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Recovery of logging residues for energy from spruce (*Pices abies*) dominated stands

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Abstract

Vast quantities of logging residue are left behind on clearcut areas. Given the suitable transportation distance, environmental and economic circumstances, they provide a possible alternative for fossil fuels. However, distribution of residual biomass over large areas during the logging operation and trampling by machines hinders the recovery. The recovery enhancing effect of three single-grip harvester work techniques on the productivity of logging residue recovery for energy was studied. Forwarder productivity, distribution of effective work time, forwarding distance, load size and the residue yield were studied.

A heavy forwarder with an enlarged 22 m^3 load space was used. The average load size was 9 tonnes. More than 50% of the forwarder's work time was spent on loading the residues. The recovery output of the trampled residues from the strip road after a conventional harvesting method was 11.4 t/E_0-h for a 9 tonnes load and a 300 m transportation distance. In contrast, the single-grip harvester methods that aimed at the post-logging residue recovery increased the recovery output to 12.0–13.3 t/E_0-h. The load size was a more significant factor than the forwarding distance in terms of machine productivity. The yield of residue recovery after the conventional roundwood harvesting method was 58.4% and from 66.8% to 78.7% for the alternative single-grip-harvester methods.

Keywords: Residual woody biomass; Logging residue; Forest transportation; Machine productivity; Residue yield; Load size; Forwarding distance

1. Introduction

Ratification of the Kyoto Agreement is forcing nations to convert away from the use of fossil fuels for energy. This task can be tackled by decreasing fuel consumption by converting into more effective technology or replacing fossil fuels with renewable or nuclear energy. Renewable fuels are biomass based, or wind and solar powers. There are many sources of both land and aquatic biomass. Forestry includes three alternative biomass sources for energy production. These are mill residues, harvesting residues and cultivated short rotation woody crops. This paper deals with residues from conventional clearcut operations. The above ground residues include crown mass, unmerchantable stem sections and small diameter understory trees. This material contains wood, bark and considerable quantities of nutrient-rich needles. When the cut-to-length method is the chosen harvesting method, the residues are left on the strip roads to increase ground bearing capacity. However, when the aim is to recover the residual biomass for energy the single-grip-harvester method should be altered in such a manner that the residues are piled along the strip road for easy recovery.

Residue recovery from clearcut areas was studied intensively in joint Nordic studies already in 1970 and 1980. At the time, the main issue was residue collection and recovery after manual final felling [1–4]. The machinery, however, has completely changed in the past two decades. The introduction of the first double-grip and later single-grip harvester has made it possible to manipulate work methods and consider recovery of the residual biomass for utilization from a new perspective. The first innovations in work method development were made in Sweden during the last decade [5–7] and later on in Finland [8]. It was found out that the alternative methods aiming at residue accumulation along the strip road impose only a minimal effect on the single-grip harvester productivity. Other studies related to residue recovery were by Mårdberg [9]

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and Brunberg [10]. Later the same decade Kärhä [11] and Asikainen [12] studied recovery logistics in integrated harvesting operations in Finland. They concluded that integrated harvesting of energy and roundwood required modifications to be made in forwarders. These included increased load space and modifications to the grapple to suit loading both energy and round wood. It has also been suggested that residue recovery may be integrated with site preparation [13]. This method, where scarification is done by a residue forwarder, was found to reduce combined residue recovery and scarification costs on small clearcuts by 10% [14]. A residue recovery method, which is fast gaining popularity, is the residue baling method. When long transportation distances dictate the transportation of loose residues or residue chips this is a good alternative for large-scale procurement organizations. However, the use of a baler involves an additional machine for an added cost all operators cannot afford. Or the procurement chain is such that it cannot support the comminution of residue logs. As a result, the vast majority of residues recovered mainly in Finland and Sweden are still for the time being recovered as loose material.

2. The objectives

Utilization of this biomass by combustion or other forms of conversion presumes contaminant free material. The prerequisite of the recovery is a clean, soil free residual biomass that is well positioned along the strip road for easy grasping, and not driven over by heavy machinery. The aim of this study was to find out how (a) forwarder productivity in residue recovery and (b) residue yield are affected by the modification of a single-grip harvester work method, and (c) what effect forwarding distance and load size have on forwarding productivity.

3. Material and methods

3.1. Harvester work method

The study area was a 11.0 ha mature Norway spruce (*P. abies*) stand. A total of 2569 m^3 of timber and 798 tonnes of green residues were removed (Table 1). Roundwood harvest was carried out with a single-grip harvester. The three harvesting methods used were

M1, felling and delimbing on one side of the strip road,
M2, felling and delimbing on both sides of the strip road,
MC, felling and delimbing in a conventional manner.

MC, the conventional method, is the most commonly used single-grip harvester method where felling is done from one side of the machine, and delimbing and bucking take place in front of the machine over the strip road. The residues accumulate on the strip road and are eventually compressed by machine wheels (Fig. 1). Two alternative

Table 1
Stand and forwarding data by work technique

	Harvester method used		
	M1	M2	MC
Total stand area (ha)	4.48	3.41	3.11
Volume of harvested roundwood (m^3)	1033	774	762
(m^3/ha)	231	227	245
Recovered residues			
Green (tonnes)	340	243	215
Dry (tonnes)	150	107	95
Dry (tonnes/ha)	33.4	31.4	30.4
Dry (kg/m^3)	144.5	138.1	124.2
Effective work time (E_0-h)	27.1	20.1	18.1
Number of loads (*n*)	36	30	24
Av. load size (tonnes)	9.4	8.1	9.0
Av. forwarding distance (m)	356	341	298
Av. length of strip road required to compose a full load (m)	78	82	85

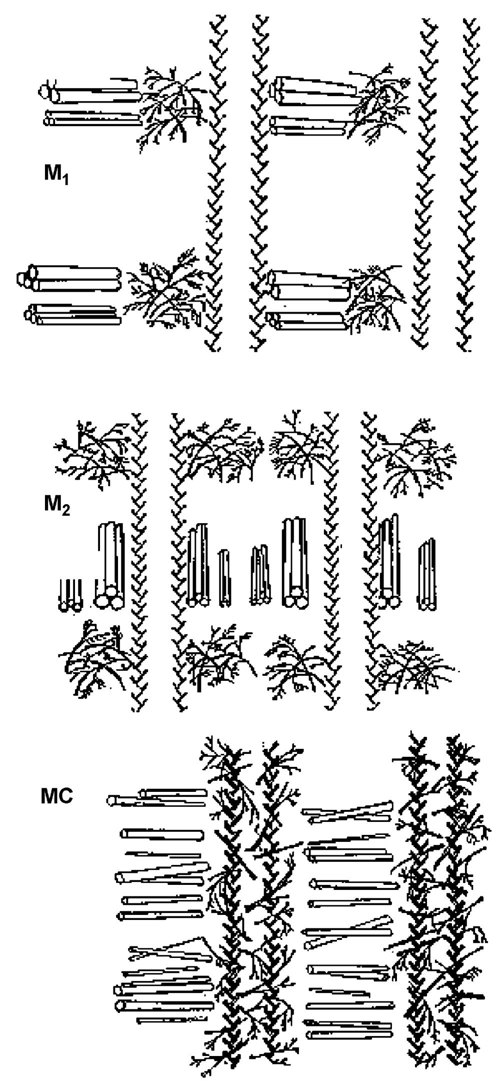

Fig. 1. Single-grip harvester work methods.

methods were tested against the traditional one. In M1 trees are felled from only one side of the machine. Delimbing and bucking of the stem is done at the side of the machine in such a manner that residues are accumulated in piles between the strip road and the roundwood piles. Roundwood bolts are positioned perpendicularly to the strip road (Fig. 1). In M2 felling and delimbing are done on both sides of the machine. Roundwood is piled parallel to the striproad and the residues are accumulated between wood piles. With these alternative methods, residues are accumulated on the side of the striproad as a separate assortment, and are not compressed by machinery. It was hypothesized that the recovery is more productive and the yields greater after the modified harvesting techniques have been applied. To accommodate recovery as well as storage at the landing all roundwood was forwarded and trucked to the mill before residue recovery.

3.2. Residue recovery

Residue recovery was carried out with a heavy Kockums 850 forwarder. Its nominal weight was 13,500 kg and had a maximum load rating of 12,000 kg. The load space had been lengthened by 80 cm to accommodate a larger, 22 m^3 load space. However, because of the operator's good loading techniques, the loads extended far beyond the nominal load space.

The mass of each residue load was measured at the landing with a grapple scale model Kajaani-60 provided by Ponsse Oy of Finland. The scale was positioned between the boom and the grapple and is connected to the central measuring unit located in the operator cabin via a 12.5 mm data cable. Scaling took place during unloading at the landing and only outside of the load space. There are two advantages to this. First, only the residues that were brought to the landing were measured. Second, unloading requires a considerable amount of pulling and tearing, which would give a false reading. The error is eliminated by programming sectors outside the load space where scaling will take place. The weights were automatically registered by the computer. The scale itself was calibrated every time before unloading with an object of a known mass. The accuracy of the scale was $\pm 2\%$. All the reported masses are green weights.

Five moisture samples were taken from each load. They were randomly taken using a chain saw after unloading the material at the landing. Each sample contained branch wood, branch bark and needle matter. A section from the top of the stem was included in every fifth sample.

A total of 450 samples weighing 250–500 g each were collected. The moisture content was analyzed by drying the sample to a constant weight at 102 °C.

The yield of residue removal was studied by making a survey of the site after the residue recovery. This was carried out by placing 2×2 m sample plots on a 30×30 m grid. The minimum distance of the plot from the edge of the study was set at 15 m. The cruise lines were set at such a manner that they were not running parallel to the strip roads. A total of 88 sample plots were measured, of which 39 plots fell on M1, 29 on M2 and 20 on MC. All the residues within the sample plot were measured to the nearest 0.1 kg. The weight of the logging residue (t/ha) left on the site after logging was calculated on the basis of the inventory. The remaining quantities of residues are given below.

Harvest method	No. of Plots	Weight of residue (kg/m^2)		
	n	X	s	Range
M1	39	3.8	5.6	0–32.8
M2	29	1.9	3.4	0–14.3
MC	20	5.0	6.0	0–20.9

Time and productivity studies were carried out to find out the effect of single-grip harvester work method on the forwarder productivity of logging residue recovery. The work study data are composed of 65 effective machine hours (E_0-h) and includes 90 loads. No breakdowns occurred. The forwarding distance varied between 40 and 650 m. The average length of strip road needed to compose a full load was 80 m.

The effective work time of the forwarder was divided into sub-times in a following manner:

(1) *Driving unloaded*: The time from the moment the forwarder leaves from the standstill position at the landing until it stops on the clearcut for loading.
(2) *Loading*: The time from the moment forwarder stops on the strip road for loading to the moment the boom is back in the transport position. Loading included the following phases:
   2a. Boom out: From the moment the boom starts to move to the moment it starts to grasp the residue pile.
   2b. Grasping the residue: From the moment the grapple starts to close to the moment the boom starts to move towards the load space. This phase might include several grasps.
   2c. Boom in: From the moment the boom starts to move to the moment the grapple is opened or the boom is resting in a transportation position. This phase includes the time spent placing the grapple contents in the load space.
   2d. Driving when loading: Driving time from the moment the boom is in a transportation position until another 'boom out'-phase (2a).
(3) *Forwarding*: Forwarding the full load from the site to the landing. The period from the moment, the boom is in a transportation position to the moment the forwarder stops for unloading at the landing.

(4) *Unloading*: The time spent unloading at the landing. The period from the moment the forwarder stops for unloading to the moment the boom is in a transportation position and the forwarder departs on another recovery cycle.

4. Results and discussion

4.1. Distribution of effective work time

The share of the loading phase was more than 50% for each of the three work methods (Table 2). Similarly unloading took about one fifth of the work time, while driving with a load demanded a quarter of the time spent. Residue loading from a site where conventional harvesting technique (MC) had been used required a greater share of loading time than loading from M1 and M2 sites ($F = 8.01$, $p = 0.001$). In a pair-wise comparison, the loading from the M2 method required a significantly lesser share of operation time than the other two methods. There was also a significant difference between M1 and MC.

Table 2 also reveals that grasping the residue caused the greatest time expenditure in the loading cycle. Grasping was most effective with the M2 method ($F = 14.99$ $P < 0.001$). There was no statistical difference grasping from one sided or conventional methods.

There is a very limited amount of published data on the division of work time in residue forwarding from a post-single-grip harvester operation. Laitila et al. [14] studied integrated recovery and site preparation in a single-pass operation. If the effect of scarification is taken into consideration, the results support each other. The remaining difference in the loading and unloading phases can most likely be explained by greater load sizes in this study.

Table 2
The division of residue recovery and forwarding

	Harvester method used			F	p
	M1	M2	MC		
Recovery cycle					
Driving unloaded	9.7[a]	11.4[b]	9.1[a]	10.93	0.000
Loading	52.7[a]	50.6[b]	56.2[c]	8.01	0.001
Forwarding	15.3[a]	15.7[a]	13.5[a]	1.65	0.198
Unloading	22.3[a]	22.3[a]	21.2[b]	4.31	0.017
Loading cycle					
Boom out	15.1[a]	16.1[a]	15.1[a]	2.35	0.101
Grasping	46.1[a]	40.1[b]	44.6[a]	14.99	0.000
Boom in	24.0[a]	26.6[b]	23.5[a]	6.42	0.003
Driving while loading	14.8[a]	17.2[a]	16.7[a]	1.77	0.178
n	36	30	24		

The figures indicated with a different upper index in horizontal direction differ from each other at 5% significance level.

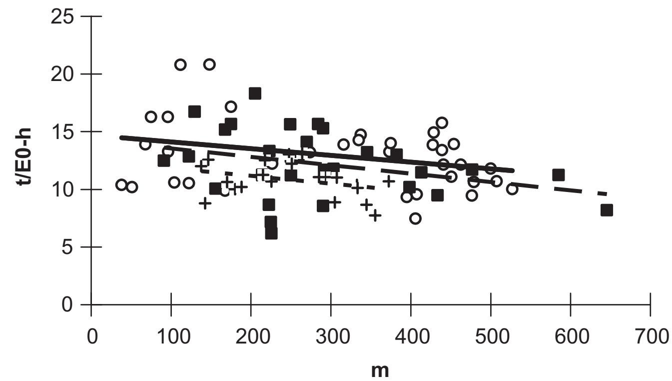

Fig. 2. The productivity of residue recovery (Mg/E_0-h) as a function of forwarding distance (m), (M1 = ——■, M2 = — — —○, MC = -------+).

4.2. Productivity of forest transportation

Harvesting method, forwarding distance, load weight, driving speed and the residue density are among the major factors affecting forwarding productivity. The average driving speed when driving empty was recorded at 3.61 and 2.64 km/h when loaded. Driving speed when loaded was not affected by the load weight ($r = 0.198$, $p > 0.05$). The hypothesis of driving distance (x) being a significant factor (Fig. 2) was rejected when used as a single-independent variable as shown by the models below:

$$\mathrm{M1}: y = 6.465 - 0.00257x,\ n = 35,\ r^2 = 0.07,$$
$$\mathrm{M2}: y = 6.282 - 0.00320x,\ n = 30,\ r^2 = 0.08,$$
$$\mathrm{MC}: y = 5.490 - 0.00295x,\ n = 22,\ r^2 = 0.12.$$

This result could be explained by the variability in the load size. Unlike normal roundwood loads, which are rather uniform in size, the weight of residue loads varied from 4 to 12 tonnes and the average was 9 tonnes, the average size being greater than in other studies reviewed. In similar conditions in Sweden Brunberg [10] reported load sizes ranging from 5 to 7 tonnes and 6–8 tonnes by Wigren [5]. The large load sizes in this study are to be credited to the large load space and an improved loading method. As a result the load weight (x) was a more significant variable than the forwarding distance.

$$\mathrm{M1}: y = 0.0011x + 1.5976,\ n = 35,\ r^2 = 0.56,$$
$$\mathrm{M2}: y = 0.0009x + 2.0661,\ n = 30,\ r^2 = 0.41,$$
$$\mathrm{MC}: y = 0.0006x + 2.6017,\ n = 22,\ r^2 = 0.43.$$

This result has to be interpreted in such a manner that the size of load space and the carrying capacity of the forwarder is of vital importance when forwarding logging residues. This has previously been shown by simulation trials [12]. It should also be noted that residue recovery is not only more productive after the application of the alternative methods but productivity is also more

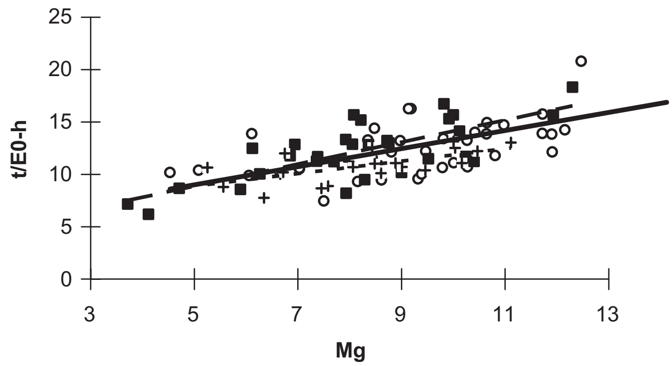

Fig. 3. The productivity of residue recovery (Mg/E_0-h) as a function of load mass (Mg), (M1 = ——■, M2 = — — —○, MC = -------+).

responsive to load size when M1 and M2 methods are used (Fig. 3).

In the next analysis two independent variables, x as the load weight in kilograms and z as the forwarding distance in meters, were used in a model [$y = a + b_1(x)$-$b_2 \log(z)$], where y is the machine productivity per effective hour (t/E_0-h). In this case, both variables were highly significant ($p < 0.05$) for all three models.

Harvesting method	A	b_1	b_2	r^2	s_{yx}
M1	18.602	0.1386×10^{-2}	7.705	0.82	1.308
M2	25.176	0.1330×10^{-2}	9.616	0.88	1.054
MC	24.238	0.0878×10^{-2}	8.361	0.81	0.689

Considering the average load weight of 9 tonnes and a 300 m forwarding distance, the model gives the following forwarding productivities: 12.0 t/E_0-h (M1), 13.3 t/E_0-h (M2) and 11.4 t/E_0-h (MC). This effect of the harvesting method was not as great as in a Swedish study. Wigren [7] reports an increase of 20–30% when recovering residues after the alternative method were used. In this study, the corresponding differences were 5–17%. It is likely that the experience of the harvester operator with the alternative methods is of paramount importance to ensure the best residue accumulation for easy recovery.

The productivity of the loading phase was also analyzed separately as harvesting method is thought to have a specific impact on it. The average weight of a grapple load was for M1, M2 and MC, respectively, 236, 226 and 220 kg. However, the differences were not found to be statistically different ($F = 0.86$, $p = 0.42$). Furthermore, the average amounts of residues recovered from a single loading point on the strip road were 929, 944 and 771 kg. Although one could conclude that residues had accumulated with the alternative harvesting methods [8], there was no statistical difference in the volumes recovered for a single loading stop ($F = 1.76$, $p = 0.18$).

Table 3
The productivity of recovery, loading and grasping phases (tonnes/E_0-h) according to the harvester work method

Work method	Recovery cycle[a]	Loading cycle[b]	Grasping	n
M1	12.0[a]	22.9[a]	53.4[a]	36
M2	12.9[b]	25.1[a]	61.4[a]	30
MC	11.6[c]	21.1[b]	45.6[b]	24
F	18.40	10.17	9.52	
p	0.000	0.000	0.000	

The figures indicated with a different upper index in vertical direction differ from each other at 5% significance level (Bonferroni test).
[a]Distance traveled and load mass used as covariates.
[b]Load mass used as covariate.

Table 4
The residue density (tonnes/ha, green weight) and recovery yield for each work method

Harvester method	Initial density (tonnes/ha)	Recovery (tonnes/ha)	Unrecovered (tonnes/ha)	Yield (%)
M1	113.5	75.9	37.9	66.8
M2	90.8	71.4	19.4	78.6
MC	119.0	69.1	49.9	58.4_

In spite of the fact that the statistical analysis did not show significant difference in the volumes recovered at loading points, the loading productivity was significantly more effective from the bigger piles created by the alternative harvesting methods M1 and M2 ($F = 10.17$, $p < 0.05$). The productivity of loading cycle for M1, M2 and MC was, respectively, 22.9, 25.1 and 21.1 t/E_0-h while grasping the residues had the following productivities: 53.4, 61.4 and 45.6 t/E_0-h. The statistics show that the alternative methods did not differ significantly from each other but the loading and grasping phases after the conventional method were significantly slower (Table 3).

4.3. *The recovery yield of forest residues*

When contemplating the overall productivity of forwarding, it is also important to consider the residue yield from a given land area. Table 4 shows the recovered residue mass, the un-recovered mass and the yield percentage. It is evident that the alternative methods made it easier to grasp and recover the residues from the well-formed heaps created by the alternative methods M1 and M2. When comparing the alternative methods with the conventional one, the yield was higher with M1 (14.4%) and M2 (34.8%). This was true in spite of the fact that the initial stocking of residues was greater on the conventional sites. Differences of similar magnitude (18–36%) have been reported in Sweden [5]. Greater yields will mean not only lower harvesting costs, but this will also increase storage size at the landing, which in its turn will make chipping and long distance transportation more effective [12]. In the case of conventional harvesting operation, only the uppermost half of the material was recovered. If the same intensity of recovery had been applied to all methods the differences in productivity would have been even greater to the advantage of the two alternative methods.

5. Conclusions

Accumulation of residual biomass in integrated harvesting operations is of key importance when planning recovery. The single-grip harvester work method had a statistically significant effect on the output of different stages of residue recovery. Grasping, collection phase and the whole procurement operation were more effective when the harvester operator had used either one of the two alternative methods where residues are accumulated in heaps along the strip road. Also the yield rates were improved by the alternative methods. Furthermore, load size proved to be a significant variable when calculating forwarding productivity. It can be increased by increasing load space or by loading the residues in a more compact way. Positioning the long tops perpendicular to the load space will not only balance the load but will also make it possible to extend the load outside the nominal load space.

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