

Communication

Feasibility of a Harvesting System for Small-Diameter Trees as Unutilized Forest Biomass in Japan

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Abstract: In order to secure a supply of forest biomass, as well as promote further utilization following the completion of the Feed-in-Tariff Scheme for Renewable Energy (FIT), small-diameter trees such as cleanings from young planted forests and broad-leaved trees from coppice forests are prospective resources in Japan. The goal of this study was to discuss effective methods for harvesting the small-diameter trees that are unutilized forest biomass in Japan. This study assumed a simplified model forest and conducted experiments and time studies of the harvesting of small-diameter trees with a truck-mounted multi-tree felling head. As a result, the machine used in the experiment could fell a maximum of six trees inward in a row from a forest road. However, the harvesting cost (felling, accumulating and chipping) was cheapest when the machine felled five trees inward in a row. Lengthening the maximum reach of a felling head to fell trees deeper inward in a row appeared effective in increasing the number of harvested trees. From the perspective of minimizing the harvesting cost, however, there were upper limits to the number of trees felled inward as well as to the maximum reach of a felling head. The results of a sensitivity analysis suggested the following machine improvements could be considered in future policy: increasing the moving velocity of a felling head and the maximum number of trees that can be held at a time are effective if it is possible to lengthen the maximum reach of a felling head. Meanwhile, shortening the machine's moving time among operation points is also effective if the maximum reach of a felling head cannot be lengthened.

Keywords: small-diameter tree; forest biomass; multi-tree felling head; time study; harvesting cost



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1. Introduction

The Feed-in-Tariff Scheme for Renewable Energy (FIT) was launched in Japan in 2012 and the scheme has increased the energy utilization of forest biomass. In the case of biomass, the electric utilities have committed to buying the electricity derived from biomass at a higher price than the normal retail one for 20 years. Thus, power generation plants that accept unused forest biomass (such as thinnings and logging residues rather than wood-based materials such as mill residues and imported woods) have been built and the initiation of plant operations are progressing, in part due to the purchase price incentive [1]. As a result, 3.03 Tg of wood chips on a dry weight basis derived from thinnings and logging residues were used as energy in Japan in 2019 [2].

The use of small-diameter trees is also promising. The area covered by planted forests that have undergone final cutting and subsequent reforestation is now gradually increasing. Thus, a cleaning operation in young planted forests will be necessary 15–20 years from now, when the FIT will expire. The development of an efficient harvesting technology for small-diameter trees can thus be expected to contribute not only to securing a source of forest biomass for power generation plants but also to the continuous tending of young planted forests after regeneration.

Broad-leaved woody coppices have substantial potential. Before and during World War II, an average of 50 million m³/y of naturally regenerated forest was felled and harvested for energy use in the form of charcoal and firewood in Japan. The annual available

amount of naturally regenerated broad-leaved trees for energy is estimated to be 9 Tg/y on a dry weight basis [3]. The rich ecosystems of coppice forests were traditionally maintained by periodic cutting. Broad-leaved forests are now left unutilized and degradation is progressing. Therefore, a new approach to hardwood forest management under cyclic logging for the purpose of energy use is proposed so that the former rich ecosystems can be restored.

The authors' research group has studied technologies and systems for harvesting, transporting and chipping logging residues on steep terrain in Japan [4–10]. In the case of logging residues, the calculation of the procurement cost begins from the harvesting operation at a logging site where the limbing and bucking processes are carried out while the felling and accumulating processes must also be considered to calculate the procurement cost of small-diameter trees. Thus, in Japan, forest biomass from small-diameter trees is considered to be a resource second to that from logging residues in the Biomass Nippon Strategy [11].

Harvesting technologies for small-diameter trees have been developed and examined in North America [12–16] and Europe [17–19]. In Nordic countries, the accumulative function equipped with feller-bunchers and harvesters is utilized in harvesting small-diameter trees for bioenergy use [20–23]. For example, Belbo compared two working methods for small tree harvesting with a multi-tree felling head mounted on a farm tractor [24] and Laitila et al. examined the forwarding of whole trees after manual and mechanized felling and bunching in pre-commercial thinning [25]. Harvesting small-diameter trees has not been examined in Japan since Japanese forestry fell behind in mechanization. Nitami et al. proposed the harvesting of small-diameter trees by introducing accumulative felling and compressing machines [26] but a developed system has never been demonstrated. In the effort to clarify effective methods of harvesting such as small-diameter trees as unutilized forest biomass appropriate for Japan, this study conducted experiments and time studies in the harvesting of small-diameter trees with a truck-mounted multi-tree felling head.

2. Materials and Methods

2.1. Assumed Simplified Model Forest and Harvesting System

In this study, an effective method for harvesting small-diameter trees as unutilized forest biomass appropriate for Japan is discussed using a simplified model forest (Figure 1) in which there was a broad-leaved coppice forest on either side of a 3 m wide forest road. The stand density and biomass per unit area were assumed to be 12,000 trees/ha (growing 0.91 m apart in a reticular pattern) and 30 BDT/ha (BDT: bone-dry ton), respectively. When a felling machine harvested the coppice trees repeatedly in a clear cut way moving each operation point in turn, the number of trees felled inward in a row that minimized the harvesting cost was examined.

The following operations by two machines were assumed (Figure 2). The first machine was a chipper equipped with a multi-tree felling head. It felled and accumulated trees, which were then comminuted. The second machine, equipped with a container, followed after the first one to receive the comminuted wood chips. Such a machine as the first one shown in Figure 2 has never been in operation in Japan; thus, a harvesting experiment (felling and accumulating) was conducted in this study while the data related to the chipping operation were referred to from the previous study by the authors of this paper [27].

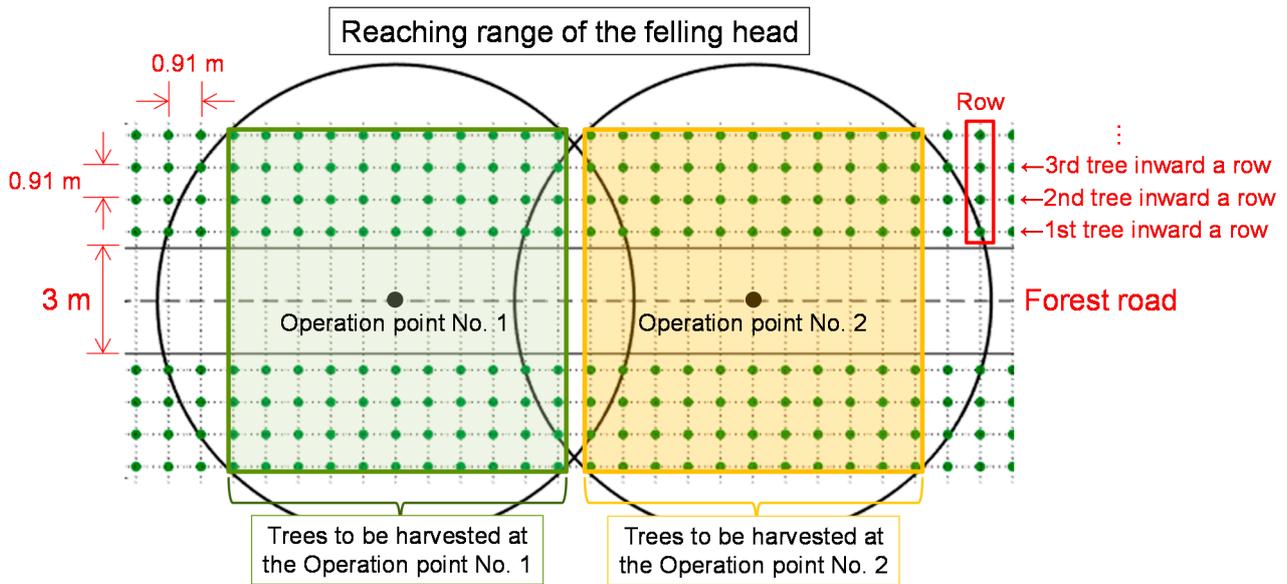


Figure 1. Assumed simplified model forest.

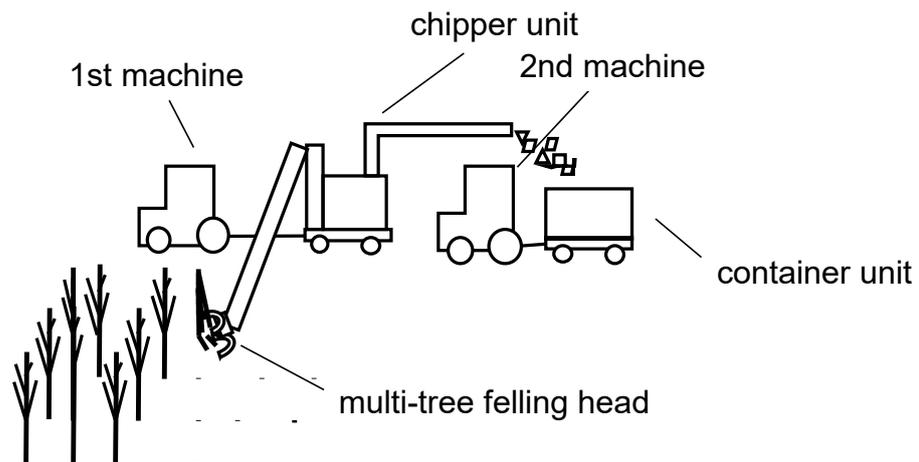


Figure 2. Assumed harvesting system.

Figure 3 contains a flow chart outlining one cycle of the harvesting operation that consists of the felling, accumulating and chipping processes. The simulation model for calculating the cycle time of harvesting operations by inputting the parameters listed in Table 1 was constructed with MATLAB (R2019a, The MathWorks, Inc., Natick, MA, USA). The productivity of harvesting could then be determined by dividing the harvest amount per cycle by the calculated cycle time as follows:

$$HP(L, n) = 3600 \times HA(L, n) / CT(L, n) \tag{1}$$

where $HP(L, n)$, $HA(L, n)$ and $CT(L, n)$ are the productivity of harvesting (BDT/h), harvest amount per cycle (BDT/cycle) and cycle time (s/cycle), respectively, when the maximum reach of a felling head is L (m) and the number of trees felled inward in a row is n . Meanwhile, this study calculated the costs taken to fell, accumulate and chip trees and considered the sum as the harvesting cost as follows:

$$HC(L, n) = MC / HP(L, n) \tag{2}$$

where $HC(L, n)$ is the harvesting cost (JPY/BDT) when the maximum reach of a felling head is L and the number of trees felled inward in a row is n and MC is the sum of the hourly costs of the two machines (JPY/h).

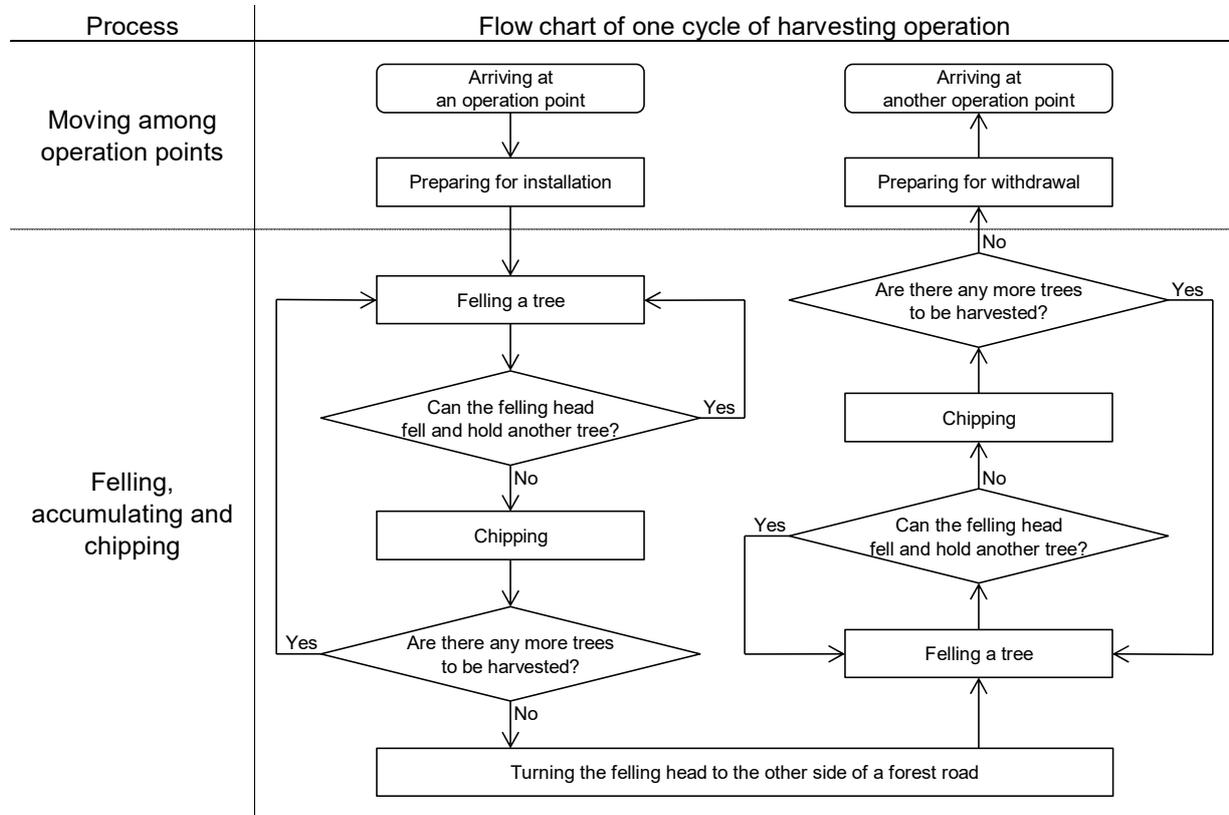


Figure 3. Flow chart of one cycle of harvesting operation.

Table 1. Parameters of the simulation model for calculating the cycle time of the harvesting operation.

Item	Parameter
Machine’s moving time among operation points (s)	$a + bl$
Time for installation and withdrawal (s)	a
Machine’s moving velocity (m/s)	b
Distance between adjacent two operation points (m) ¹	l
Maximum reach of the felling head (m)	L
Time for felling a tree (s)	f
Moving velocity of the felling head (m/s)	v
Maximum number of trees that can be held at a time	h
Time for chipping (s)	c

¹ Distance between adjacent two operation points, l , is determined depending on the maximum reach of a felling head, L , and the number of trees felled inward in a row, n . For example, Figure 1 shows the case of $L = 6.7$ m and $n = 4$ and the distance between the Operation points 1 and 2, which corresponds to l , is then determined to be 10 m.

2.2. Harvesting Experiment

A 10 m wide and 5 m long plot alongside a forest road was established for the harvesting experiment. The felling machine (the first one) was assumed to be located at an operation point (the center of the forest road) so as to fell all trees inside the plot. There were broad-leaved coppices of which the dominant species was konara oak (*Quercus serrata* Thunb.), once repeatedly harvested. There were 50 trees in total inside the plot, the age of the oldest tree was about 20 years old and the average diameter at ground level was 9.1 ± 3.7 cm.

The harvesting experiment was carried out with the multi-tree felling head (ENERGY WOOD GRAPPLE 300, Biojack, Finland; Table 2) used for felling and accumulating small-diameter trees in Nordic countries; the felling head was attached to a crane (LOGLIFT 61Z, Hiab, Sweden; outreach: 7.1 m, weight: 1360 kg) mounted on a log transportation truck (Figure 4). The time it took to fell and accumulate coppice trees was measured in order to collect basic data related to the parameters of the simulation model listed in Table 1.

Table 2. Technical data of the ENERGY WOOD GRAPPLE 300, Biojack [28].

Item	Technical Data
Weight	260 kg
Cutting diameter	250–300 mm
Working pressure	2.00×10^7 – 2.50×10^7 N/m ² (total pressure–back pressure)
Oil flow	60–100 dm ³ /min
Grapple opening	840 mm
Height in felling position	600 mm



Figure 4. Harvesting experiment with a truck-mounted multi-tree felling head.

3. Results and Discussion

3.1. Results of the Harvesting Experiment

An experiment on a felling and accumulating operation and its time study was carried out and the data necessary for calculating the cycle time were acquired (Table 3). The felling head cut a tree, of which the diameter at ground level was 20 cm, smoothly during the experiment (Figure 5). In the authors' previous study, a sugar cane harvester was used for harvesting 3- to 5-year-old willow trees (ezonokinu willow (*Salix schwerinii* E.L.Wolf.) and onoe willow (*S. sachalinensis* Fr.Schm.)) of which cultivation was aimed at short rotation forestry but it could not cut down 9 cm in diameter at ground level [29], suggesting that the felling head used in the experiment was appropriate for harvesting small-diameter trees in a broad-leaved coppice forest.

Table 3. Results of the time study.

Element Operation	Frequency	Average	Std. Dev. ¹
Time for installation	1	155 s	-
Time for withdrawal	1	115 s	-
Time for felling a tree	50	10 s	2.8 s
Moving velocity of the felling head	12	5.7 m/s	1.2 m/s
Maximum number of trees that could be held at a time	6	8.3	1.6

¹ Std. Dev.: standard deviation.

**Figure 5.** Cut end of a stump of which the diameter at ground level was 20 cm.

The maximum reach of the felling head used in the experiment, L , was 6.7 m, so that the machine could fell a maximum of six trees inward in a row from a 3 m wide forest road (width taken into consideration) in the model forest. With respect to the other parameters acquired from the time study, the time for installation and withdrawal, a , the time for felling a tree, f , the moving velocity of the felling head, v , and the maximum number of trees that could be held at a time, h , were set to be 270 s, 10 s, 0.57 m/s and 8, respectively, based on Table 3. The simulation model for calculating the cycle time of the harvesting operation was completed assuming that the machine's moving velocity, b , and the time for chipping, c , were 5 m/s and 10 s [27], respectively; thus, the productivity of harvesting could be calculated. Finally, the harvesting cost per BDT of small-diameter trees, $HC(L, n)$ of Equation (2), was calculated by dividing the sum of the hourly costs of the two machines (listed in Tables 4 and 5 as 12,250 JPY/h (= 7173 JPY/h for the first machine plus 5077 JPY/h for the second machine), by the harvesting productivity, $HP(L, n)$, calculated from Equation (1).

Table 4. Hourly costs of the two machines. ¹

Item	1st Machine	2nd Machine	Note
Labor cost (JPY/h)	2000	2000	(a)
Machine cost (JPY/h) ²	3330	1579	(b)
Fuel cost (JPY/h)	1843	1498	(c) = (d) × (e)
Hourly fuel consumption (dm ³ /h)	16	13	(d)
Unit fuel price (JPY/dm ³)	115.2	115.2	(e)
Total hourly cost (JPY/h)	7173	5077	(f) = (a) + (b) + (c)

¹ The exchange rate was roughly 1 USD = 104 JPY and 1 EUR = 126 JPY in December 2020. ² The detail of calculating the hourly costs of the two machines is listed in Table 5.

Table 5. Detail of calculating the hourly costs of the two machines.

(a) 1st Machine				
Item	Tractor	Felling Head	Chipper	Note
Price (10 ⁶ JPY)	9.45	5.00	4.00	(a)
Hourly price (JPY/h)	900	667	533	(b) = (a) × 10 ⁶ / {(c) × (d)}
Life (y)	7	5	5	(c)
Annual operation hour (h/y)	1500	1500	1500	(d)
Hourly repair cost (JPY/h)	630	333	267	(e) = (f) × 10 ³ / (d)
Annual repair cost (10 ³ JPY/y)	945	500	400	(f) = (a) × 10 ⁶ × 0.1 / 10 ³
Total hourly cost (JPY/h)	1530	1000	800	(g) = (b) + (e)
(b) 2nd machine				
Item	Tractor	Container		Note
Price (10 ⁶ JPY)	9.45	0.30		(a)
Hourly price (JPY/h)	900	29		(b) = (a) × 10 ⁶ / {(c) × (d)}
Life (y)	7	7		(c)
Annual operation hour (h/y)	1500	1500		(d)
Hourly repair cost (JPY/h)	630	20		(e) = (f) × 10 ³ / (d)
Annual repair cost (10 ³ JPY/y)	945	30		(f) = (a) × 10 ⁶ × 0.1 / 10 ³
Total hourly cost (JPY/h)	1530	49		(g) = (b) + (e)

Figure 6 shows the relationship between the number of trees felled inward in a row and the harvesting cost. The harvesting cost was cheapest when the machine felled five trees inward in a row. The following reasons are considered to explain this result: the more trees inward in a row the machine felled, the more trees were harvested at one operation point. In this case, however, the machine's total moving time markedly increased because the frequency of moving among operation points increased. Therefore, it was concluded that there was an optimum number of felled trees inward in a row that could minimize the harvesting cost.

3.2. Length of the Maximum Reach of a Felling Head

In order to increase the harvest of trees, it seemed it would be effective to lengthen the maximum reach of the felling head and fell trees deeper inward in a row; thus, the following two factors were examined in the case that the maximum reach of a felling head could be lengthened: (1) the maximum number of felled trees inward in a row that would minimize harvesting cost and (2) the minimum harvesting cost itself. With regard to factor (1), 12 trees inward in a row from a forest road was the highest possible number when the length of the maximum reach was increased to 18.2 m (Figure 7a). This meant that felling trees deeper than the twelfth one inward in a row using a longer reach felling head would not reduce the harvesting cost. Concerning factor (2), the cheapest harvesting cost of 10,658 JPY/BDT was obtained when the length of the maximum reach was 10.4 m (Figure 7b). This meant that using a felling head with a maximum reach longer than 10.4 m

could not reduce the harvesting cost. These findings indicated that, from the perspective of minimizing harvesting cost, there were upper limits to the number of trees felled inward in a row from a forest road as well as a maximum reach of a felling head. This may help forest road network planning in broad-leaved coppice forests for the purpose of energy wood production and utilization when using a harvesting system for small-diameter trees such as that examined in this study.

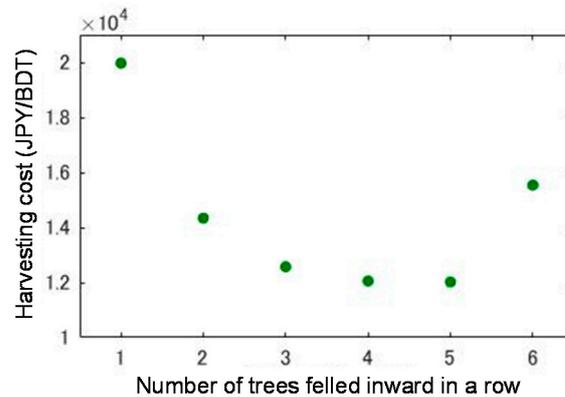


Figure 6. Relationship between the number of trees felled inward in a row and the harvesting cost.

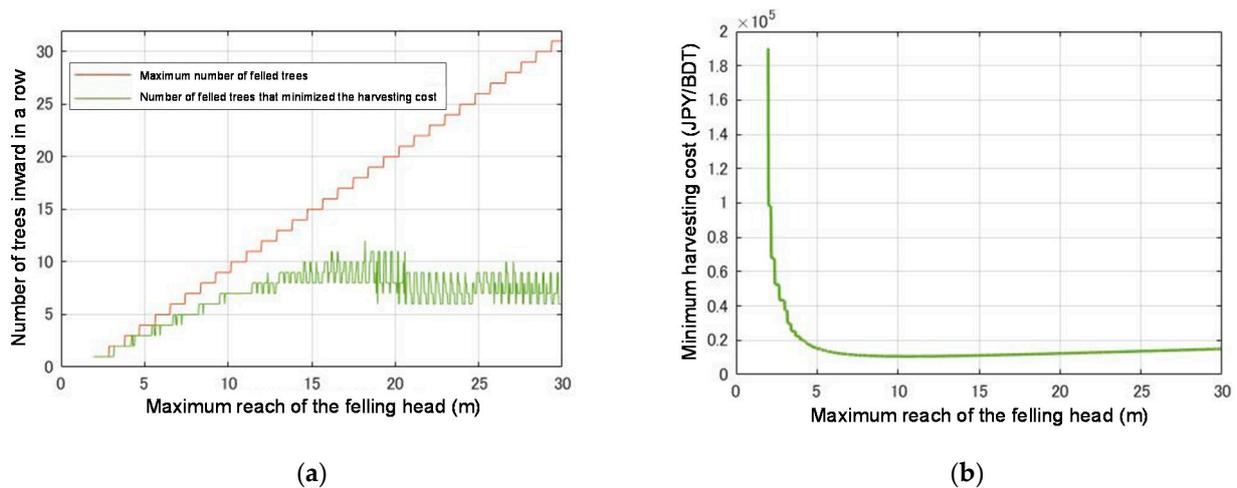


Figure 7. Two factors were examined in the case where the length of the maximum reach of a felling head was varied: (a) Maximum number of felled trees inward in a row that would minimize harvesting cost; (b) Minimum harvesting cost itself.

Although this study was a limited analysis based on various assumptions, the harvesting cost calculated in this study was more expensive than that in the U.S. [12], Italy [18] and Finland [21]. However, the general trend concerning the procurement cost of wood chips from forest biomass in Japan was identified; that is, the cost from small-diameter trees calculated in this study was more expensive than that from logging residues [30] but cheaper than that from short rotation woody crops [31].

3.3. Sensitivity Analysis

A sensitivity analysis was carried out on the results to determine how the felling machine used in the experiment might be improved. When the moving velocity of the felling head was doubled, as was the maximum number of trees that could be held at a time, the cost reduction effect increased with the longer maximum reach of the felling head used (Figure 8a,b). On the other hand, the shorter the maximum reach of the felling head used, the greater the cost reduction effect as the machine's moving time among operation

points was halved (Figure 8c). Thus, the following regarding the improvements of the machine for future policy are suggested: increasing the moving velocity of a felling head and the maximum number of trees that can be held at a time is effective if it is possible to lengthen the maximum reach of a felling head. Meanwhile, shortening the machine's moving time among operation points is also effective if the maximum reach of a felling head cannot be lengthened.

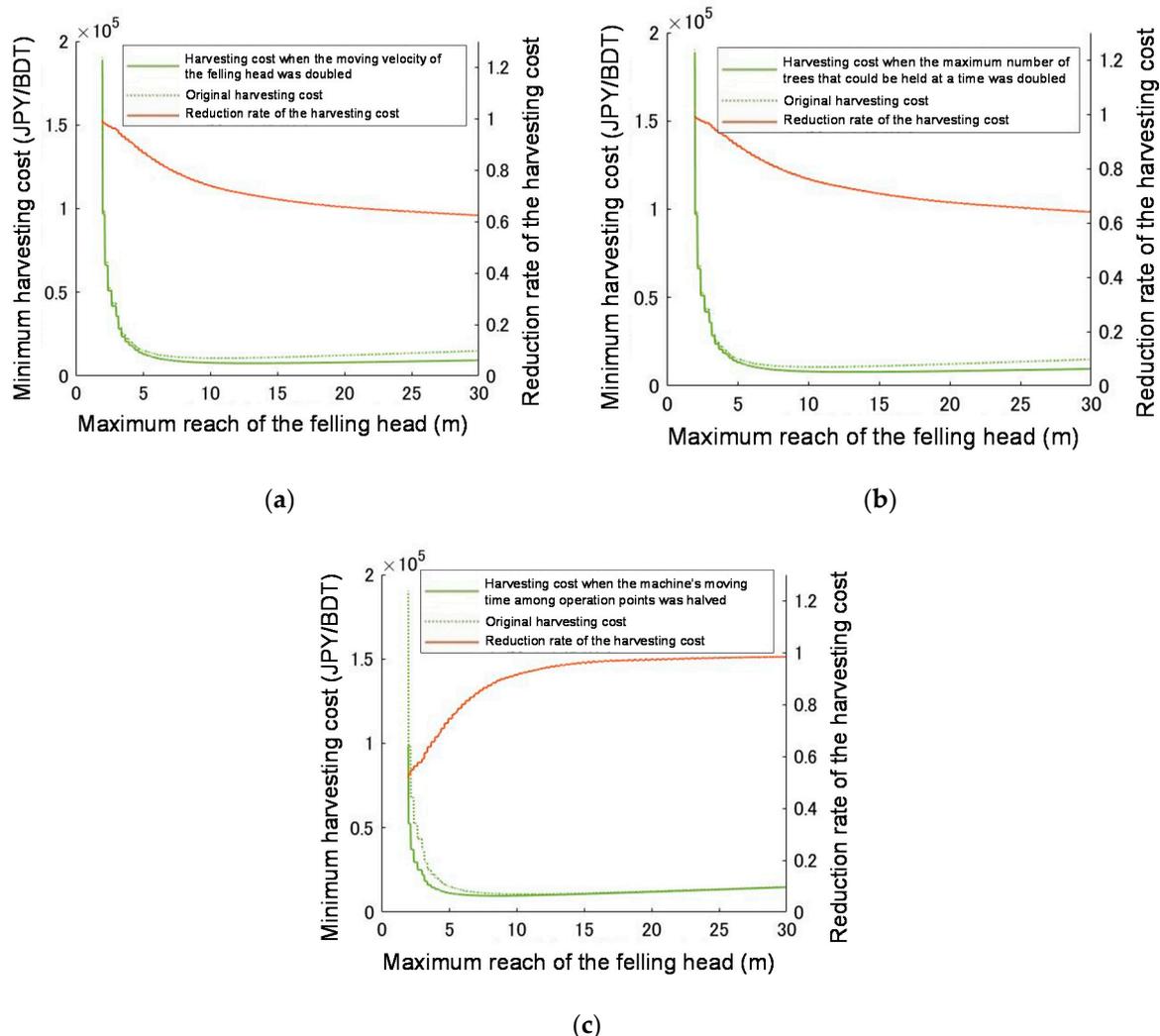


Figure 8. Results of the sensitivity analysis: (a) When the moving velocity of the felling head was doubled; (b) When the maximum number of trees that could be held at a time was doubled; (c) When the machine's moving time among operation points was halved.

4. Conclusions

The goal of this study was to discuss effective methods for harvesting small-diameter trees that are unutilized forest biomass in Japan. This study assumed a simplified model forest and conducted experiments and time studies of the harvesting of small-diameter trees with a truck-mounted multi-tree felling head. The findings are summarized below:

- The machine used in the experiment could fell a maximum of six trees inward in a row from a forest road. The harvesting cost was cheapest, however, when the machine felled five trees inward in a row.
- Lengthening the maximum reach of a felling head to fell trees deeper inward in a row appeared to be effective in increasing the number of harvested trees. From the

perspective of minimizing harvesting cost, however, there were upper limits to the number of trees felled inward as well as to the maximum reach of a felling head.

- The results of a sensitivity analysis suggested the following machine improvements could be considered in future policy: increasing the moving velocity of a felling head and the maximum number of trees that can be held at a time are effective if it is possible to lengthen the maximum reach of a felling head. Meanwhile, shortening the machine's moving time among operation points is also effective if the maximum reach of a felling head cannot be lengthened.

Author Contributions: T.Y., T.T. and T.N. conceived, designed and performed the field experiment; T.Y. and T.T. analyzed the data; T.T. contributed the simulation model; T.Y. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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