Observations on the effects of rough-delimbing and load compression on harvesting system costs in fuel wood thinning

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Abstract:
In this study, the effects of rough-delimbing and load-compression in fuel wood thinning were investigated with the aim of evaluating the technical and economical efficiency of these processes compared to the extraction of un-processed/un-compacted whole tree parts. The time consumption and production of two harvesters and two forwarders were monitored in a field study of fuel wood thinning operations in Sweden. The harvesters either felled trees with an accumulating felling head and then cross-cut bunches, or trees were felled and accumulated with the harvester head and then roughly delimbed and cross-cut. The density of each forwarder load was calculated by measuring the length and mass of randomly selected wood piles and comparing to literature load-density curves. The literature data were also used for calculations on the effects of load compression. The results showed that load compression resulted in a 16% increase in bulk density and ca.5% reduction in harvesting costs, whereas rough-delimbing resulted in a 73% increase in bulk density and ca.12% reduction in harvesting costs.

Keywords: bulk density, early thinning, forest biomass, payload, tree parts

1 Introduction

In Sweden, 17.3% (3.9 million ha) of the total productive forested area is young forest, which is dominated by trees at least 1.3 m tall with a diameter at breast height (DBH) below 10 cm over-bark (o-b) (Anon, 2009). Stands dominated by trees with a DBH of up to 14 cm account for 21.9% (ca. 748 million m3 solid o-b) of the total standing volume in Swedish forests (Anon, 2009). When a stand reaches an average height of ca. 3 m, it should be pre-commercially thinned prior to commercial first thinning (FT) when the stems reach an average DBH of ca. 12-14 cm. Pre-commercial thinning (PCT) is costly and therefore often neglected. In general, without PCT stands become dense, heterogeneous in tree size and biomass rich, which can make a FT operation for pulpwood troublesome. If however, the whole trees are harvested for fuel wood, it is not necessary to consider, e.g., tree size.

FT for fuel wood is generally carried out using conventional forest machines and systems, usually a two-machine system comprising a harvester equipped with an accumulating harvesting/felling head together with a forwarder. The productivity of thinning harvesters is affected by the average size of the harvested stems, the stand density, and the intensity of removal (Eliasson, 1999). Compared to pulpwood, harvesting for fuel wood (whole trees) increases biomass removals by 15-50%. In addition, the use of multi-tree handling heads increases productivity by 35- 40% compared to single-tree handling (Björheden et al., 2003; Jylhä & Laitila, 2007). Consequently, the harvesting costs of fuel wood from stump to roadside can be reduced by 20-40% compared to pulpwood extraction (Hakkila, 2003).

Piled whole small trees are bulky, and thus typically as little as 25-35% of the pile's bulk volume is solid mass. As a consequence, only 30-60% of the forwarder's load capacity is normally used when hauling whole trees (Nordén, 1991), and the small load size is especially evident when the stem volume of harvested trees is below 30 dm3 (Kärhä, 2006). However, when thinning, it is not possible to compensate by using a large forwarder load space because strip roads should be kept narrow and remaining trees are likely to be damaged if wide loads are transported. If the forwarder is equipped with flexible stakes for load compression, load densities of small diameter trees can be increased by 35-60% (Nordén, 1984). If the trees are subjected to rough-delimbing (i.e., removing most of the branches, or breaking and flattening branches), the forwarder's payloads can be increased significantly (cf. Bergström et al., 2010; Iwarsson Wide, 2009). In addition, load compression can also be carried out later prior to road transport. Thus, technical solutions for increasing payloads can be adopted at different stages along the supply chain.

In the study described in this paper, the effects of rough-delimbing and load compression in fuel wood thinning were investigated to assess the technical and economic efficiency of these processes compared to the extraction of unprocessed/uncompacted whole-tree parts.

2 Material and Methods

A field study of fuel wood thinning operations was performed during the summer of 2010 in two young stands (Table 1) located in the North of Sweden. In each of the stands, the harvesting and forwarding operations involved in extracting tree parts to the roadside were studied. Two thinning harvesters (John Deere 770D, 11 t) and two medium-sized forwarders (John Deere 1110D, Ponsse Elk, 15 t) operated by a total of six experienced drivers were used. The work time consumption and production (harvested biomass) was monitored.

Table 1: Stand characteristics.

Initial Stand	**1**	**2**
Composition of Pine: Spruce: Birch [%]	82:9:9	67:8:25
Density [trees/ha]	2719	3248
DBH [cm]	7.7	8.8
Basal area [m^2/ha]	15	22
Average stem-volume [dm^3]	32	40
Biomass [od t/ha]	52	81
Removal		
Density [trees/ha]	1367	1651
DBH [cm]	6.7	7.6
Basal area [m^2/ha]	5	9
Average stem-volume [dm^3]	21	27
Biomass [od t/ha]	17	28

The two harvesters were equipped with two different heads, and therefore used different work methods (M): the harvester equipped with the accumulating guillotine felling head (Ponsse EH 25) firstly felled the trees and piled them on the ground, then cross-cut the bunches (M1a), whereas the harvester equipped with the single-grip harvesting head (John Deere H742) felled, accumulated, roughly delimbed and then cross-cut the trees before piling (M2a). Both harvesters produced piles of tree sections along strip roads (spaced at intervals of 20 m). The two forwarders then hauled the biomass to the roadside using ordinary grapples.

The work time consumed was recorded with snap-back timing. For each stand, the number of harvested trees and wood piles produced were registered. The mass of 37 randomly selected piles was measured in-stand using a dynamometer (500 kg, PIAB Sweden AB). The bulk density (kg/m^3) of each forwarder load was calculated by counting the number of loaded piles in each load and then multiplying by the average pile mass; the volume was obtained by multiplying the cross-sectional area of the filled forwarder bunk by the measured average length of the tree sections. The bulk densities of loads recorded in the study for methods M1a and M2a were compared to literature values (Bergström et al., 2010) to evaluate two hypothetical cases: as per method M1a but incorporating load compression (referred to as method M1b) and as method M2a but omitting rough-delimbing (referred to as M2b). This allowed the effects of load compression and rough-delimbing to be assessed (Table 2).

Table 2: Treatment combinations compared in the study.

	Treatment			
	M1a	**M1b**	**M2a**	**M2b**
Harvester, rough-delimbing	No	No	Yes	No
Forwarder, load compression	No	Yes	No	No

An economic analysis of harvesting and forwarding operations was performed using the stand data for the various methods (Table 2). For the treatment M2b, the harvester's productivity was assumed to be 1.1 times the productivity of the harvester for M2a to take account of the larger biomass amount produced per each harvested tree without rough-delimbing.

The productivity of the forwarder in treatments M1b and M2b was evaluated using the average time required per load in the field and load density results from a previous study of rough- delimbing and load compression (Bergström et al., 2010). All calculations were based on a forwarding distance of 100 m.

Fresh weight was converted into dry weight by assuming a moisture content (MC) of 47%, which was an average value obtained from follow-up data on fresh delivered biomass from 16 fuel wood thinnings in the North of Sweden during 2010. The effective productivity (PW) was converted into hourly work productivity (WT) (IUFRO, 1995) using a factor of 1.16 for the harvesters and 1.14 for the forwarders, as recorded during the field study for a total of 76 WT hours. The hourly costs of the harvesters and forwarders were set to 80 €/WT and 70 €/WT, respectively. No costs for machine relocations were included in the analysis.

3 Results

3.1 Field study

The harvested stem volume was 29% larger for M2 than for M1. The harvesters' productivity was affected by the harvested stem volume and in average it was 9% higher for M2 than for M1 (Table 3). The number of accumulated trees per crane cycle was 1.5 when using the single-grip harvester, method M1a, compared to 2.2 when using the accumulating felling head, M2a. The tree-section piles produced via M1a contained an average of 151 kg of biomass and were 5.8 m in length, whereas for M2a, the pile mass and length were 365 kg and 5.4 m, respectively.

In total, 35 forwarder loads were studied in the field; 18 loads for M1a and 17 loads for M2a. For M1a, the average bulk density of loads was 207 kg/m^3, corresponding to a fresh mass of 5.39 t (2.86 od t, MC= 47%) and 45% of the forwarder load capacity (12 t). For M2a, the average bulk density of loads was 296 kg/m^3, corresponding to a mass of 7.19 t (3.81 od t, MC= 47%) and 60% of forwarder load capacity. The average time consumed (PW time) per load for the forwarder was 35.45 min, and varied only slightly (ca. 6.6%) between drivers and for different stand conditions. Therefore, the forwarding productivity was mainly affected by the load size/bulk density.

3.2 Theoretical analysis

For M1b, load compression resulted in a 16% higher bulk density (240 kg/m^3) than that measured for M1a, corresponding to a mass of 6.25 t (3.31 od t) and 54% of the forwarder load capacity. For M2a, rough-delimbing resulted in a 73% higher bulk density than for non-processed biomass (M2b).

The forwarding operations represented on average 34% of the total harvesting cost (Table 3). The cost of forwarding in M1b (using load-compression) was 14% lower than in M1a (without compression), resulting in a 5% lower total harvesting cost (Table 3). The use of rough-delimbing in M2a reduced the forwarding cost by 42% compared to M2b. Consequently, the total harvesting cost of M2a was 12% lower than for M2b (Table 3).

Table 3: Productivity and cost of harvesting and forwarding work in the four studied treatments.

	Treatment			
	M1a	**M1b**	**M2a**	**M2b**
Harvester productivity [od t/PW hour]	2.84	2.84	2.94	3.23
Forwarder productivity [od t/PW hour]	4.86	5.61	6.45	3.72
Harvesting cost [€/od t]	33.53	33.53	32.39	29.45
Forwarding cost [€/od t]	16.83	14.51	12.63	21.89
Toal cost [€/od t]	50.36	48.04	45.02	51.33

4 Discussion

The use of rough-delimbing and load compression appears to be technically and economically beneficial. In this study, we assumed that the cost of a forwarder with compacting stakes (M1b) was the same as a standard forwarder. This is valid considering the costs for installing flexible stakes, the required hydraulics and steering system are minor costs compared to the total cost of the machine and would insignificantly increase the hourly rate for the machine. However, if we assume a 45% increase in bulk density by using compression stakes, then to produce a reduction in total harvesting costs of 10%, the cost of additional compressing devices should not exceed 3% of the standard forwarder hourly cost, which corresponds to a maximum of 7% of the purchase price for a 15 t forwarder (e.g., €16,000 on a purchase price of €230,000).

Clearly, load-compression should be carried out using cost- and energy-efficient technologies, such as those described in, e.g., Nordén (1984) and Bergström et al. (2010). However, different methods, despite being similar in many aspects, may require a different force to compress the biomass to a certain level. For example, Nordén (1984) reported a 10 times higher compaction force was required to achieve a 35-60% increase in bulk density of forwarder loads of small trees than was required to produce a 16-32% increase using a similar method described in Bergström et al. (2010). Bergström et al. (2010) in their experiment used a smaller forwarder than in Nordén (1984), then this could have had an effect on the compaction process, since as it is known smaller loads are easier to compress than larger ones (Nordfjell & Liss 2000).

The length of tree sections, and consequently the overall length of the load, also affects the productivity. Björheden (1997) suggested that tree sections should be as long as possible to maximize payloads, but concerns over the forwarder being tail-heavy and difficult to maneuver in strip roads must be borne in mind. In addition, Brunberg et al. (1994) noted that loading was complicated when trees exceeded 7-8 m in length. The forwarder can be equipped with a grapple-saw to allow trees to be cut-to-length while loading. In this way the harvester work can be relieved of bucking. The use of a grapple-saw would decrease the productivity of the forwarder while loading, but the productivity of the harvester would be increased, and it is therefore a useful alternative that should be considered for improving the harvesting system's efficiency.

The single-grip harvester used in this study had a high capacity for rough-delimbing (compressing) the biomass, but no/limited capacity for accumulating small-sized trees. Therefore, when harvesting trees with a stem volume below 30 dm^3, an accumulating felling function should be used (Kärhä, 2006). In addition, Bergström et al. (2010) showed that feed-rollers can double the compaction effect when the harvested stem volumes exceed 30 dm^3, and the effect is even larger as the tree size increases (crown width increases).

Rough-delimbing causes significant loss of mainly fine branches and needles. If demand for extractive rich fractions (i.e., needles) increases in the future, e.g., for biorefinery processes, then it would be desirable to reduce the loss of such raw materials in the forest. In that case, the biomass could be bundled at the harvesting site or, e.g., chipped and compacted in enclosed plastic for consistency, e.g., the prototype Flispac (cf. Flispac AB, 2011). Studies on bundle-harvesters have shown that it is possible to significantly increase the pay-loads of the forwarder and trucks. However, studies in Finland on a prototype bundle-harvester Fixteri (Fixteri Oy) suggested the prototype was not economically competitive with the two-machine system (Jylhä & Laitila, 2007; Nuutinen et al., 2011). It is likely that further developments of bundlers and, e.g., bundle-harvesters will occur. To achieve the highest possible efficiency, it is important that technologies are developed for specific purposes since there is a large difference in the best method of handling/bundling of different components, e.g., logging residues from clear cuttings compared to tree parts from thinning.

5 Conclusions

The results from this study show that rough-delimbing and load compression can increase the harvesting efficiency in fuel-wood thinnings. Future development and optimization of cost-effective compressing and bundling equipment could allow harvesting operations of young thinnings to be more profitable than present.

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