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Productivity of a Prototype Truck-Mounted Logging Residue Bundler and a Road-side Bundling System

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When recovering logging residues (LR) for bioenergy its density should be increased before road transport, otherwise a low proportion of the trucks' load capacity will be used. One way this can be currently done is to compress LR into bundles that are forwarded to roadside landing. A less well-developed alternative is to forward loose LR and bundle it at landing. In the presented study, a prototype specifically developed for road-side bundling was found to produce larger, heavier bundles than bundling machinery intended for in-field use (mean length, diameter and raw bulk density 4.7 m, 0.8 m and 285 kg m^{-3}, respectively, with 299–445 kg oven dry matter per bundle). The machine was also at least 30% more productive than previously described in-field bundling systems, producing 14–19 bundles per productive work hour (PWh), equivalent to 5.2–7.8 oven-dry tonnes PWh^{-1}. Bundles were estimated to use 67–86% of an LR truck's 30 tonnes load capacity, similar to proportions used when transporting loose LR. However, a continuous feeding and compressing process would probably almost double productivity, while longer bundles would enable full use of truck load capacity. With such improvements bundling at road-side could provide a viable alternative to current LR-recovering systems.

Keywords Bioenergy, compaction, composite residue logs, densification, road-side landing, slash, supply chain
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1 Introduction

With increasing concerns about climate change and the use of fossil fuels, interest has grown in the use of forest biomass for energy production. Up to circa half of the harvested stemwood is already used as fuel in Sweden and Finland, Nordic countries in which forestry is highly industrialized (Hakkila and Parikka 2002). In addition to this use of process residues from traditional forest industries, the use of previously unmerchantable parts, sizes and species of trees (forest residues) has become attractive as a way to increase energy production from forest biomass. Sweden and Finland are pioneers of the systematic large-scale use of forest residues for energy production (Hakkila and Parikka 2002), with logging residues (LR), i.e. tree tops and branches, being the main assortment used (Finnish Statistical ... 2007). LR is currently collected from 38% of the final felling area in Sweden (National Board of Forestry 2008).

The productivity of LR recovery for bioenergy depends on the work involved in preceding logging operations (i.e. harvester and forwarder work in the cut-to-length system) (Andersson et al. 2002, Kärhä and Vartiamäki 2006, Nurmi 2007). Thus, to maximize its profitability the recovery of LR has to be considered in early stages, before felling and processing trees, and throughout subsequent operations. However, even when preceding work is optimized it can still be challenging to make profits from recovering LR. One of the problems is that LR has low value, so its profitability is strongly dependent on transport costs (Björheden and Eriksson 1989, Angus-Hankin et al. 1995, Ranta and Rinne 2006). Furthermore, it has low bulk density (mass per unit volume) so low proportions of load capacities are generally used since load sizes in terrain and road transport are limited by volume rather than mass capacity (Andersson et al. 2002).

Several systems are used to transfer LR from its point of origin to the ultimate processing point. One system (a) is to transport LR as it is (loose LR) out of the forest to road-side landing points, and from landing to industrial sites, where it is comminuted before combustion. In other systems it is comminuted earlier in the supply chain, either at landing (b) or in-field (c) (Andersson et al. 2002). In (b), loose LR is forwarded to landing while in (c) the comminuted material is forwarded to landing, but a shared feature of both (b) and (c) is that trucks transport comminuted material to industrial sites. Another system is bundling (d), in which LR is compressed in-field into bundles (also called cylindrical bales or composite residue logs) by specially equipped forwarders, then normal forwarders take the bundles to landing (Andersson et al. 2002, Kärhä and Vartiamäki 2006). Finally, trucks transport the bundles to industrial sites, where they are comminuted. Bundles are typically 3.0 m long, with a diameter of 0.7 m, a raw bulk density of 320 kg m^{-3} and a raw mass of ca. 390 kg, of which ca. 220 kg is oven-dry matter (ODm) (Kärhä and Vartiamäki 2006). When using terminals, systems (a)–(d) can be combined, e.g. loose LR can be transported to a terminal where it is comminuted, then transported from the terminal to the end user. Systems (b)–(d) all increase the material's bulk density and thus enable higher load capacity utilization, (d) also enables more efficient comminution at the terminal or end user-site. Moreover, the bundling of LR in system (d) preserves the fuel quality and reduces space requirements during storage compared to storage of loose LR in windrows. Loose LR is remoistened during winter (Pettersson and Nordfjell 2007), while the storage of comminuted LR leads to substance losses, heat development with risk of self-ignition and risk to human health due to high concentrations of allergenic microspores in the air (Jirjis 1995). None of those negative effects arise when storing and handling LR bundles (Jirjis and Nordén 2005). Bundling has also been applied when harvesting whole trees in thinnings for bioenergy production (Nordfjell and Liss 2000, Jylhä and Laitila 2007). When the bundling methodology was originally developed, one main idea was that regular timber trucks could be used (Andersson et al. 2002). However, small pieces can fall off and cause traffic hazards (Johansson et al. 2006), so when bundles are transported by road in the Nordic countries they are normally carried by LR truck-trailers with solid bottoms and boarded sides surrounding the load space (Ranta and Rinne 2006).

A system under development is to forward LR to windrows at road-side landing and bundle it

Fig. 1. The studied prototype machine (Rogbico GTK 4800). Note that the loading chamber is not pivoted towards the windrow in the picture.

there (e.g. Stampfer and Kanzian 2006, Spinelli and Magagnotti 2009). Potential benefits of such a bundling process include higher concentrations of LR and avoidance of requirements for the bundling vehicles to have off-road capabilities. It would also enable LR recovery in some otherwise unfeasible or unprofitable situations, e.g. whole tree harvests in areas with small landings or small, scattered cutting areas (Spinelli and Magagnotti 2009). However, since bundling increases the work in the supply chain, it has to generate sufficient benefits in later operations in order to be economically competitive. Hence, in an evaluation it is important to address the whole system and not only the single operation of road-side bundling.

Promising results have already been obtained with an in-field-bundling unit mounted on a truck instead of a forwarder (Spinelli and Magagnotti 2009), but there have been no previous analyses of the productivity of vehicles designed for road-side bundling operations. A prototype truck-mounted bundler was recently created for such a system and dimensioned to make larger bundles than the in-field version in an attempt to improve bundling productivity and utilization of truck load capacity. The aims of the study reported here were to evaluate the bundle characteristics and productivity of this prototype and to consider the implications of the findings for the potential productivity of a road-side bundling system.

2 Material and Methods

The studied concept machinery consisted of a GTK 4800 (Rogbico AB, Sweden) prototype bundler mounted on a 580 truck (Scania AB, Sweden) equipped with an Epsilon 140L crane (Palfinger AG, Austria) and a Supergrip SG260R grapple (Hultdin System AB, Sweden) (Fig. 1). The bundling components were operated through the hydraulic power of the truck. One bundle was produced at a time, in a top-fed compression chamber with an internal length of 4.80 m, height of 0.95

Table 1. Features of logging residue (LR) windrows; dimensions, quality, moisture content on a wet weight basis (MC) and net calorific value as received ($q_{p,\text{net,ar.}}$) per oven dry tonne (ODt) for each of the four permutations of study occasion and LR material (mean and standard deviation, n = 5 per combination).

Study occasion	LR material	Dimensions a) (m)	Grade b)	MC (%)	$q_{p,\text{net,ar.}}$ (MWh ODt^{-1})
1	Green	50 × 5.1 × 3	4	52.2 (4.1)	4.73 (0.13)
	Brown	50 × # × 4	4	37.5 (11.2)	5.06 (0.24)
2	Green	36 × 5.6 × 4	3	47.4 (1.0)	4.86 (0.02)
	Brown	38 × 4.6 × 3	4	32.4 (7.0)	5.15 (0.11)

a) Length × height × width.
b) Quality measure based on species mixture, organization of material and stemwood content, where 1 is the lowest and 5 is the highest grade.
Data missing.

m and internal width of 2.10 m at the top and 1.80 m at the bottom. LRs were loaded from the left side of the truck and, after closing the chamber lid, a lateral compressing force of 735–784 kN was applied and three polyester bands (16 mm wide and 0.8 mm thick) were wrapped around the resulting bundle. The compression chamber was then reopened and the bundle was unloaded by the crane, which had a 10.3 m reach. To facilitate loading of LR, the compression chamber was pivoted circa 20° horizontally to the left, towards the windrow during work. The pivoting point was located circa 1 m from the rear of the chamber. The mass of the bundling components was circa 9.5 tonnes, while the mass of the truck was 12.5 tonnes and that of the crane 4 tonnes. In total, the concept machine's dimensions were (length × width × height) 11.0 × 2.6 × 4.2 m and it was allowed to travel at up to 80 km h^{-1} on Swedish public roads.

The operator was male, 49 years old and had four months of experience of using the machine prior to the first study occasion. Being a former timber truck driver, he was well experienced with the crane type used.

The effects of three factors were examined. To assess effects of bundle size, bundles of two different sizes were produced, normal and large. The former had currently standard dimensions, with a target diameter of 0.80 m, while the large bundles were intended to have as high mass as possible. To assess the effects of drying LR materials green bundles of both sizes were produced from "fresh" LR (trees harvested in November 2006–March 2007) and brown bundles of both sizes from "dried" LR (trees harvested in May–August 2006). Hence, the LR in brown bundles had been stored for longer, including all or part of the summer, and were expected to contain less moisture and to have lost some of their original needles. These four types of bundle were produced on two different study occasions in 2007, the first in mid-March and the second in mid-April. The two study occasions were included to investigate the effects of technical improvements of the machine (adjustment of the wrapping apparatus) and increases in the operator's experience. However, differences in productivity between study occasions will also have been influenced by differences in work location (i.e. LR and windrow characteristics; Table 1) and possibly weather (seasonal climate change). The time elements required to produce 25 bundles, and relevant characteristics of the bundles produced, were examined for all eight bundle size, LR material (green/brown) and study occasion permutations except normal-sized, brown bundles during study occasion 1, for which 24 bundles were examined. Hence, the total sample size was 199 bundles.

The study was conducted at sites in southeastern Norrbotten (ca. 65°N, 21°E), northern Sweden, dominated by Norway spruce with varying proportions of Scots pine and scattered birches. At the study sites, cut-to-length final fellings adapted to LR recovery had been conducted, with LR forwarded to road-side landing and organized in windrows. Windrows were measured by the researchers, while the bundler operator graded the piles according to arrangement of the material, species mixture and stemwood content (Table 1). Well-organized piles of spruce LR with high stemwood contents have higher bulk density than

Table 2. Work elements and their priority. If multiple work elements were performed simultaneously, the element with the highest order of priority (lowest number) was recorded.

Element	Definition	Priority
Compression	Started when the lid of the compression chamber started closing and ended when the grapple gripped the completed bundle for unloading.	1
Crane work	Included all crane work directly involved in bundle production (i.e. feeding LR, unloading bundles and piling them at landing).	2
Moving	Repositioning of the truck. Started when support legs were retracted and stopped when they were fully extended.	2
Miscellaneous work	Productive work that was not part of any of the other elements above, e.g. repositioning of LR, snow cleaning and reloading bundling cord.	2
Delay	Non-productive work, not included in the analyses.	3

other types, hence they can be more efficiently handled and were assigned the highest grades on the scale (which ranged from 1 to 5).

For each bundle we determined the length, mass, diameter and volume (calculated as a cylinder, with a diameter determined from the mean of measurements at both ends and between two of the bundle cords). In addition, five bundles of both green and brown LR produced on each study occasion were randomly selected for moisture content (MC) analysis. The selected bundles were crosscut 5 cm from one end using a chainsaw, and the sampled material was weighed directly after sampling and re-weighed after drying at 105° C to constant weight to determine their MC (Table 1). The resulting value (in percent of wet mass) was used to calculate the net calorific value as received ($q_{p,\mathrm{net,ar}}$, also called effective heating value with moisture, W_{em}) according to Equation 1 (after Hakkila and Parikka 2002, and described in detail in ISO 1928:1995 and EN 14918:2010). The net calorific value of oven dry LR ($q_{\mathrm{p,net,d}}$) was set to 19.7 MJ kg^{-1} for both green and brown LR, since storage for a year has very little effect on this variable (Pettersson and Nordfjell 2007). The coefficient 2.45 in Eq. 1 is the energy (in MJ) required to vaporize 1 kg of water.

$$q_{p,net,ar} = q_{p,net,d} - 2.45\frac{MC}{100 - MC} \quad (\mathrm{MJ\ kg^{-1}}) \qquad (1)$$

Calorific values in MWh ODt^{-1} (Table 1) were obtained by dividing values in MJ kg^{-1} by 3.6. Since net calorific value as received is the basis for pricing such fuel in Sweden, this unit is used hereafter.

Work was filmed and the time consumption for each work-element (listed in Table 2) was analyzed from films through continuous time studies using Husky FS3 hand-held computers running Siwork 3 version 1.1 software (Kofman 1995).

For each combination of study occasion and LR material, normal-sized bundles were always produced before large bundles. Consequently, machine movements were likely to occur more frequently when producing large bundles. When moving time was included, it was therefore distributed evenly over the 49 or 50 bundles in both size classes.

In a static system analysis, road-side bundling was compared with recovery of loose LR and in-field bundling. Costs of unstudied work operations in the road-side bundling system and costs of the other two systems were estimated using previously published data (Engblom 2007). In road-side bundling, loading, unloading and comminution were estimated to have the same piece-rate as in-field bundling, but with more ODm per piece (0.390 ODt vs. 0.25 ODt). Raw bulk density was assumed to be 130 kg m^{-3} for brown loose LR and 180 kg m^{-3} for green loose LR (Angus-Hankin, et al. 1995). Load space dimensions (length × width × height) were assumed to be 7.2 × 2.45 × 3.0 m for the truck and 12.4 × 2.45 × 3.0 m for the trailer. Hence, the total load volume was 144 m^3. The total weight limit of a loaded truck with trailer was 60 tonnes, of which the

Table 3. Levels of significance (p-values) and explained proportion of variance (r^2-values) obtained from the analysis of variance of the treatments' effects on bundle characteristics, work efficiency and work elements' time consumption. Error DF = 191.

	Study occasion (O)	LR material (M)	Bundle size (S)	O×M	O×S	M×S	O×M×S	r^2 (%)
Bundle characteristics								
Length (m)	0.830	0.925	**<0.001**	0.792	0.746	0.201	0.657	8.2
Diameter (m)	0.066	**0.005**	**<0.001**	0.156	0.699	**0.043**	**0.001**	23.6
Volume (m^3)	0.079	**0.005**	**<0.001**	0.164	0.693	**0.021**	**0.001**	26.2
Raw mass (kg)	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.380	0.622	74.2
Oven dry mass (kg)	**<0.001**	0.559	**<0.001**	**0.013**	**<0.001**	0.942	0.911	52.9
Raw bulk density (kg m^{-3})	**<0.001**	**<0.001**	0.247	**0.002**	**<0.001**	0.095	**0.001**	65.9
Grapple loads (n $bundle^{-1}$)	**0.004**	0.101	**0.007**	**0.019**	0.117	0.485	0.397	13.0
Work efficiency (time consumption)								
PWh $bundle^{-1}$	0.269	0.122	**<0.001**	**0.001**	0.366	0.504	0.091	15.2
PWh ODt^{-1}	**<0.001**	**0.044**	0.579	**<0.001**	**<0.001**	0.401	0.091	30.3
Work elements' time consumption (PWmin ODt^{-1})								
Compression	**0.003**	0.234	0.335	**<0.001**	**<0.001**	0.625	**0.038**	21.3
Crane work	**<0.001**	**<0.001**	0.542	**<0.001**	**0.020**	0.187	0.161	34.4
Miscellaneous work	**<0.001**	0.997	0.320	0.985	0.308	0.438	0.168	10.3
Mean move time [b)]	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.748	0.968	82.2

Significant values ($p < 0.05$) in bold. Time-related data were Ln-transformed prior to analysis. [a)] Within each combination of study and LR material, moving time was evenly distributed over bundles in both size classes.

unloaded weight for this kind of vehicle (including the crane) was 30 tonnes. Consequently, the maximum load capacity was 30 tonnes.

The effects (main and interactive) of bundle size, material type and study occasion on bundle characteristics and productivity were evaluated by Analysis of Variance (ANOVA), using the general linear model (GLM) procedure implemented in Minitab 15 (Minitab Ltd.), and significant differences between the eight treatment combinations were identified by Tukey's simultaneous test of means. Multiple regression was used to analyze the relationships between work time consumption and bundle features. Time-related dependent variables were transformed to natural logarithms (Ln) to meet assumptions of normality and homogeneity of variance of residuals. The critical significance level was set to 5%.

3 Results

3.1 Bundle Characteristics

The analyses of bundle characteristics showed there were generally few consistent treatment effects (Table 3). In general, there were significant secondary and sometimes also significant third-way interactions, indicating that the levels of main treatment effects varied between treatment combinations. Results are therefore generally presented for all eight treatment combinations rather than pooled.

Bundle length differed slightly, but significantly, between the two bundle sizes (Table 3), the mean lengths of the normal and large bundles being 4.62 m (SD 0.12) and 4.69 m (SD 0.11), respectively. No other treatment effects were observed for length. Large bundles and brown bundles had significantly larger mean diameters and volumes compared to normal and green bundles, respectively, but the level of differences varied over the treatment combinations (Tables 3 and 4). Over all eight treatment combinations, the maximum mean differences in diameters and volumes were 8 cm and 0.52 m^3, respectively (Table 4).

Table 4. Bundle characteristics (mean and SD).

Study occasion	LR material	Bundle size	Mean diameter (m)	Volume (m^3)	Mass (kg) Raw	Mass (kg) Oven dry	$q_{p,\text{net,ar}}$ 1) (MWh)
1	Green	Normal	0.81 ^{ab} (0.04)	2.35 ^{ab} (0.24)	903 ^{a} (137)	433 ^{a} (66)	2.0 ^{ac} (0.3)
		Large	0.87 ^{c} (0.05)	2.80 ^{c} (0.33)	927 ^{a} (108)	445 ^{a} (52)	2.1 ^{a} (0.2)
	Brown	Normal	0.81 ^{ab} (0.04)	2.41 ^{ab} (0.24)	679 ^{b} (72)	421 ^{ab} (45)	2.1 ^{a} (0.2)
		Large	0.81 ^{ab} (0.04)	2.43 ^{ab} (0.24)	694 ^{b} (89)	430 ^{a} (55)	2.2 ^{a} (0.3)
2	Green	Normal	0.81 ^{ab} (0.04)	2.37 ^{ab} (0.26)	564 ^{c} (56)	299 ^{c} (30)	1.5 ^{b} (0.1)
		Large	0.83 ^{a} (0.04)	2.54 ^{a} (0.24)	725 ^{b} (83)	384 ^{b} (44)	1.9 ^{c} (0.2)
	Brown	Normal	0.79 ^{b} (0.04)	2.28 ^{b} (0.23)	471 ^{d} (65)	320 ^{c} (44)	1.6 ^{b} (0.2)
		Large	0.83 ^{a} (0.04)	2.53 ^{a} (0.26)	597 ^{c} (75)	406 ^{ab} (51)	2.1 ^{a} (0.3)

Within columns, different superscript letters indicate significant differences ($p<0.05$) (Tukey test).
1) Net calorific value as received.

Table 5. Work productivity based on total time required to produce 25 bundles.

Study occasion	LR material	Bundle size	Bundles h^{-1}	Bundles PWh^{-1} a)	ODt PWh^{-1}	MWh b) PWh^{-1}
1	Green	Normal	16.6	18.1	7.8	37.0
		Large	14.2	16.7	7.4	35.2
	Brown	Normal	14.3	17.7	7.4	37.6
		Large	10.7	14.4	6.2	31.4
2	Green	Normal	13.6	17.3	5.2	25.1
		Large	12.6	15.0	5.8	28.0
	Brown	Normal	17.6	19.2	6.2	31.7
		Large	17.1	18.3	7.4	38.2

a) Productive work hour, i.e. excluding delay time. b) net calorific value as received.

The raw mass of large bundles and of green LR bundles produced during study occasion 1 was significantly higher than that of corresponding bundles produced during study occasion 2 (Tables 3 and 4). However, the ODm content did not differ significantly between LR materials, although it was significantly lower in normal-sized bundles and bundles produced during study occasion 2 than in large bundles and bundles produced during study occasion 1 (Tables 3 and 4). The bundles' net calorific value as received was significantly lower during study occasion 2 than during study occasion 1, for all kinds of bundles except large bundles of brown LR (Table 4). The mean bulk density (raw mass per unit volume) was higher for green bundles and for those produced during study occasion 1 than for brown counterparts and those produced during study occasion 2, respectively, but there was no significant main effect of bundle size in this respect. The pooled mean bulk density was 285 kg m^{-3} (n=199, SD 74).

The mean number of crane grapple loads required to produce a bundle ranged from 3.2 to 4.1, with large bundles and those produced during study occasion 2 requiring significantly more loads than normal-sized bundles and those produced during study occasion 1, respectively (Table 3).

For all 100 green bundles, the mean volume was 2.5 m^3 (SD 0.3), raw mass 780 kg (SD 178), bulk density 311 kg m^{-3} (SD 69), OD mass 390 kg (SD 76) and net calorific value as received 1.9 MWh (SD 0.3). The corresponding values for all 99 brown bundles were 2.4 m^3 (SD 0.3), 610 kg (SD 116), 254 kg m^{-3} (SD 48), 394 kg (SD 65) and 2.0 MWh (SD 0.3), respectively.

3.2 Work Efficiency

The total study time was 13 h and 59 min, of which 2 h and 13 min (16%) consisted of delays. During the total study time, the productivity ranged between 10.7–17.6 bundles h^{-1} (Table 5).

Table 6. Productive work (minutes) required for production of 1 ODt (mean and SD).

Study occasion	LR material	Bundle size	Time consumption Compressing	Crane work	Miscellaneous	Move [1)]	Total
1	Green	Normal	3.16 [a] (1.12)	3.78 [ab] (1.00)	0.32 [a] (0.27)	0.53 [a] (0.08)	7.81 [a] (1.61)
		Large	3.24 [a] (1.09)	3.64 [ab] (0.79)	0.71 [a] (0.61)	0.51 [a] (0.06)	8.10 [ab] (1.43)
	Brown	Normal	4.08 [ab] (3.07)	3.33 [a] (0.75)	0.47 [a] (0.50)	0.26 [b] (0.03)	8.15 [ab] (3.34)
		Large	5.16 [b] (2.58)	3.76 [a] (0.77)	0.52 [a] (0.43)	0.26 [b] (0.03)	9.70 [bc] (2.56)
2	Green	Normal	5.07 [b] (1.95)	5.23 [c] (0.91)	1.01 [a] (0.71)	0.42 [c] (0.04)	11.73 [d] (2.25)
		Large	4.01 [ab] (1.89)	4.82 [c] (0.85)	0.81 [a] (0.81)	0.33 [d] (0.04)	10.40 [cd] (2.37)
	Brown	Normal	4.69 [b] (1.96)	4.04 [bc] (0.70)	0.65 [a] (0.57)	0.48 [a] (0.07)	9.85 [bc] (2.43)
		Large	3.28 [a] (0.76)	3.71 [a] (0.73)	0.76 [a] (0.67)	0.38 [e] (0.04)	8.13 [ab] (1.35)

Within columns, different superscript letters indicate significant differences ($p<0.05$) (Tukey test on Ln-transformed observations). [1)] Within each combination of study occasion and LR material, moving time was evenly distributed over bundles in both size classes.

Excluding delay time and (thus) solely during productive work hours (PWh), the productivity was on average 2.5 bundles higher per hour. Hereafter, productivity values are generally based on productive work time, unless otherwise stated. The productivity in terms of energy-related measures was 5.2–7.8 ODt PWh^{-1} and 25.1–38.2 MWh PWh^{-1} (Table 5).

The time consumption per bundle was significantly higher when producing large bundles (Table 3), but there was no significant size-related difference in time consumption per ODt. During the second study occasion significantly more time was consumed per ODt than during study occasion 1. However, the effects of bundle size and LR material on time consumption per ODt varied between study occasions (Tables 3 and 4).

For all work elements, the time required to produce 1 ODt was significantly higher during study occasion 2 than during study occasion 1, but the level of the effect varied among treatment combinations (Tables 3 and 6). For the *Compression* work, time requirements did not differ between LR materials while *Crane work* required less time for brown LR material. However, neither of the two work elements was affected by the differences in bundle size. The total mean time required to bundle one ODt ranged from 7.81 to11.73 min (Table 6). In relative terms, *Compression* required on average 44% (SD 10), *Crane work* 45% (SD 9), *Miscellaneous* 7% (SD 6) and the mean *Moving* time 5% (SD 2) of the bundling time per ODt. During the first study occasion, the machine was moved three times (11.7 min) when bundling green LR and twice when bundling brown LR (5.49 min); during the second study occasion, it was moved twice (6.25 min) and three times (7.52 min), respectively.

Table 7. Total load and proportion of load capacity used when loading 33 bundles on a self-loading logging residue truck with trailer. The assumed maximum load capacity was 30 tonnes and 144 m^3.

	Logging residue material Green		Brown	
	Total load	% of max	Total load	% of max
Raw mass (10^3 kg)	25.7	85.7	20.1	67.0
Volume (m^3)	82.5	57.3	79.2	55.0

The time required to bundle 1 ODt was significantly ($p<0.001$) related to the studied oven dry bundle mass (0.242–0.579 ODt $bundle^{-1}$), according to

$$Y = e^{2.92 - 1.80x}$$

where Y is time consumption (PWmin ODt^{-1}) and x is oven dry bundle mass (ODt $bundle^{-1}$) and the constant is corrected for logarithmic bias. The model explained 24% of the observed variance.

3.3 Truck Load Utilization

Given the dimensions of the transport equipment used, it should be possible to stack two piles of eleven 0.8 m diameter bundles (three rows of three, and two additional bundles on top) in the load space of each trailer and one such 11-bundle pile on each truck. Hence, the total theoretically possible load is 33 such bundles, which equals only slightly more than half of the available load

Table 8. Costs (US$/Odt) and productivity (Odt/PWh) for recovering logging residues (LR; here green LR with a moisture content of 50%) for three systems and their work operations. For Loose LR and In-field bundling, data from Engblom (2007) were used with a currency rate set to 1 US$ = 8 Swedish crowns.

Operation	System Loose LR Cost	 Productivity	 In-field bundling Cost	 Productivity	 Road-side bundling Cost	 Productivity
Forwarding (LR)	20.3	4.0	–	–	20.3	4.0
Forwarding (bundles)	–	–	9.0	9.0	–	–
Bundling	–	–	28.3	5.3	25.5	4.9
Truck loading [1)]	6.5	11.9	2.3	32.4	1.4	53.9
Road transport 100 km [1)]	34.9	3.5	25.6	4.7	29.9	4.1
Truck unloading [1)]	1.3	59.4	1.7	45.0	1.0	74.9
Comminution	15.5	11.3	8.3	21.0	5.3	32.8
Total	78.5		75.2		83.4	

[1)] Payloads were set to 11.0 ODt for Loose LR, 15.0 ODt for In-field bundling and 12.9 ODt for Road-side bundling.

volume (Table 7). Based on mean values from the study, 86% of the load weight capacity is used when transporting green bundles and 67% with brown bundles (Table 7). However, in terms of dry mass the quantities per load of 33 bundles are very similar: 12.9 ODt with green LR and 13.0 ODt with brown LR. In terms of energy, the net calorific value as received per load is 72 MWh with brown bundles and 68 MWh with green bundles.

The proportion of the raw mass load capacity used is 5% and 1% lower for brown and green road-side bundles compared to the proportion that would theoretically be used with loose LR, respectively.

3.4 Analysis of the Supply Systems

Compared to loose LR, the comminution, truck loading and road transport are cheaper for road-side bundling, but not sufficiently cheaper to cover the cost of bundling (Table 8). In comparison to in-field bundling, the comminution and bundling are estimated to be cheaper with the road-side bundling system. However, the savings are insufficient to compensate for the higher costs of forwarding and road transport. To match the in-field system, the road-side bundling productivity would have to increase by at least 18%, or its hourly costs would have to be decreased by 15%. Such improvements seem to be at least theoretically feasible, and would make the system competitive at the analyzed transport distance of 100 km (each way). However, given the specified payloads and work operation, loose LR will be more competitive in situations with shorter transport distances whereas in-field bundling will be more competitive in situations with longer distances.

4. Discussion

This study presents the first descriptive information of bundle characteristics and typical time requirements for this kind of bundle production (Tables 4–6). Surprisingly, the productivity was lower during study occasion 2 than during study occasion 1, given the expected positive influences of technical adjustments of the prototype, the operator's greater experience and improvements in operating conditions due to seasonal climatic changes during the second occasion. The unexpected reduction in productivity was probably mainly due to the strong (uncontrolled) effects of previous forest operations on LR windrow quality. Bundle dimensions did not significantly differ between study occasions, but mass-related characteristics did differ, indicating that the LR materials differed between occasions. Hence, although bundles of the same dimensions were produced, the productivity in mass-related terms was lower during study occasion 2. Since the MC of the material was lower during occasion 2 (Table 1), the factors responsible for these differences are likely to be related to LR composition in terms of species mixture, material organization and stemwood content. In these terms the windrow of green LR used on study occasion 2 was graded as inferior to other windrows (Table 1). Moreover, LR windrows are quite heterogeneous and the grading system quite crude. Hence, there may be substantial, unaccounted differences between them. Nevertheless, although unknown factors appear to have influenced the results, several general trends can be discerned or deduced for this new system to recover LR.

The productivity of the studied prototype machinery for bundling at road-side was between 14–19 bundles per PWh (Table 5), which is similar to productivity observed in previous studies of in-field bundling (Öhlund 2003, Cuchet et al. 2004, Kärhä and Vartiamäki 2006) and road-side bundling with an in-field bundling unit mounted on a truck (Spinelli and Magagnotti 2009). However, the bundles in this study had larger volumes, and contained on average 21% more ODm than the 4-m long bundles produced in the studies by Spinelli and Magagnotti (2009), and 77% and 44%, respectively, more ODm than those observed during in-field bundling by Kärhä and Vartiamäki (2006) and Öhlund (2003). Consequently, the average ODm-based productivity over the eight treatment combinations in this study (6.7 ODt PWh^{-1}) was 31% higher than that of the 4-m bundle production at road-side observed by Spinelli and Magagnotti (2009) (5.1 ODt PWh $^{-1}$). The productivity in the present study was also considerably (68% and 34%) higher than the 4 and 5 ODt PWh $^{-1}$ reported by Kärhä and Vartiamäki (2006) and Öhlund (2003), respectively. However, Kärhä and Vartiamäki (2006) only excluded delay times longer than 15 min, and if they had excluded all delays the difference in productivity would have been lower. Thus, ca. 30% is probably a more valid general estimate of the increase in productivity that the tested system can provide, compared to in-field bundling units mounted on either forwarders or trucks. However, since the studied truck-mounted bundler was an early prototype there should be possibilities to enhance productivity by both technical and work methodology improvements.

The lack of the requirement for another vehicle to transport the truck-mounted bundler between different work sites is an additional advantage compared to forwarder-mounted in-field bundlers, which require transport on trailers (and hence extra costs and non-productive work time) when work sites are far apart. Consequently, road-side bundling is likely to be most advantageous when many movements between sites are involved and the mean quantity of LR at each work site is low.

Although the force used for compression was high (735–784 kN), the bundles created in the present study had substantially (>25%) lower raw bulk density than those created by in-field bundle units (Kärhä and Vartiamäki 2006, Spinelli and Magagnotti 2009). Differences in the compression equipment used in the bundlers and, possibly, in LR characteristics can probably partly explain the difference in density. However, Nordfjell and Liss (2000) found that the larger the bundle diameter the more difficult it was to compress bundles to high bulk density. Furthermore, the increase in bulk density obtained by compressing bundles leveled out at quite low applied forces (circa 30 kN, when compressing by tightening one bundle cord at a time in their study). Thus, the lower density of the bundles examined in the present study was probably also partly due to their larger diameter. Hence, the compression force required for the prototype should be further investigated to ensure that the dimensions of the equipment are appropriate to meet bulk density targets. Despite the lack of gains in bulk density with the large bundles, a small diameter increase gave significantly higher bundle volumes and bundle mass (Table 3). However, producing larger bundles did not improve bundling productivity, since the same work time per ODt was required for the normal-sized and larger bundles. Consequently, bundle size could be chosen instead to match the requirements for the subsequent road transport and comminution equipment.

The estimated road-side bundle loads were slightly heavier than those observed by Näslund (2006) in a follow-up study of 3000 road-transport loads of green, loose LR, with mean masses of 19–25 tonnes and large seasonal differences in moisture content (47–60%). However, when transporting green in-field bundles on normal round-wood trucks in the cited study the mean load was 32 tonnes at an MC of 49%. Assuming that the same amount of bundles would fit on the covered trucks that would be used in populated areas, this implies that their load capacity (30 tonnes) could be fully used. Consequently, the load capacity of road transport vehicles can be more fully exploited by producing in-field bundles than landing bundles, mainly because the 3-m-long in-field bundles fit better in the truck and trailer load spaces.

Since neither the volume nor the weight capacity is fully used when transporting the road-side bundles, it would be desirable to add extra load. This could be done either by increasing the raw bulk density of the bundles, or by making larger bundles. To achieve full loads with the given bundle dimensions, the raw bulk density would have to be circa 370 kg m^{-3}, i.e. almost 20% and 50% higher than that of the green and brown bundles produced in this study, respectively. Alternatively, to optimize the bundle size, it would be important to match the bundles' dimensions and geometry to that of the load space. Since the width of the load space is 2.45 m, the small increase in bundle diameter that could be obtained by maximizing bundle mass would actually decrease the load since fewer bundles would fit. However, the desired increase in load could instead be obtained by making longer bundles that fully exploit the load area, which could accept uniform bundles up to 6.2 m long. With such a 35% increase in bundle volume, more than the full raw weight load capacity could be met (116%) for green bundles and 90% of the capacity for brown bundles. Moreover, if the full length of the truck loadbed (7.4 m) could be used, 123% and 96% of the raw weight capacity could be exploited, respectively. This would, however, require the ability to produce bundles with different lengths. In addition, the wrapping of bundles would probably have to be improved to enable such long bundles with low stemwood content to be handled.

The studied prototype has similar limitations to the WoodPac in-field bundler (Komatsu Forest, Sweden) for batch processing; the creation of one bundle with a fixed length at a time, with no possibilities to simultaneously feed and compress LR. Since compression accounted for nearly half of the time per produced bundle (Table 6), during which the crane was standing idle, if adjustments were made allowing simultaneous feeding and compression productivity could be nearly doubled. More efficient batch processing in this manner is possible, as shown by the Fixteri prototype in-field thinning bundler (Jylhä and Laitila 2007). The alternative to batch processing by in-field technology is to create a "continuous bundle" of continuously fed and compressed LR that is cut whenever a chosen length is reached. This approach is afforded by machines such as the FibrePac (Deere & Company, U.S.A). In in-field bundling, indications that continuous bundling provides higher productivity than batch processing with separate feeding and compressing modes have been found (Kärhä and Vartiamäki 2006). Moreover, a continuous bundling technique would also enable bundle lengths to be adapted to both customer demands (as in Spinelli and Magagnotti 2009) and the load space length of trucks in given operations, and hence maximize the trucks' load capacity usage.

In contrast to the bundles produced by most in-field equipment currently available, the bundles produced by the prototype had to be unloaded by the crane. On landings crane work might be required to organize bundles after unloading, which could be performed in conjunction with the crane unloading. Nevertheless, valuable work time could probably be saved if other unloading solutions could be found.

When evaluating a new system for LR recovery it is important to address the whole system and not only single work operations. The outcome of such a system analysis heavily depends on the productivity and cost inputs, which may vary substantially (especially productivity). Nevertheless, the analysis enables the major differences compared to other systems to be scrutinized. Although the road-side bundling system is the most expensive of those analyzed here, this undeveloped system tallies the costs rather well and the mentioned improvements might increase productivity in bundling and road transport sufficiently to make it competitive. Moreover, a recent study indicates that road-side bundles can be comminuted twice as rapidly as in-field bundles of the same size (Edman 2009), and thus half as cheaply. However, comminution only accounts for a minor part of total costs, so even major improvements in this part of the process would only slightly affect total costs. On the other hand, if the full loading capacity of trucks could be used (and thus the road transport costs reduced to those of in-field bundling), the costs of the road-side bundling system would be similar to those of the loose LR system.

Finally, it can be concluded that a number of technical improvements could considerably increase the competitiveness of the truck-mounted road-side bundler studied here. Notably, continuous feeding and compressing could almost double productivity, and the ability to make longer (or shorter) bundles would enable full use of truck load capacity. With such improvements, the road-side bundling system could provide a viable alternative to present LR-recovering systems. However, whether or not such enhancements to the road-side bundling system could make it more profitable than other LR recovery systems is too early to say at this stage of methodological and technological development. When the system has been further developed, comparative system analyses of the whole LR supply chain will be needed to evaluate the road-side bundling system's economic and practical merits.

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