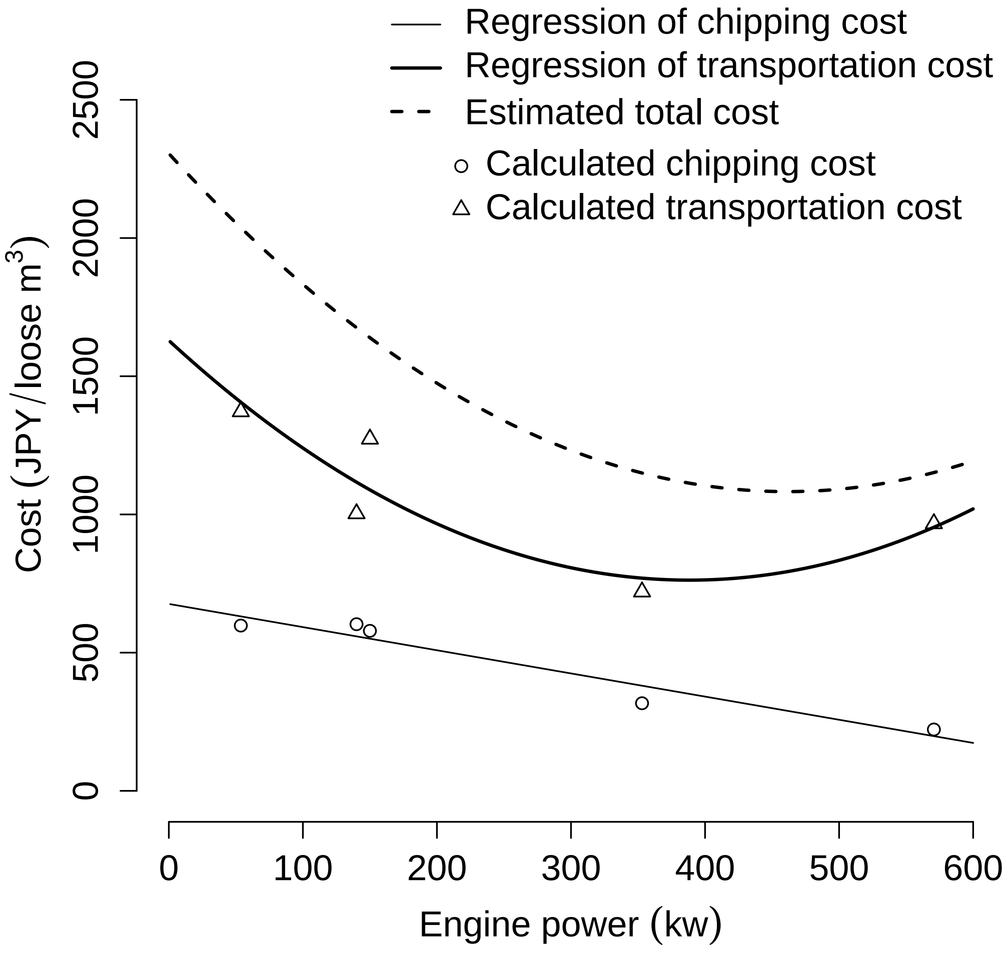


Fig. 4.4: Total system, chipping, and transportation costs depending on engine power of chippers

5 Effective allocation of mobile chippers for the establishment of a stable wood chip supply chain

5.1 Introduction

To contribute the mitigation of climate change, Japanese government has been tried to increase thinning areas as well as the promotion of wood use for electricity generation (Forestry Agency 2015a). From the aspect of the efficient use of woody materials for that purpose, it was promoted to use logging residues composed of branches, tops and the lower quality timbers which left on forest lands after thinning as a source of woody bioenergy.

In spite of such social opinion, the amount of logging residues was estimated 20 million solid m^3/yr in 2010 (Forestry Agency 2011) and the same amount of logging residues was still reported in 2014 (Forestry Agency 2015a). The use of logging residues seems not to proceed as the government intends while 20 wood bioenergy power plants are currently registered as new power plants whose total power capacity will be 252 MW (Ministry of Economy, Trade and Industry in Japan 2015). While it is succeeded in creating huge demand, the demand is concentrated and the area to collect material will be expand and in some cases the plants with such huge demand will be failed and smaller ones will be more realistic since its economical risk is smaller (Kumar et al. 2003). Then, the total supply cost will be varied by the location of material and the system to supply fuel chip.

Looking at the structure of entrepreneurs, the suppliers are composed 92 % of small scale entrepreneurs producing less than 10,000 solid m^3/yr and 8 % of large scale entrepreneurs producing more than 10,000 m^3/yr (Forestry Agency 2015a). It is said that the mechanization in forestry has proceeded from the larger entrepreneurs (Forestry Agency 2015a). However, machines such as harvesters or forwarders are usually high cost and heavy for lower standard infrastructure of small scale forestry. Compared to the creation of huge demand for power plants, it is obviously necessary to involve the small scale entrepreneurs. The market for logging residues, however, has not existed and it meant such small entrepreneurs should manage the residues personally. The transportation of bulky logging residues has already clarified to be expensive (Sultana and Kumar 2011). Then, one of the ways is to introduce a small chipper which can be depreciated by such entrepreneurs.

To find the best system which can minimize the total supply cost from the possible systems, a lot of studies has been conducted from the aspect of transportation engineering and operational research. The improvement of transportation efficiency was performed by increasing a truck capacity, by using the truck with unique technology such as walking floor (Wolfsmayr and Rauch 2014), by the modal shift from truck to train or ship (Karttunen et al. 2012, 2013, Wolfsmayr and Rauch 2014), by drying material (Stampfer and Kanzian 2006, Talbot and Suadicani 2006), and by optimizing supply flow (Kanzian et al. 2009). This study will present the chip supply chain which combines the supply from large and small suppliers, and the aim of this study is to show the efficiency of whole supply chain including large and small suppliers for satisfying a large demand.

5.2 Materials and methods

5.2.1 Cost calculation

In this study, the conventional system is a system using a fixed chipper in a factory. The data was obtained at a typical chipping factory located at Yuzawa city in Akita prefecture by personal communication. The chipping cost of conventional system CC_c (JPY/loose m^3) was calculated by the following equation:

$$CC_c = (kA + B_i + kC)/p_i \tag{20}$$

where k was the weighting coefficient of depreciation cost of factory for machineries; A, the hourly depreciation cost of factory properties (JPY/hr); B, the hourly depreciation cost of machineries (JPY/hr); C, the variable cost to run the factory (JPY/hr); pmh_1, the rate of productive machine hours of a fixed chipper(PMH); and p_1 was the productivity of the fixed chipper. Because there were a lot of machineries, each machinery was identified by the machinery identification number i. The cost components were summarized in Table 5.1, and the productivity of a fixed chipper p_1 was 40.0 loose m^3/hr. The boundary of whole system was expressed by $\mathbb{C}_i$.

Model area is the same as used in the previous section The available amount of chip material at landing j V_j (loose m^3) was separately calculated to the conventional and mobile chipping systems as follows:

$$V_j = \begin{cases} du_1 zV_{t,j} & \text{(the conventional system)} \\ d(u_1+u_2)zV_{t,j} & \text{(the mobile chipping system)} \end{cases} \tag{21}$$

Material form was round wood and its transportation cost is categorized according to the transportation distance. The cost table of truck transportation was used here which used according to distance in practice (Table 5.2). The round wood transportation cost from material accumulated landing j TTC_j (JPY/solid m^3) was categorized according to the shortest distance on the public road which was measured by using the Arc GIS network analyst.

In the mobile chipping systems, two different sized chippers — the smaller was Farmi380 (machine identification number i =5) and the larger was MUS-MAX (machine identefication number i =6) — and 10 tonnes sized trucks were used. Farmi380 was a disk chipper attached to a tractor and MUS-MAX was a drum chipper mounted on a truck. Both had a high mobility with a self grapple loader. Their depreciation costs calculation m_i (JPY/loose m^3) were calculated by the same equation shown in Table 5.1 and the chipping cost of mobile chipper i CC_{mi} was calculated by the following equation:

$$CC_{mi} = B_i/p_i + f_i \tag{22}$$

where f_i was the fuel cost of the chipper i (JPY/loose m^3). The data of these chippers were summarized in Table 5.3. The payload of truck assumed 10 tonne whose capacity V was 20 loose m^3 (machine identification number i =7) and the machine description and transportation cost from landing j when using chipper i TC_{ij} was used as the same way in the previous section

5.2.2 Linear optimization

The objective function was minimizing total supply cost when using chipper i TSC_i

$$TSC_i = \begin{cases} \min\{\sum_{j\in\mathbb{C}_i}(CC_c + x_j TTC_j)\} & \text{(the conventional system)} \\ \min\{\sum_{j\in\mathbb{C}_i}(CC_{mi} + x_{ij} TC_{ij}\} & \text{(the mobile chipping system)} \end{cases} \tag{23}$$

which subject to

$$\sum_{i,j\in\mathbb{C}_i} x_{ij} \geq D \tag{24}$$

$$\sum_{j\in\mathbb{C}_i} x_{ij} \leq vl_i \tag{25}$$

where x_{ij} was the collection material volume from landing j when using chipper i (loose m^3/yr); and vl_i was the limitation in the production amount by chipper i (loose m^3/yr) that was expressed by the following equation:

$$vl_i = p_i m h_i \tag{26}$$

Because of this limitation, several chippers were necessary to satisfy the demand D in the mobile chipping system so that there were several options on the machine combination: using only Farmi380; using both Farmi380 and MUS-MAX; and using only MUS-MAX. Because it was easier to introduce Farmi380 for the lower initial investment, the system with one MUS-MAX chipper and several Farmi380 chippers was considered when using both Farmi380 and MUS-MAX.

To analyze the effect of machine allocation, the collected material volume x_j was distributed from the chipper which close to the plant in the optimization process. The combinations of allocation and machines could be classified into four cases (Table 5.4). For each case, the total supply cost and the average of transportation distance were obtained.

5.3 Results

The shortest distance to the power plant from landing j were calculated for totally 31 landings which were regarded as the origins of material supply because landings 15 and 30 were not connected to public road network for the insufficient road network data. The average of distance was 86.7 km (SD=29.3, Max=135.3, Min=19.3). Material volumes, ranking of the landing close to the power plant and transportation costs of 31 landings were summarized in Table 5.5. The chipping cost of conventional system CC_c was 1,007 JPY/loose m^3 and those of mobile chipper CC_{mi} were 603 JPY/loose m^3 for Farmi380 and 317 JPY/loose m^3 for MUS-MAX, respectively.

The machine combinations in mobile chipping system could be set for each allocation case: 11 of Farmi380 in the case 1; One of MUS-MAX and eight of Farmi380 in the cases 2 and 3; Four of MUS-MAX in the case 4. Five cost calculation results — one for the conventional system and the rest for the mobile chipping systems — were obtained and materials were distributed successfully from the closest landings by linear optimization. The total supply costs were summarized in Table 5.6 and the summary of transportation distance was shown in Table 5.7. The cost of cases 4 ad 3 in mobile chipping system were lower than that of conventional system by 30 % and 12 %, respectively. The cost of cases 1 and 2 were higher than that of conventional system by 12 %. The costs of the cases 1 and 2 were more varied than those of the others. It meant that the variance of total supply cost were more wider in the cases 1 and 2. The average of transportation distance of conventional system was longer than that of mobile system.

5.4 Discussion

It was clarified that the economy of a system was affected by the geographic location of landing and the allocation of machines. The locations of landings in this study were located at remote places and the transportation cost might be higher than that in general. The material volumes of the two systems were different and the volume in the mobile chipping system was larger because it was possible to include branches. The overall catchment area was, therefore, smaller in the mobile chipping system and the chip transportation cost could be saved.

The conventional system was more economical than the mobile systems of cases 1 and 2. In the conventional system, it is possible to reduce the chipping cost by increasing the production amount and such scale of economy will make the conventional system more competitive unless the round wood transportation cost will increase.

The transportation cost in the mobile system system using Farmi380 was more expensive than that with MUS-MAX (Table 5.5). The less productivity of Farmi380 extended a cycle time of returning trip than that of MUS-MAX, and resulted in the higher cost of chip transportation cost. Moreover, the collection costs in the system with Farmi380 as from landings 7, 16 and 24 were about double of the collection costs because of the limitation on truck driver 's working time and it meant that there was waiting time. Truck dispatching to other jobs may improve transportation efficiency (Zamora-Cristales et al.).

Comparing the cases 2 and 3 in the mobile chipping system, it was clarified that it was more economical to allocate the smaller machine close to the power plant. Because the transportation cost when using Farmi380 was higher and the material amount supplied by the system using Farmi380 was larger than that from the system with MUS-MAX, the supply cost by the system using Farmi380 at farther places (the Case 2) was higher than that by the system using Farmi380 at closer places (the Case 3). Comparing Cases 1 to 4, the total supply cost will be decreased by replacing the smaller chippers to the larger ones, and the difference in cost caused by machine allocation will be negligible small.

It is difficult to select and allocate machines in such idealistic way in practice because there is a competition among stakeholders to have landings close to the power plant, but the idealistic selection and allocation of machineries will benefit the power plant. It can be recommended for power plants to positively manage the machinery selection and allocation.

5.5 Conclusion

It was interesting that there were difference in the total supply costs by the allocation of machineries. The chip supply costs were the same between the conventional system using a fixed chipper and the mobile chipping system using smaller ones close to the power plant. Moreover, the total supply cost of larger mobile chippers which had high potential of reducing chipping cost will be superior to that of conventional system. This result encourages the stakeholders to start to use logging residue even they cannot introduce the larger chipper, and benefits the society by the wise use of woody materials.

Table 5.1: Cost components of the conventional system using fixed chipper

Symbol	Cost component	Factor and setting conditions
A	Hourly depreciation cost of a factory (JPY/hr)	$A = FP/(DP \cdot AH)$
FD	Factory depreciation cost (JPY)	$FD = FP + FC + FT$
DP	Depreciation years of a factory (yr)	20
AH	Annual working hours of a factory (hr/yr)	2,240
FP	Factory property cost (JPY)	23,945,900
FC	Factory construction cost (JPY)	204,519,000
FT	Fixed property tax of a factory (JPY/yr)	$FT = rFP \sum_{t=1}^{DP}(1 - 1/DP)^t$
r	Fixed property tax ratio	0.014
B_i	Hourly depreciation cost of machineries (JPY/hr)	$B_i = \sum_{i \in \mathbb{C}} m_i/mh_i$
i	Identification number for machineries	i=1, fixed chipper; 2, grapple loader; 3, shovel loader; and 4, wheel loader
m_i	Depreciation cost of machine i (yr)	$m_i = mp_i(1 - sal_i)(1 + mm_i)/md_i + sAVI$
mh_i	Annual scheduled machine hours of machine i (hr/yr)	$mh_i = 2000 \cdot pmh_i$ (i=1, 2, 3, 4)
pmh_i	Rate of productive machine hours	0.75 (i=1, 2, 3, 4)

md_i	Depreciation years of machine i	8 (i=1, 2, 3, 4)
mp_i	Price of machine i (JPY)	27,100,000 (i=1); 9,713,000 (i=2);1,069,000 (i=3); and 8,925,000 (i=4)
sal_i	Salvage rate of machine i	0.1 (i=1, 2, 3, 4)
mm_i	Maintenance rate of machine i	0.5 (i=1, 2, 3, 4)
AVI	Average value of yearly interest	$AVI = mp_i(1-sal_i)(md_i+1)/2md_i + mp_i sal_i$
s	Rate of insurance,interest, and tax	0.23 (i=1, 2, 3, 4)
C	Hourly variable cost to run the factory	$C = l + (ele + fuel)/AH$
l	Hourly cost for five workers (JPY/hr)	$l = 2500 \cdot 5$
ele	*Annual cost for electricity at the factory (JPY/yr)	6,790,000
$fuel$	*Annual cost for diesel fuel at the factory (JPY/yr)	3,885,000
k	Weighting coefficient of depreciation cost of factory for chip production	$k = AH/mh_1$

Table 5.2: Round wood collection cost table for actual contract

Distance (km)	Transportation cost (JPY/solid m^3)
< 20	2,400
< 30	2,700
< 60	3,000
≥ 60	3,750

Table 5.3: Cost components of Farmi 380 and MUS-MAX

Symbol	Farmi 380 (i=5)	MUS-MAX (i=6)
mp_i	29,030,000	55,000,000
md_i	5	5
sal_i	0.1	0.1
mm_i	0.68	0.68
p_i	0.75	0.75
f_i	130.9	30.7

Table 5.4: Mobile chipper allocation and combination

		Close	
		Farmi 380	MUS-MAX
Far	Farmi380	Case 1	Case 2
	MUS-MAX	Case 3	Case 4

Table 5.5: Material volumes and collection costs

System			Conventional		Mobilechipping		
Landing j	Distance (km)	Ranking of landing close to the plant	Volume V_j	Round wood transportation cost TTC_j	Volume V_j	Chip transportation cost TC_{ij}	
						Farmi380	MUS-MAX
1	117	29	35307	3750	55609	3055	2825
2	117	25	5742	3750	9044	2999	2769
3	46	2	19425	3000	30594	1333	1000
4	91	20	14857	3750	23400	2933	2702
5	52	10	14309	3000	22537	2857	2627
6	100	18	9768	3750	15384	2927	2696
7	60	8	14043	3000	22118	2844	1443
8	102	19	6325	3750	9962	2932	2702
9	53	4	13688	3000	21558	1592	1109
10	114	24	8847	3750	13934	2994	2763
11	19	1	18223	2400	28702	1003	653
12	101	23	2438	3750	3840	2986	2756
13	111	22	2926	3750	4608	2969	2738
14	127	28	4922	3750	7752	3045	2814
16	53	6	3100	3000	4883	2837	1437
17	83	13	6192	3750	9753	2866	2636
18	61	5	11126	3750	17523	1619	1220
19	72	7	16577	3750	26109	2840	1440
20	118	27	4852	3750	7641	3041	2810
21	86	16	13558	3750	21354	2901	2670

22	34	3	3266	3000	5144	1341	1092
23	77	11	2252	3750	3546	2860	2630
24	79	9	2466	3750	3885	2849	1532
25	126	30	10245	3750	16135	3065	2835
26	111	21	9150	3750	14412	2963	2732
27	91	17	1149	3750	1810	2908	2677
28	113	26	1274	3750	2006	3008	2778
29	80	15	2633	3750	4147	2886	2655
31	75	12	248	3750	391	2866	2635
32	135	31	6494	3750	10228	3142	2912
33	86	14	11700	3750	18428	2875	2644

Landings 15 and 30 were missing.

Table 5.6: Total supply costs

Cost(JPY/loose m^3)	Conventional	Mobile chipping			
		Case 1	Case 2	Case 3	Case 4
Average	2,138	2,377	2,395	1,885	1,497
SD	159	710	804	236	251
Maximum	2,347	3,447	3,447	2,222	1,760
Minimum	1,865	1,606	970	1,536	970

Table 5.7: Summary of transportation distance

Distance (km)	Conventional	Mobile chipping			
		Case 1	Case 2	Case 3	Case 4
Average	64.2	49.8	49.8	49.8	49.8
SD	33.2	16.5	16.5	16.5	16.5
Maximum	116.8	71.8	71.8	71.8	71.8
Minimum	19.3	19.3	19.3	19.3	19.3

6 Energy chip supply chain establishment with satisfying stakeholders' benefits from a commercial distribution viewpoint

6.1 Introduction

The use of forest resource for energy is a global trend. It is one of the biggest issues to establish an efficient chip supply chain at low cost depending on the local and/or global forestry conditions. Technical requirements for improving its economy have been researched by many articles. About transportation process, for instance, intermodal transportation system was pointed out to be an interesting research topic (Wolfsmayr and Rauch 2014). About chipping process, its productivity would be improved by using sharp knives, the larger size of material and screen (Nati et al. 2010, Assirelli et al. 2013, Spinelli et al. 2014) and the use of chipper with larger engine (Spinelli and Hartsough 2001). In addition to such technical or operational improvement, supply chain management was also indispensable to establish and maintain a stable supply chain, but seldom to be discussed through the eye of forestry operation system while it was discussed from economical, energetic or ecological aspects in the downstream of supply chain (e.g. Dornburg and Faaij 2001, Mizuishi et al. 2013).

The detailed cost can be calculated by estimating each machinery cost, and such detailed cost data enables us to analyze the cost and economical benefit of a supply chain which expresses the status of economical satisfaction on each stakeholder. There is a variety of chip supply chain as explained in the next section and keys for success in establishing and maintaining a stable chip supply chain will be clarified from the aspect of economical satisfaction among stakeholders. The aim of this study is to point out keys to establish chip supply chains successfully by overviewing some examples of supply chain and by analyzing a model supply chain in Denmark as an advanced case with using cost and benefit rate. In this study, the term of "m^3" means loose m^3.

6.2 Materials and methods

6.2.1 Examples of supply chain

Some examples of chip supply chain in advanced countries were overviewed as our preliminary study (Table 6.1). In the example of Denmark, the national forest owned chip material and had two chip supply chains. One chain was a cooperation system with a local farmer in chipping operation, and the other was performed by their own production system. In the example of United States, a private forest company was responsible for the whole chip supply to the customer—an electric power plant. The customer also prepared chip material by itself in case. In the example of Austria, one of the forest owners associations was collecting chip materials from the members, and arranged chip production operated by a contractor. At the same time, private chipping companies and customers also enlarged their own collection of chip material to secure chip supply. In Italy, two examples were observed. One was a larger scale supply chain for CHP plant where a private chipping company was responsible for the whole supply chain, and the customer also secured another chain by itself. The other example was a smaller scale supply chain for private heating plants whose owners managed whole supply chain by using contractors. Thus, the stakeholder structure of supply chains shown above were different each other while the production techniques were common or similar.

6.2.2 Cost analysis of a supply chain

The chip supply chain using the cooperation system with a local farmer in chipping operation observed in Denmark was analyzed as an advanced model in this study. The main reason of choosing this example was that involved a person from local community as a chipping operator and would be bring a positive economical effect for local community. The stakeholders were national forest, a chipping operator whose principal occupation was a farmer, a transportation operator, and a consumer. Danish national forest owned residual wood materials for energy chip after clear cuts in their forest, and dried them about one year at a roadside. They sold chip according to the market price in order to make more profit as much as possible. The operational site located in Sorø, Zealand, and they offered a part time chipping operation for cooperative local people according to their necessity, whereas they employed permanent chipping teams using large mobile chippers within their organization to produce a certain amount of chip constantly. In this model case, a local farmer got the job. This operator rented a mobile chipper that was tractor traction type, and equipped a grapple loader to his own tractor for loading material to the chipper. The specification of the rented chipper, Jenz HEM 581, was shown in Table 6.2. In this study, between a chipping operation and a truck transportation process, there was an additional short transportation of fully loaded container with chip from the chipping operation landing to a truck accessible landing. This van was directly transported to consumers by a third party logistics company and it benefited to realize stable transportation cost. The customer of this supply chain was a district heating plant (DHP) established by the local residents. From the aspect of forest engineering, the cost and benefit between the chipping operator and national forest was analyzed intensively because the other stakeholders were subject to market condition.

The data for cost analysis was mainly obtained from our observation and personal communication to the chipping operator at the operational site in Sorø. Because the data is not always clear, the rental fee for a similar chipper was substantially obtained from personal communication to a contractor at Padova, Veneto, Italy. The cost of farmer C_f (EUR/GJ) at the chipping site before truck transportation was calculated by the equation (27):

$$C_f = C_c + C_e \tag{27}$$

where C_c was chipping cost (EUR/GJ); and C_e was the short transportation cost between chipping site and truck transportation landing (EUR/GJ). Chipping cost C_c was calculated by the equation (28):

$$C_c = \big\{(T + R)/p + f_p f_r(1 + e)\big\}/d_{GJ} + k \tag{28}$$

where T was the depreciation cost of a tractor (EUR/hr); R, the rental fee of a chipper (EUR/hr); p, chipping productivity (m^3/hr); f_p, fuel price (EUR/L); f_r, fuel consumption of chipper (L/m^3); e, the coefficient rate of lubricants for fuel; d_{GJ}, the energy density of one cubic meter of chip (GJ/m^3); and k was the cost of knives (EUR/GJ). The depreciation cost of a tractor T (EUR/hr) was expressed by the following equations derived from (Miyata

1980):

$$
\begin{gathered}
T = (F + V)/H + w + f_p f_t(1 + e) \qquad (29) \\
F = P(1 - s)/N + rP\big\{(1 - s)(N + 1)/2N + s\big\} \\
V = mP(1 - s)/N
\end{gathered}
$$

where F was the fixed cost of the tractor (EUR/yr); P, the price of the tractor including an equipped grapple loader (EUR); s, salvage rate; N, depreciation years (yr); r, the total of tax, insurance, and interest rates; V, the variable cost of the tractor (EUR/yr); m, the maintenance rate; H, annual scheduled working hours (hr/yr); w, hourly wage (EUR/hr); and f_t was the fuel consumption of the tractor (L/hr). Here, the wage w could be set as zero because the operator worked by himself without employment. The cost for an additional short transportation between the chipping site and truck accessible road side landing C_e (EUR/hr) was derived from the equation (30):

$$C_e = t_t(T + R)/(d_{GJ}V_c) \qquad (30)$$

where t_t was the cycle time of a short transportation (hr); and V_c was the container volume (m^3).

The empirical chipping productivity was 700 m^3 for 8 hours, i.e. 87.5 m^3/hr, obtained from personal communication to the operator. At the same time, a cycle of stable chipping operation was observed for 32 minutes with no delay and the produced amount was 47 m^3. The productivity was, therefore, calculated as 88.1 m^3/hr. Although it could not be evaluated statistically, these two figures were regarded as the same here. The reason was supposed that the chipping operation is consisted of only feeding and chipping operations and stable owing to its simplicity (Röser et al. 2012). The average productivity of these two figures was 87.8 m^3/hr and this average was applied as productivity in this study. The cycle time of a short transportation was also obtained from the observation and set at 0.33 hours. The data for above calculations and the coefficients for unit conversion were summarized in Table 6.3.

6.2.3 Calculation of cost and benefit rate

Contract prices of outsourced chipping and transportation were expressed as C_f^* and C_t^*, respectively. Here, C_t^* was substituted as 1.06 EUR/GJ obtained from a personal communication at Leoben, Steiermark, Austria. Although the price of produced chip P_c varied depending on seasons in actual, the fixed price of 4.83 EUR/GJ (36 DKK/GJ) was used in this study from a Danish literature (Serup et al. 1999). Thus the cost and benefit rates (benefit/cost) of national forest and the chipping operator were analyzed. The components of cost and benefit were summarized in Table 6.4.

6.3 Results

6.3.1 Structure of the model chip supply chain

The structure of the model chip supply chain was shown in Table 6.5. This supply chain consisted of three operational phases evolving five operations. As descending the supply chain stream, the form of material/product was transferred from woody solid material to heat via woody chip. In the model supply chain, trading of material/product once occurred at the end of supply chain directly from the supplier—Danish national forest —to the customer— DHP—while a 3PL company delivered the product to the DHP. The commercial distribution among stakeholders could be, therefore, illustrated as Fig.6.1.

The cost could not be accounted during logging and drying operations because the material was accumulated during log harvesting operations and dried on their own forest land. The stakeholders were different between the material/product owner (national forest) and operators (farmer and 3PL company) in chipping and transportation processes. Because the material or product was owned by national forest for all the time, all information, money and ownership were accumulated at the national forest. It could be said that the national forest played the role of manager in this chip supply chain and could control the balance of production and trading according to the market price.

6.3.2 Results of cost analysis

The cost of farmer C_f was 2.3 EUR/GJ. The changes of cost benefit rate of chipping operator and national forest were shown in Fig. 6.2 according to the change of the chipping contract price C_f^*. There existed the case that the rates of both chipping operator and national forest exceeded one at the same time when the chipping contract price C_f^* was from 2.3 EUR/GJ to 3.8 EUR/GJ. The even point in the rate of chipping operator and national forest was 1.2 when the C_f^* was 2.8 EUR/GJ. At this even point, the net profit of chipping operator and national forest were 0.5 EUR/GJ and 0.9 EUR/GJ, respectively. In other words, the daily net profit of chipping operator and national forest could achieve 984 EUR/day and 1,671 EUR/day, respectively.

6.4 Discussion

Cost breakdown in the model supply chain was clarified from the actual data, and it was proved that the model supply chain could benefit the chipping operator and the chip supplier. This model succeeded in realizing an economical and reliable chip supply. One of the reasons of this success was that the part time chipping job system benefited on both ordering and receiving sources in terms of economy. The chipping operator—the receiving source—was well motivated to operate economically simply because he/she could earn extra income by using their available time, and this motivation would be accelerated under the reasonable chipping contract price C_f^*. This extra income of chipping operator would also bring good effects in local economy. On the other hand, the national forest—the ordering source—could react against the increase of demand rapidly, played an important role as a buffer to secure stable supply by combining even small scale supply chains (Yoshida and Sakai 2014a), and save its supply cost. These two stakeholders could have those benefits at the same time and spontaneously establish a rational and flexible supply chain.

From tactical aspect, the material ownership plays an important role in supply chain management. The model supply chain has great advantages from the aspect of material collection because it has a large amount of material stock managed by a unified command system as Danish national forest. On the other hand, the situation of Japanese national forest is not similar to that of Danish national forest because of the different timber/material sale system. Japanese national forest applies a standing sale system where "the wood buyer is in charge of harvesting and delivering to the roadside" (Uusitalo 2005) while Danish national forest applies a delivery sale system where "the wood seller is in charge of these activities" (Uusitalo 2005) as illustrated in Fig. 6.1. Japanese national forest does not have the right to treat produced timbers directly in spite of its large stock volume.

Indeed the standing sale system has merits, for example, to strengthen the business bases of logging or chipping companies in the region, but makes material collection more complex because the ownership of wood material would be further fragmented into many cases. In a previous case study on the relationship between ownership and business scale (Van-Belle et al. 2003), it was clarified that producers of large volume (produced more than 60,000 m^3/yr) played an important role as core producers in a chip supply chain which accounted 60 – 70 % of the whole demand at a competitive price, while smaller scale loggers and farmers (produced less than 10,000 m^3/yr) acted as a buffer who could produce only a marginal portion at a higher price of 2.1 EUR/GJ. It indicated that it was necessary to have a large volume of production for core chip supply with a reasonable cost. In the model supply chain, by applying a delivery sale system and preparing two kinds of supply chains in an organization, Danish national forest managed both core and marginal production systems successfully.

Material availability according to the seasonality is another important issue in energy production (Akhtari et al. 2014). From logistical point of view, the necessity of storages in forest or at depots has been already mentioned several times in many articles such as (Eriksson and Björheden 1989, Gunnarsson et al. 2004, Kanzian et al. 2009, Rauch and Gronalt 2011). However, because the storage process involved an inventory cost during a certain period, the possibility to be in charge of storage process would be limited. In the model system, the storage system was simple and free for charge because they dried their own properties at a year-round accessible roadside on their own lands with no facility. The unified land and material ownerships saved its storage and handling cost. Additionally, drying process increases the energy content of chip and improves the transport efficiency (Talbot and Suadicani 2006) so that drying is also an important process of storage system. Simultaneously, it was clarified that the cost added from long unmanaged storage time seriously affected the quality of fiber and the economic health of industries (Gallis 1996).The importance of balancing the trade off relationship in fiber quality and economy during a storing period was indicated (Uusitalo 2005).

6.5 Conclusion

This study pointed that a key for the success of establish and maintain a supply chain existed in the stakeholders who had material ownership in relation with the timber/material sales systems within the commercial distribution. Although it was difficult to improve the basic tactical problems such as fragmented ownership or scarce forest road network in Japan immediately, the merits of changing the timber/material sales system from standing sale system to deliver sale system was suggested from the analysis of one Danish supply chain. The efficient use of production inputs such as production properties and labours should be achieved by breaking down the barriers of communication and information flow within and between stakeholders (Pulkki 2001). This indicates the importance of managing the social relationship in chip supply chain for winning the satisfaction of stakeholders and the necessity of the person in charge for the chip supply chain management.

Table 6.1: Examples of chip supply chain

Country	Stakeholders and their roles	Production technique	Material
Denmark	National forest (M & C), Farmer (C), Third party logistics (T), DHP (U)	C: Mobile chipper (Tractor traction type with self engine), T: Container trailer	Logging residue (tree tops) from several small clear cuts
United States	Private forest company (M & C & T),Electric power plant (M & U)	C: Mobile grinder (Self engine), T: Chip van	Logging residue from several small clear cuts
Austria	Forest owners association (M),Private chipping company (M & C & T), DHP & CHP (M & U)	C: Mobile chipper (Truck mounted), T: Chip truck	Logging residue (branches) from a thinning operation
Italy (larger)	Private chipping company (M & C & T), CHP (M & U)	C: Mobile chipper (several types),T: Chip truck	Logging residue and sawmill waste
Italy (smaller)	Private logging and chipping companies (M & C),Third party logistics (T), Heating plant (U)	C: Mobile chipper (tractor traction and truck mounted)	Logging residue and sawmill waste

The abbreviation of M meant material collection; D, drying; C, chipping; T, chip transportation; and U meant chip utilization.

Table 6.2: Specification of the rented chipper

Chipper	Jenz HEM 581 (Drum type)
Engine	Mercedes Benz, 357 kW
Length, Width, Height (m)	8.55, 2.55, 3.95
Loading conveyer width and length (m)	1.2, 0.68
Knives	12 knives

Table 6.3: Values of cost calculation on the tractor and chipper

Cost element	Tractor	Chipper
Hourly cost (EUR/hr)	26.67	270
Price P (1,000 EUR)	75.55	
Salvage rate s	0.1	
Depreciation year N (yr)	5	
Annual working hours H (hr)	1500	
Annual working days (days)	200	
Daily working hours (hr)	8	
Productive time	0.75	
Maintenance and repair rate m	0.5	
Tax, interests, and insurance r	0.4	
Fuel consumption f_t (L/hr), f_r (L/m^3)	5	0.5
Lubricant rate e	0.2	0.2
Wage w (EUR/hr)	0	0
Knife cost k (EUR/GJ)		0.007
Productivity p (m^3/hr)		87.8
Container volume (m^3) V_c		47
Net energy density d_{GJ} (GJ/m^3)	2.6	
Volume density d_v (m^3/solid m^3)	2.8	

Table 6.4: Costs and benefits of two stake holders

Stakeholder	Cost	Benefit
National forest	Sum of contract cost for chipping and transportation $C_f^*+C_t^*$	Chip price P_c
Chipping operator	Chipping cost C_f	Chipping contract price C_f^*

Table 6.5: Supply chain structure in the model

Operational phase	Material procurement		Production		Use
Operation	Logging	Drying	Chipping	Transport	Heating
Ownership	National forest	National forest	National forest	National forest	District heating plant
Operator	National forest	National forest	Farmer	3PL company	District heating plant

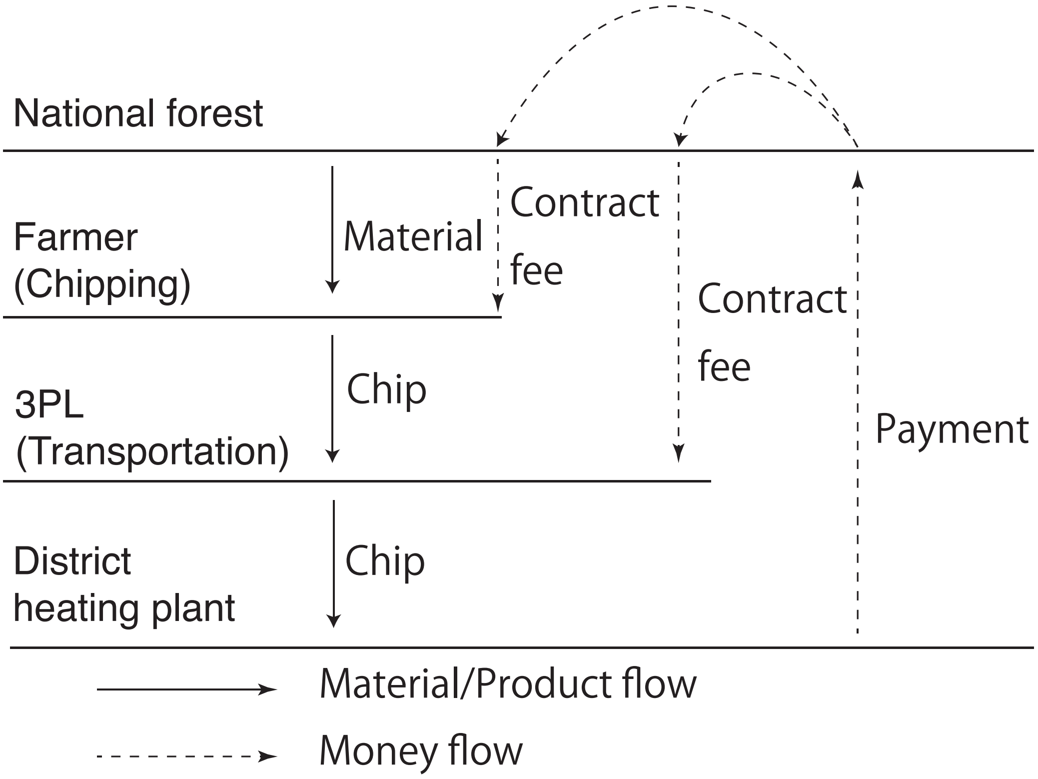


Fig. 6.1: Diagram of commercial distribution among stakeholders in the model supply chain

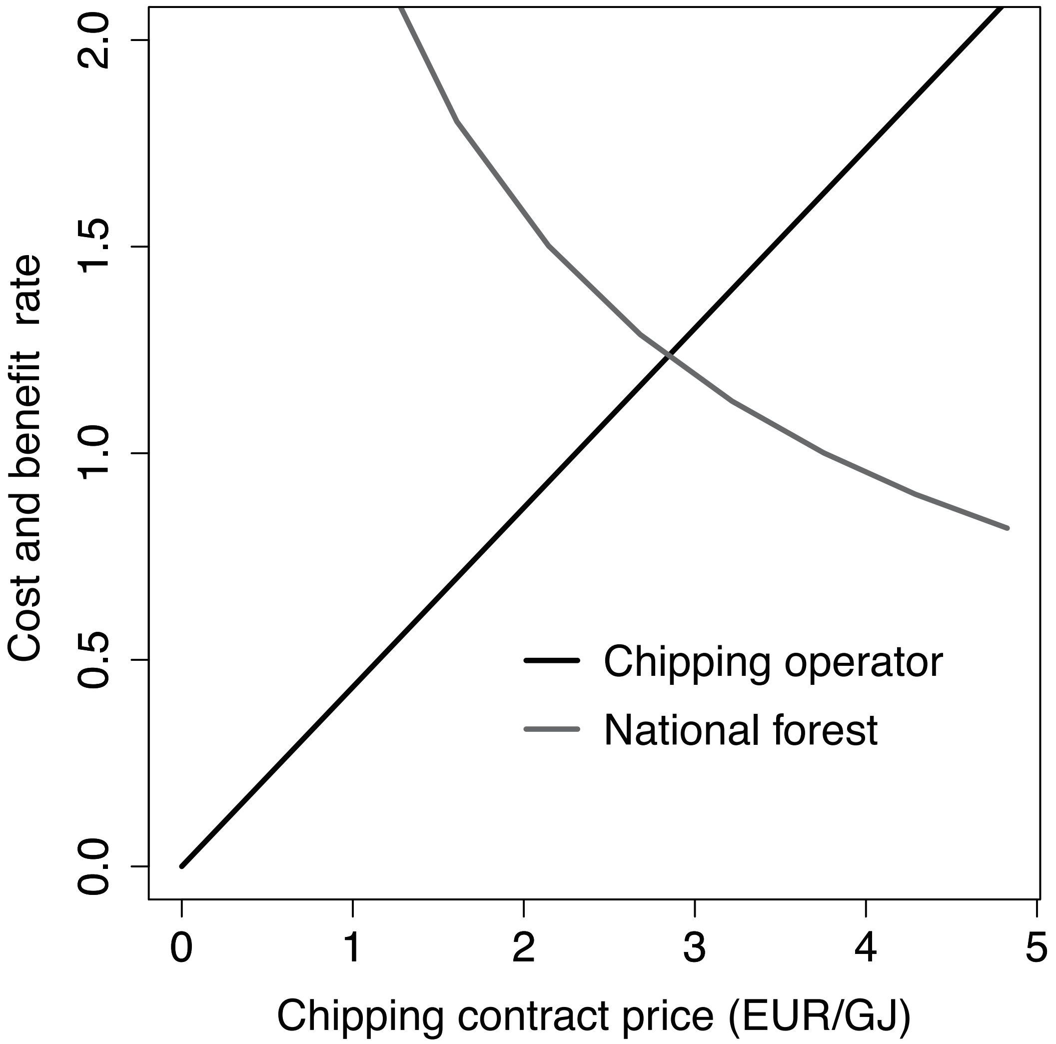


Fig. 6.2: Cost and benefit rate of chipping operator and national forest

7 Concluding summary

The chip supply chain for bioenergy was analyzed in this study to support its establishment while securing its cost-efficiency. Discussion was started from the very first point of supply chain — material harvesting. Because logging residues were considered to be the material for fuel chip, first of all efficient whole tree harvesting systems were required. Then, the introduction of mobile chippers was suggested to improve the handling and transportation efficiencies of logging residues. While the use of mobile chippers had been common already in foreign countries, the choice of chipper seemed to be difficult because there were a variety of cost components and also local situation was differed between Japan and other countries. The rational way of chipper choice was discussed in relation with initial investment, business scale and chipping productivity. The chippers with middle or large engine power were clarified to be useful under the current Japanese situation while realizing a lower supply cost. The chippers with small power were useful for small scale forestry where material collection was much smaller while its production cost was about 600 JPY/loose m^3 higher than that of larger ones. From the viewpoint of stable chip supply for the power plant with huge demand, it was clarified that the allocation of mobile chippers would affect the transportation cost. As extending the transportation distance, the chip supply cost of supply chain would increase. There was a gap among total supply costs and the inappropriate allocation of chippers negatively affected on the economy of chip supply chain.

Finally, the key to establish chip supply chains by satisfying the benefits of stakeholders was clarified from the analysis of an advanced example of chip supply chain in Denmark. The owners of material for chip were the important players who could manage the commercial distribution of chip.

This study analyzed the establishment of supply chain from different perspectives such as forestry operation, commercial distribution and stakeholder benefit. Indeed costs composing the total supply cost could be obtained by the analysis of forestry operation but it was also shown that the tactical decisions such as chipper allocation or timber/material sales systems would also influence on the total cost. It indicated that involving all stakeholders was indispensable to optimize a supply chain as well as improving cost efficiency of each process in the supply chain.

The geographic and social structures of forestry in Japan have several weaknesses for efficient operations as mentioned through this study. This study suggested the necessity of overcoming such difficulties and showed the possibility of economical success by integrating the stakeholders in a supply chain. This point of view will be useful to support the promotion of bioenergy use not only in Japan but also other countries where suffered to establish economical bioenergy supply chains. The specific ways to integrate stakeholders should be discussed on local basis and the result of this study could contribute to encourage such practical movements.

References

Agency for Natural Resources and Energy (2014). *Energy in Japan in 2014*. Agency for Natural Resources and Energy, Tokyo.

Akhtari, S., Sowlati, T., and Day, K. (2014). Economic feasibility of utilizing forest biomass in district energy systems – a review. *Renewable and Sustainable Energy Reviews*, 33:117–127.

An, H., Wilhelm, W. E., and Searcy, S. W. (2011). Biofuel and petroleum–based fuel supply chain research: A literature review. *Biomass and Bioenergy*, 35(9):3763–3774.

Angus-Hankin, C., Stokes, B., and Twaddle, A. (1995). The transportation of fuelwood from forest to facility. *Biomass and Bioenergy*, 9(1âĂŞ-5):191–203. International Energy Agency Bioenergy Agreement Progress and Achievements 1992/94.

Asikainen, A. (1998). Chipping terminal logistics. *Scandinavian journal of forest research*, 13(1-4):386–392.

Asikainen, A., Liiri, H., Peltola, S., Karjalainen, T., and Laitila, J. (2008). Forest energy potential in Europe (EU27). Technical report, Finnish Forest Research Institute.

Asikainen, A. and Pulkkinen, P. (1998). Comminution of logging residues with evolution 910r chipper, moha chipper truck, and morbark 1200 tub grinder. *International Journal of Forest Engineering*, 9(1).

Assirelli, A., Civitarese, V., Fanigliulo, R., Pari, L., Pochi, D., Santangelo, E., and Spinelli, R. (2013). Effect of piece size and tree part on chipper performance. *Biomass and Bioenergy*, 54:77–82.

Barua, S. K. and Bonilha, R. (2013). Economic competitiveness of forest biomass energy. In Kellomäki, S., Kilpeläinen, A., and Alam, A., editors, *Forest BioEnergy Production*, pages 239–251. Springer New York.

Biomass Trade and Logistics Centres (2014). Prices of wood fuels in selected countries in March 2014. http://www.biomasstradecentre2.eu/wood-fuel-prices/. Last access 2015-11-24.

Dornburg, V. and Faaij, A. P. (2001). Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. *Biomass and Bioenergy*, 21(2):91–108.

Eriksson, L. O. and Björheden, R. (1989). Optimal storing, transport and processing for a forest-fuel supplier. *European Journal of Operational Research*, 43(1):26–33.

European Commission (2013). Report from the commission to the european parliament, the council, the European economic and social committee and the committee of the regions, renewable energy progress report. Technical report, European Commission, Brussels.

Forestry Agency (2011). *Annual Report on Forest and Forestry in Japan, Fiscal Year 2010*. Forestry Agency.

Forestry Agency (2013). *Annual Report on Forest and Forestry in Japan, Fiscal Year 2012*. Forestry Agency.

Forestry Agency (2014). *Annual Report on Forest and Forestry in Japan, Fiscal Year 2013*. Forestry Agency.

Forestry Agency (2015a). *Annual Report on Forest and Forestry in Japan, Fiscal Year 2014*. Forestry Agency.

Forestry Agency (2015b). *Heisei 26 nen Mokuzaijyukyuhyou [Table of supply and demand of wood products in 2014]*. Forestry Agency.

Francescato, V., Antonini, E., Bergomi, L. Z., Metschina, C., Schnedl, C., Krajnc, N., Koscik, K., Gradziuk, P., Nocentini, G., and Stranieri, S. (2008). *Wood fuels handbook, production, quality requirements, trading*. AEIBIOM.

Gallis, C. T. (1996). Activity oriented stochastic computer simulation of forest biomass logistics in greece. *Biomass and Bioenergy*, 10(5 - 6):377–382.

Ganeshan, R. and Harrison, T. P. (1995). An introduction to supply chain management. http://mason.wm.edu/faculty/ganeshan_r/documents/intro_supply_chain.pdf.

Ghaffariyan, M., Stampfer, K., and Sessions, J. (2010). Optimal road spacing of cable yarding using a tower yarder in southern austria. *European Journal of Forest Research*, 129(3):409–416.

Ghaffariyan, M. R., Spinelli, R., and Brown, M. (2013). A model to predict productivity of different chipping operations. *Southern Forests: a Journal of Forest Science*, 75(3):129–136.

Government of Canada (2014). About electricity — Natural Resources Canada. http://www.nrcan.gc.ca/energy/electricity-infrastructure/about-electricity/7359. Last access 2015-11-24.

Government of Canada (2015). Forest bioenergy. http://www.nrcan.gc.ca/forests/industry/bioproducts/13325. Last access 2015-11-24.

Greenhouse Gas Inventory Office of Japan, Centre for Global Environmental Research, and National Institute for Environmental Studies (2015). *National Greenhouse Gas Inventory Report of Japan.* National Institute for Environmental Studies, Ibaraki.

Gunnarsson, H., Rönnqvist, M., and Lundgren, J. T. (2004). Supply chain modelling of forest fuel. *European Journal of Operational Research*, 158(1):103–123.

Harrill, H. and Han, H.-S. (2010). Application of hook-lift trucks in centralized logging slash grinding operations. *Biofuels*, 1(3):399–408.

Hytönen, J. and Moilanen, M. (2014). Effect of harvesting method on the amount of logging residues in the thinning of scots pine stands. *Biomass and Bioenergy*, 67:347–353.

Imatomi, Y. (1997). An ergonomic study on the geometrical design and density of tractor skidding-roads. *Bull For For Prod Res Inst*, 373:1–71.

Iwate Prefecture (2012). *Heisei24nendoban, Iwatekenringyonosihyou [The report on forestry in Iwate prefecture in 2011].* Iwate Prefecture, Iwate.

Jackson, S. W., Rials, T. G., and Taylor, A. M. (2010). Wood 2 energy, a state of the science and technology report. http://www.wood2energy.org/StateofScience.htm.

Johansson, J. (1997). Small tree harvesting with a farm tractor and crane attached to the front. *Journal of Forest Engineering*, 8(1):21–33.

Kamimura, K., Kuboyama, H., and Yamamoto, K. (2012). Wood biomass supply costs and potential for biomass energy plants in japan. *Biomass and Bioenergy*, 36:107 – 115.

Kanzian, C., Holzleitner, F., Stampfer, K., and Ashton, S. (2009). Regional energy wood logistics–optimizing local fuel supply. *Silva Fennica*, 43(1):113–128.

Kärhä, K. (2011). Industrial supply chains and production machinery of forest chips in finland. *Biomass and Bioenergy*, 35(8):3404 – 3413.

Karttunen, K., Lättilä, L., Korpinen, O.-J., and Ranta, T. (2013). Cost-efficiency of intermodal container supply chain for forest chips. *Silva Fennica*, 47:article id 1047.

Karttunen, K., Väätäinen, K., Asikainen, A., Ranta, T., et al. (2012). The operational efficiency of waterway transport of forest chips on finland 's lake saimaa. *Silva Fennica*, 46(3):395–413.

Kumar, A., Cameron, J. B., and Flynn, P. C. (2003). Biomass power cost and optimum plant size in western canada. *Biomass and Bioenergy*, 24(6):445 – 464.

Kumazaki, M. (2011). *Mokushitsu energy business no tenbo*. Zenkokuringyo-kairyo-fukyu-kyokai, Tokyo.

Laitila, J. (2008). Harvesting technology and the cost of fuel chips from early thinnings. *Silva Fennica*, 42(2):267.

Laitila, J., Heikkilä, J., and Anttila, P. (2010). Harvesting alternatives, accumulation and procurement cost of small-diameter thinning wood for fuel in central finland. *Silva Fennica*, 44(3):465–480.

Leo, B., Rudolf, H. H., and L., C. R. (2014). Optimizing cable harvesting layout when using variable-length cable roads in central europe. *Canadian Journal of Forest Research*, 44(8):949–960.

Ministry of Economy, Trade and Industry in Japan (2015). Information disclosure web site for feed in tariff law in japan. http://www.fit.go.jp/statistics/public_sp.html. Last access 2015-10-11.

Ministry of Land, Infrastructure, Transport and Tourism (2014). *Heisei26nendo kensetsukikai sonryou santeihyou [Table of factors for cost calculation of construction equipment in 2014]*. Ministry of Land, Infrastructure, Transport and Tourism, Tokyo.

Miyata, E. (1980). Determining fixed and operating costs of logging equipment.

Mizuishi, T., Ikaga, T., Murakami, S., Kuzuki, R., and Yamada, K. (2013). Cost–benefits analysis of non-energy benefits (NEB) for each stakeholders and consideration for redistribution of NEB. *Journal of Environmental Engineering*, 78(684):175–181.

Moriguchi, K., Suzuki, Y., Gotou, J., Inatsuki, H., Yamaguchi, T., Shiraishi, Y., and Ohara, T. (2004). Cost of comminution and transportation in the case of using logging residue as woody biofuel. *Journal of the Japanese Forestry Society*, 86(2):121–128.

Nakama, K., Ota, T., Mizoue, N., and Yoshida, S. (2011). Effects of recovering logging residues on strategy and benefits of forest stand management. *Journal of the Japanese Forest Society*, 93(5):226–234.

Nati, C., Spinelli, R., and Fabbri, P. (2010). Wood chips size distribution in relation to blade wear and screen use. *Biomass and Bioenergy*, 34(5):583–587.

Nihonrindokyokai (1982). *Shouwa 57 nendoban rindouhikkei sekkeihen [Technical regulation for forest road construction in 1982]*. Nihonrindokyokai, Tokyo.

Nordfjell, T., BjÃűrheden, R., Thor, M., and WÃďsterlund, I. (2010). Changes in technical performance, mechanical availability and prices of machines used in forest operations in sweden from 1985 to 2010. *Scandinavian Journal of Forest Research*, 25(4):382–389.

Pan, F., Han, H., Johnson, L. R., and Elliot, W. J. (2008). Net energy output from harvesting small-diameter trees using a mechanized system. *Forest products journal*, 58(1/2):25.

Pulkki, R. (2001). Role of supply chain management in the wise use of wood resources. *The Southern African Forestry Journal*, 191(1):89–95.

Ranta, T. and Rinne, S. (2006). The profitability of transporting uncomminuted raw materials in Finland. *Biomass and Bioenergy*, 30(3):231–237.

Rauch, P. and Gronalt, M. (2011). The effects of rising energy costs and transportation mode mix on forest fuel procurement costs. *Biomass and Bioenergy*, 35(1):690–699.

Röser, D., Mola-Yudego, B., Prinz, R., Emer, B., and Sikanen, L. (2012). Chipping operations and efficiency in different operational environments. *Silva Fennica*, 46(2):275–286.

Saito, M., Goshima, M., Aruga, K., Matsue, K., Shuin, Y., and Tasaka, T. (2013). Study of automatic forest road design model considering shallow landslides with lidar data of funyu experimental forest. *Croatian Journal of Forest Engineering*, 34(1):1–15.

Sakai, H. and Kamiizaka, M. (1980). Statistical analysis of cable-yarding operations in japan. ii. an analysis of the effect of operational conditions of cable-yarding systems on productivity by means of the quantification theory. *Journal of the Japanese Forestry Society*, 93(5):254–263.

Sakai, H. and Kamiizaka, M. (1985). Prehauling systems for logs from thinnings. *Journal of the Japanese Forestry Society*, 67(3):82–91.

Samset, I. (1990). *Some observations on time and performance studies in forestry*, volume 43. Norsk Institutt for Skogforskning Ås.

Serup, H., Falster, H., Gamborg, C., Gundersen, P., Hansen, L., Heding, N., Jakobsen, H., Kofman, P., Nikolaisen, L. a., and Thomsen, I. (1999). Wood for energy production. Technology-environment-economy. Technical report, Videncenter for Halm-og Flisfyring (Denmark).

Shinrinsegyouplannerkyokai (2012). *Shinrinsegyou planner text kisohen [Text for forest management planners]*. Shinrinsegyouplannerkyokai, Tokyo.

Shirasawa, H., Hasegawa, H., and Umegaki, H. (2013). Cost-reducing effectiveness of selecting the type of transportation vehicle in a roundwood supply chain : a case study in hyogo prefecture(<special issue>effective and efficient utilization of local forest resources). *Journal of the Japan Forest Engineering Society*, 28(1):7–15.

Son, J., Sakurai, R., Nitami, T., and Sakai, H. (2014). Development of a method of forest road network planning using gis that discriminates and avoids dip slopes. *Bulletin of the University of Tokyo Forests*, (130):1–13.

Sowa, J. M. and Szewczyk, G. (2013). Time consumption of skidding in mature stands performed by winches powered by farm tractor. *Croatian Journal of Forest Engineering*, 34(2):255–264.

Spinelli, R., Cavallo, E., Eliasson, L., and Facello, A. (2013). Comparing the efficiency of drum and disc chippers. *Silva Fennica*, 47(2):article id 930.

Spinelli, R., Glushkov, S., and Markov, I. (2014). Managing chipper knife wear to increase chip quality and reduce chipping cost. *Biomass and Bioenergy*, 62:117–122.

Spinelli, R. and Hartsough, B. (2001). A survey of italian chipping operations. *Biomass and Bioenergy*, 21(6):433–444.

Spinelli, R. and Magagnotti, N. (2010). A tool for productivity and cost forecasting of decentralised wood chipping. *Forest Policy and Economics*, 12(3):194–198.

Spinelli, R., Magagnotti, N., and Lombardini, C. (2010). Performance, capability and costs of small-scale cable yarding technology. *Small-scale Forestry*, 9(1):123–135.

Spinelli, R. and Visser, R. J. (2009). Analyzing and estimating delays in wood chipping operations. *Biomass and Bioenergy*, 33(3):429 – 433.

Stampfer, K. and Kanzian, C. (2006). Current state and development possibilities of wood chip supply chains in austria. *Croatian Journal of Forest Engineering*, 27(2):135–145.

Sultana, A. and Kumar, A. (2011). Optimal configuration and combination of multiple lignocellulosic biomass feedstocks delivery to a biorefinery. *Bioresource Technology*, 102(21):9947–9956.

Suzuki, Y., Setiawan, A. H., and Gotou, J. (2015). Timber harvesting systems in japan's aging plantation forests: Implications for investment in construction of forest road networks. *Journal of the Japanese Forest Society*, 97(4):191–202.

Talbot, B., Stampfer, K., and Visser, R. (2015). Machine function integration and its effect on the performance of a timber yarding and processing operation. *Biosystems Engineering*, 135:10–20.

Talbot, B. and Suadicani, K. (2005). Analysis of two simulated in–field chipping and extraction systems in spruce thinnings. *Biosystems Engineering*, 91(3):283–292.

Talbot, B. and Suadicani, K. (2006). Road transport of forest chips: containers vs. bulk trailers. *Forest Studies*, 45:11–22.

The World Bank (2015). The statistic data about forest area. http://data.worldbank.org/indicator/AG.LND.FRST.ZS. Last access 2015-11-24.

Tolosana, E., Laina, R., Martínez-Ferrari, R., and Ambrosio, Y. (2011). Recovering of forest biomass from spanish hybrid poplar plantations. *Biomass and Bioenergy*, 35(7):2570–2580.

Toyama, K., Tatsuhara, S., and Shiraishi, N. (2012). Simulation under diverse conditions for profitable thinning regime and clearcutting age in planted *cryptomeria japonica* forest. *Journal of the Japanese Forest Society*, 94(6):269–279.

US Energy Information Administration (2015). Annual Energy Review. http://www.eia.gov/totalenergy/data/monthly/index.cfm. Last access 2015-10-20.

Uusitalo, J. (2005). A framework for CTL method-based wood procurement logistics. *International Journal of Forest Engineering*, 16(2):37–46.

Valente, C., Spinelli, R., Hillring, B. G., and Solberg, B. (2014). Mountain forest wood fuel supply chains: comparative studies between norway and italy. *Biomass and Bioenergy*, 71:370 – 380.

Van-Belle, J., Temmerman, M., and Schenkel, Y. (2003). Three level procurement of forest residues for power plant. *Biomass and Bioenergy*, 24(4–5):401–409. Proceedings of the

IEA Bioenergy Task 31 Workshop, Principles and Practice of Forestry and Bioenergy in Densely-Populated Regions.

Wolfsmayr, U. J. and Rauch, P. (2014). The primary forest fuel supply chain: A literature review. *Biomass and Bioenergy*, 60:203–221.

Yamada, Y., Kondo, M., and Yogi, K. (2010). Comparative study on physiological burden of a choker man between ground-lead skidding and high-lead logging : A case study with swing yarder in miyoshi city, hiroshima. *Journal of the Japan Forest Engineering Society*, 25(4):233–237.

Yoshida, C., Nakazawa, M., Mozuna, M., Jinkawa, M., Ikami, Y., Takano, T., Imatomi, Y., Oka, M., Furukawa, K., Usuda, H., and Iwaoka, M. (2011). Investigation of the harvesting method for logging residues using wood shear for rough chipping : Productivity of harvesting system to landing. *Journal of the Japan Forest Engineering Society*, 26(1):57–64.

Yoshida, M. and Sakai, H. (2014a). Fuel chip supply system with low price mobile chippers. *Croatian Journal of Forest Engineering*, 35(1):9–14.

Yoshida, M. and Sakai, H. (2014b). Importance of capital cost reduction of chippers and their required productivity. *Journal of Forest Research*, 19(4):361–368.

Yoshino, S., Yabe, K., and Sato, T. (2010). The possibility of wood biomass usage by line thinning: The case of the profit sharing forest of tokyo university of agriculture. *Journal of Agriculture Science, Tokyo University of Agriculture (Japan)*, 55:31–37.

Yoshioka, T. (2011). Study on the feasibility of a harvesting, transporting, and chipping system for forest biomass resources in japan. *Agri–Biosci Monographs*, 1:1–60.

Yoshioka, T., Aruga, K., Sakai, H., Kobayashi, H., and Nitami, T. (2002). Cost, energy and carbon dioxide (co2) effectiveness of a harvesting and transporting system for residual forest biomass. *Journal of Forest Research*, 7(3):157–163.

Yoshioka, T., Iwaoka, M., Sakai, H., and Kobayashi, H. (2000). Feasibility of a harvesting system for logging residues as unutilized forest biomass. *Journal of Forest Research*, 5(2):59–65.

Yoshioka, T., Sakurai, R., Aruga, K., Nitami, T., Sakai, H., and Kobayashi, H. (2006). Comminution of logging residues with a tub grinder: Calculation of productivity and procurement cost of wood chips. *Croatian Journal of Forest Engineering*, 27(2):103–114.

Zamora-Cristales, R., Boston, K., Sessions, J., Murphy, G., et al. (2013). Stochastic simulation and optimization of mobile chipping and transport of forest biomass from harvest residues. *Silva Fennica*, 47(5):22.

Zamora-Cristales, R., Sessions, J., Boston, K., and Murphy, G. (2015). Economic optimization of forest biomass processing and transport in the Pacific Northwest USA. *Forest Science*, 61(2):220–234.

Zenkokuringyoukairyouhukyukyoukai (2001). *Kikaika no management [Management of mechanization]*. Zenkokuringyoukairyouhukyukyoukai, Tokyo.