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Winch Harvesting on Flat and Steep Terrain Areas and Improvement of its Methodology

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Abstract

With the increase of importance of bioenergy, the whole tree harvesting system was reconsidered. As a simple way of a whole tree harvesting system, this study analyzed two winching procedures in terms of productivity and influence from terrain conditions. One of the winching procedures was observed on flat terrain, where the felled trees were scattered and then, one-by-one, attached to the winch rope. The other was observed on a steep terrain, where the felled trees were concentrated in a line and then attached, at one time, to the winch rope. A significant difference caused by slope conditions appeared only in the reeling velocity. When increasing the harvested volume in a cycle, the productivity increased. The difference in productivity between two sites was slight with the same harvested volume. By the one-by-one procedure, the full volume harvested in a cycle was only skidded from the nearest felling points, while the bundled procedure skidded the full volume from various points including the farthest point. The one-by-one procedure will save the winch rope tension and reduce engine acceleration. Fuel consumption, therefore, will be decreased by applying the one-by-one procedure instead of the bundled procedure. Additionally, reducing the weight of felled trees by natural drying in a forest is effective for reducing fuel consumption not only in transportation but also in winching operation, and for enhancing the calorific value of bioenergy.

Keywords: fuel consumption, thinning, whole tree harvesting, winching, winch rope tension

1. Introduction

FIT (Feed in Tariff) law came into 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 encourage harvesting of unused wood materials. In this context, the whole tree harvesting method using cable harvesting systems had been reconsidered. A previous work that studied the relationship between material prices and production cost of line thinning emphasized the need to fully utilize felled trees in order to reduce the production cost (Yoshino et al. 2010). The whole tree harvesting method is suitable to fully utilization of trees because the method keeps the recovery rate at an operation site (Latia et al. 2010). Moreover, logging residues 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 one of the basic harvesting systems. It can be applied to uphill and downhill harvesting on flat and steep slopes. In 2010, wheel tractors with a winch were introduced on both flat and steep slope areas in Japan, while until then the winch equipment had mostly been installed on excavators. Fei et al. (2008) pointed out that the high production cost and energy/fuel cost associated with mechanical harvesting of forest biomass were the major factors that could impede the use of forest biomass for energy. Multifunction tractors have various kinds of attachments and can reduce the harvesting cost by being used efficiently in many ways (Johanson 1997). Therefore, the winch system on a wheel tractor can be expected to realize lower harvesting cost especially in young forest stands. Moreover, such multi-functional characteristic seems to be appropriate to small scale operational sites because they have insufficient operational areas to keep working on a single operation.

It is important to know the appropriate time standards to follow the proper harvesting procedures and to plan rationally the operations (Sowa and Szewczyk 2013). Besides the time standards, for above purposes it is also important to study the effect of slope conditions on harvesting productivity, as well as the winch harvesting procedure itself. In this study, two winching procedures were analyzed during the actual thinning operations performed by a tractor with a winch on flat and steep slopes. Winch harvesting productivity and operator's walking speed on flat and steep terrains were analyzed based on results of time studies, and two types of winching procedure, from the aspect of load and fuel reduction, were evaluated.

2. Materials and methods

2.1 Materials

Two typical different thinning sites, sites A and B, were investigated. Site A was located in a forest in Tsurui Village, Hokkaido Island, whose terrain was moderately flat. The surface of skidding corridors was covered with bamboo grass and logging residues (Fig. 1). On-ground winch harvesting was practiced by the tractor, Fendt Werner Wario 714 (96 kW), with Schlang & Reichrt's remote controlled double winches. One of the winch drums was equipped with a 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 a 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 both winches was 8.2 tonnes. Trees were previously thinned and delimbed by chainsaw. Tree species was larch (*Larix laptorepis*) and it was easy to delimb because of fewer branches. The average volume of harvested trees was 0.28 m^3. An operator harvested logs from the forest to spur roadside by the remote controlled winch in a tree length condition with the textile rope. The operator had two and a half years' experience, and was mainly engaged in tractor operations for two years.

Fig. 1 Surface conditions of Site A

Site B was located in a forest on a steep terrain in Kami City, Shikoku Island, where the average degrees of 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 – 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 the forest to forest roadside in a whole tree condition with the wire rope.

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

2.2 Observation methods

Time of winch harvesting was measured by stopwatch 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 of 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 position of the worker and tractor was recorded by GPS logger with one second interval to measure skidding distances because the felled trees were scattered and it was difficult to measure the distance during the 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 the operation by eyesight because the 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 the analysis were obtained by interview.

The velocities of releasing and reeling operations were calculated from operation time and skidding distance. Average times of attaching and detaching operations and stop were also calculated. The data obtained from these observations were used in the following analysis.

2.3 Productivity calculation method

Cycle time and 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 equations by Sakai and Kamiizaka (1985).

$$C_y = D \cdot \left(\frac{1}{v_1} + \frac{1}{v_2} \right) + i \cdot T_a + T_d + T_s \qquad (1)$$

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

$$P = \frac{3600 \cdot j \cdot V}{C_y} \qquad (2)$$

$$i, j = \leq 3 \qquad (3)$$

where j is the number of harvested trees in a cycle (j trees/cycle); and V is the average tree volume (V m^3/tree).

Productivities of both procedures on actual sites were calculated and also simulated to define when the average volume of trees V was set to 0.2 m^3, which represented a young forest. The combinations of i and j were expressed as (i, j), and based on the observation it was assumed that a maximum of 3 trees could be harvested in a cycle. 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.

3. Results

The examples of GPS data are shown in Fig. 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 situation of Procedures A and B could be schematically illustrated as shown in Fig. 3 from this GPS data. In Procedure A, logs scattered around a skidding corridor were, one-by-one, attached to the 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, with 9 logs located at locations 1 to 3, the number of har-

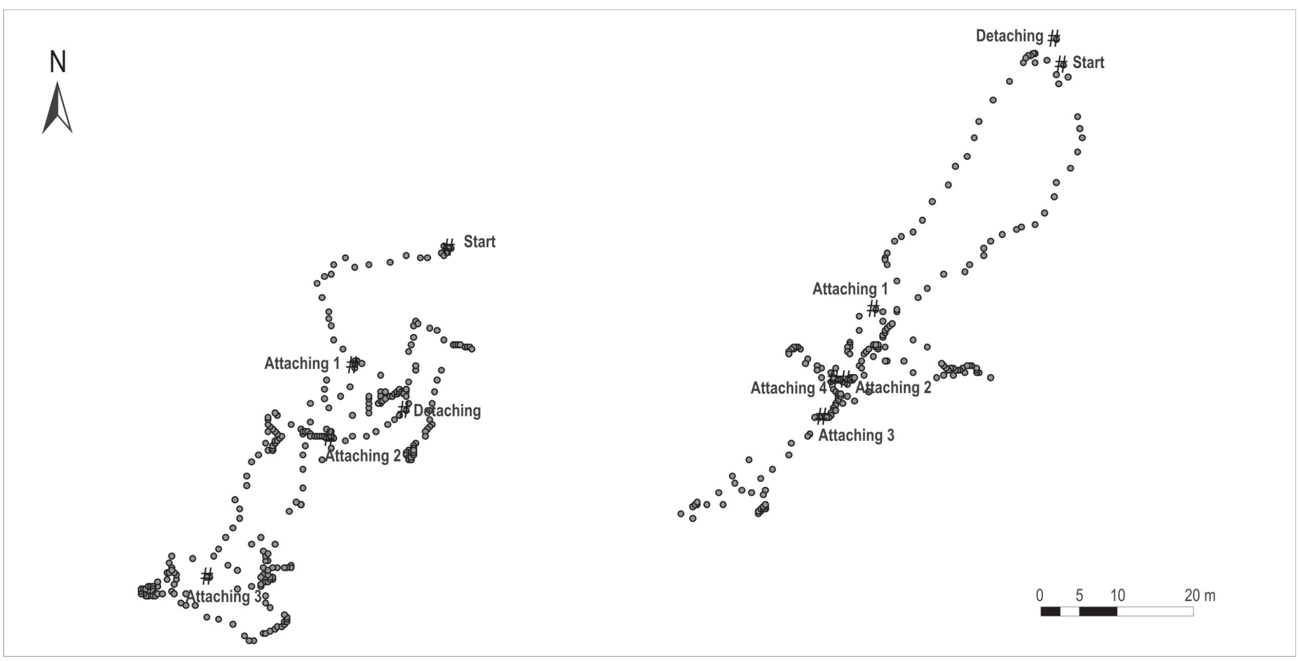

Fig. 2 Two examples of GPS data of harvesting operation on Site A

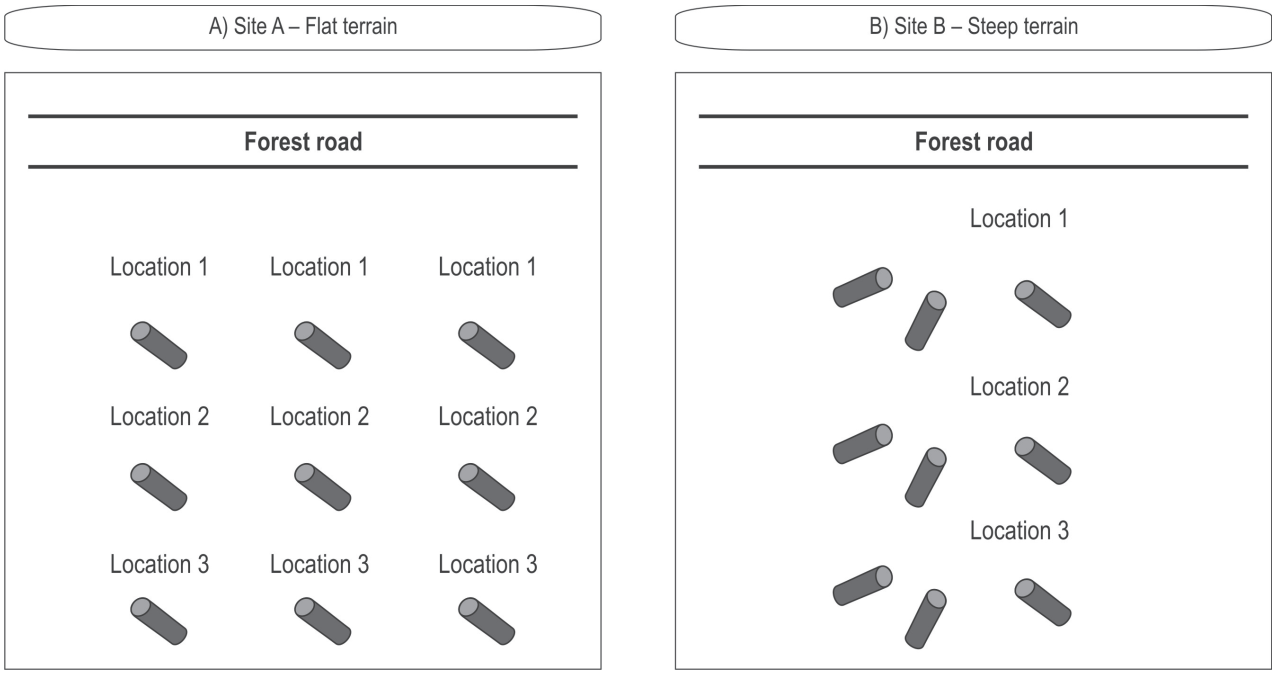

Fig. 3 Harvesting situation on flat terrain (site A) and steep slope (site B)

vested trees and cycles were the same in Procedures A and B, as discussed later.

At site A, among the total of 18 observed cycles, 17 cycles of winch harvesting operation lasting 1.3 hours were used to analyze the 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 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 operations were 18 sec ($n=53$, $SD=13$, max = 67, min = 2), and 22 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 was 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 of 0.28 m^3.

At site B, the total time of the observed winch harvesting operation 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 it 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, 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 was 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 number of attaching operation in a cycle and harvested trees in a cycle was 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 of 0.5 m^3. These data were summarized in Table 1 including the average times for stop.

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 time consumptions of attaching, detaching, and stop ($p>0.05$) although the experience of operators was much different.

The productivity P on each site was simulated as shown in Fig. 4. The results showed 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 with the increase of the number of attaching i, although the reduction was slight. Comparing the Procedures A (3, 3), B (3,3)

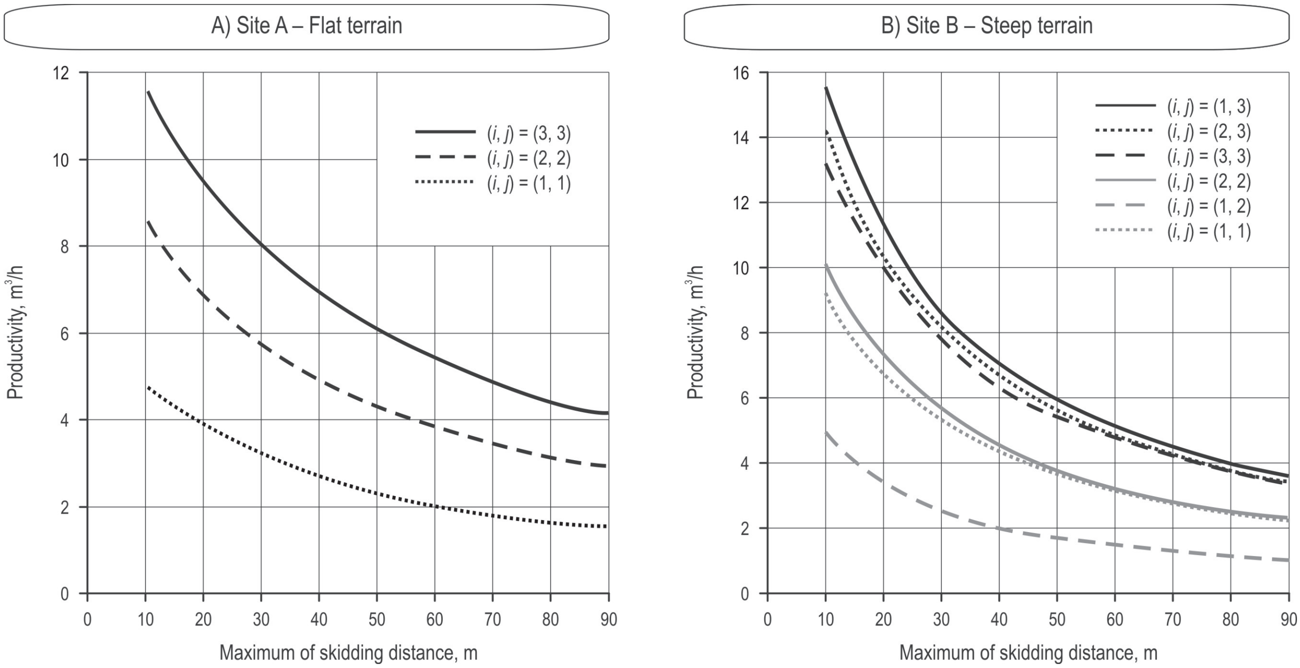

Fig. 4 Harvesting productivity (for the number of attaching operation in a cycle – *i*; and the number of harvested trees in a cycle – *j*)

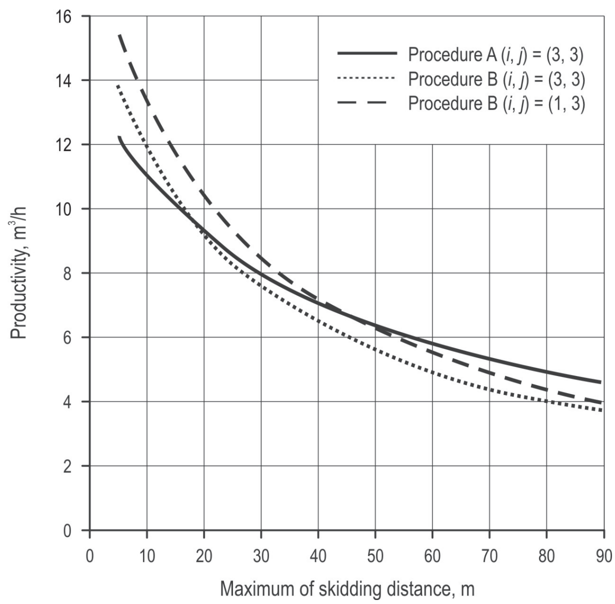

Fig. 5 Comparison of productivity among Procedures A and B (operations in a cycle – *i*; the number of harvested trees in a cycle – *j* was 3)

and B (1, 3), as shown in Fig. 5, it was recognized that the procedures with the maximum harvested volume could achieve high productivity in a short skidding distance even in a young stand 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 a single attaching operation.

Table 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 stopping, T_s	sec	68	57

4. Discussion

4.1 Difference between velocities

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 residues 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.

4.2 Mechanical work of winch harvesting

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

$$a = \frac{2 \cdot \pi \cdot R \cdot r}{\eta} \tag{4}$$

where R is effective diameter of winch drum (m); r is acceleration of the engine rotation (s^{-2}); and η is the speed reduction ratio, and

$$p = W \cdot \left(\mu \cdot \cos\theta + \sin\theta\right) + d \cdot w \tag{5}$$

where W is the weight of harvested logs (kg); μ is the coefficient of friction between soil and logs; θ is the degree of slope (where downhill skidding uses minus); d is the skidding distance (m); and w is the weight of rope (kgm^{-1}). The mechanical work of winch harvesting F (N) was calculated by the following equation (6).

$$F = a \cdot p \tag{6}$$

From equations (4) to (6), 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 (3,3) while that occurs from further points as locations 2 and 3 with Procedure B (1,3). The procedure A is preferable in operation site B to reduce fuel consumption with keeping higher productivity especially when the maximum skidding distance exceeds about 40 m as shown in Fig. 5.

4.3 Winch harvesting productivity

The results of productivity simulation show that the harvested volume in a cycle had the highest effect on productivity in both procedures. Therefore, to increase on-ground winch harvesting productivity, it is effective to increase the harvested volume in a cycle even if the number of attaching operations in a cycle increases. Hence, it was concluded that when applying Procedure A, productivity could be improved by gradually increasing the number of attaching trees in a cycle within selection thinning conditions.

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 in order to improve productivity, the volume of trees should be increased. This fact is also supported by the result showing that the productivity in late thinning sites was higher than the productivity 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 skidding distance so that such short skidding distance is appropriate for efficient winch harvesting. For harvesting at longer distances, the use of a mini tower yarder attachment for tractors was recommended (Spinelli et al. 2010). Its productivity did not vary much with longer skidding distances compared to on-ground winch harvesting. Harvesting productivity will be improved by using properly different attachments according to the maximum harvesting distance from the forest road.

5. Conclusion

The number 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 conditions. However, the difference in productivity between 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 high productivity can be achieved by winch harvesting even in a young forest within a short skidding distance and by increasing the harvested volume in a cycle.

The number of tests was insufficient and more investigations should be made for accurate productivity estimation. However, we proposed a new method of winch harvesting related to felling operations. As the mechanical work will become heavier with the increase of the harvested volume in a cycle and as the extension of skidding distance, Procedure A with 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 at longer skidding distances from the aspect of saving fuel consumption, although the skidding distance is usually short in actual logging operations.

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

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6. Literature

Pan, F., Han, H., Johnson, L.R., Elliot,W. J., 2008: Net energy output from harvesting small–diameter trees using a mechanized system. For. Prod. J. 58(1): 25–30.

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.

Johansson, J., 1997: Small tree harvesting with a farm tractor and crane attached to the front. J. For. Eng. 8(1):21–33.

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

Sakai, H., Kamiizaka, M., 1985: Prehauling systems for logs from thinnings. J. Jpn. For. Soc. 67(3): 82–91.

Sowa, J.M., Szewczyk, G., 2013: Time consumption of skidding in mature stands performed by winches powered by farm tractor. Croat. J. For. Eng. 34(2): 255–264.

Spinelli, R., Magagnotti, N., Lombardini, C., 2010: Performance, Capability and Costs of Small-Scale Cable Yarding Technology. Small Scale For. 9(1): 123–135.

Stampfer, K., Kanzian, C., 2006: Current state and development possibilities of wood chip supply chains in Austria. Croat. J. For. Eng. 27(2): 135–145.

Talbot, B., Suadicani, K., 2006: Road transport of forest chips: containers vs bulk trailers. Forestry studyes Metsanduslikud Uurimused 45: 11–22.

Yoshino, S., Yabe, K., Sato, T., 2010: The possibility of wood biomass usage by line thinning, the case of the profit sharing forest of Tokyo University of Agriculture. J. Agric. Sci. Tokyo Nogyo Daigaku 55(1): 31–37.

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