Compression Processing and Load Compression of Young Scots Pine and Birch Trees in Thinnings for Bioenergy

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Abstract

In many boreal countries forest biomass from dense young stands has great potential to meet growing demands for bioenergy. However, there is currently no cost-effective operational system for harvesting such stands. When harvesting, it would be desirable to compress trees and leave some of the foliage and fine branches in the stand in order to reduce extraction of nutrients and improve the harvested material's fuel properties from a reduced ash content point of view. The objectives were to evaluate experimental systems (a boom-tip mounted unit for processing bunches, and a small prototype forwarder for compressing loads) in terms of their utility for compressing and partially debranching fresh and stored bunches of Scots pine trees and compressing forwarder loads of fresh Scots pine and birch trees. Processing of fresh bunches resulted in mass losses of about 10% (dbh-class 5-8 cm; not significant) to 15% (dbh-class 12-15 cm; significant) with 35 to 50% reductions in ash contents and increases in bulk and net energy density of about 80 to 160%. In-stand storage of bunches before processing generally yielded no significant advantages except for a 10%-unit reduction in moisture content. Compression of forwarder loads resulted in 16 (pine) to 32% (birch) increases in load densities, with a significant increase for birch trees.

The described techniques facilitate productivity increases of off-road and road transport of tree parts, and a substantial proportion of the ash-rich materials such as needles and fine branches are left in the stand. If both tested techniques are applied during the harvesting of young trees the benefits would be substantial.

Keywords: Bulk density, bundling, early thinning, foliage loss, forest biomass, payload, fuel wood, tree parts.

Introduction

In many boreal countries forest biomass (including the biomass in young stands) has great potential to meet growing demands for bioenergy. Of the total land area in Sweden (~ 41.3 million ha), 55.4% is forested, including 12% supporting dense young stands with trees less than 12 m tall and biomass contents exceeding 30 oven-dry tonnes (ODt) per ha (Anon. 2007, Nordfjell et al. 2008). To meet some of the rising demand for bioenergy, it could be of interest to harvest trees from such stands. However, according to current standard Swedish silvicutural recommendations, a forest stand that has reached a height of about 3 m should be pre-commercially-thinned (PCT) in such a way that the remaining stems are evenly distributed with a density of about 2000-3000 trees× ha^{-1}, and the cut biomass should be left in the forest to optimize the volume growth of the remaining trees for the production of timber and pulpwood (Claesson et al. 1999). Nevertheless, in practice, forest owners often neglect PCT operations because they are expensive. Consequently, their stands become denser and contain higher amounts of biomass per hectare than stands that are subjected to PCT. In such stands a first commercial thinning could be performed to harvest material for bioenergy processes, and thus the forest owners could potentially generate an income, or at least cover a major part of the PCT costs, at an early stage.

In Sweden, first thinnings for bioenergy are not common, but when conducted they are generally carried out with conventional forest machines where trees between strip-roads are thinned from below (Richardson et al. 2002). Felling and bunching operations in early thinning are only productive in stands with high standing volumes; hence, new techniques and operational systems are required to significantly improve

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their productivity (Johansson & Gullberg 2002, Kärhä et al. 2005, Bergström et al. 2007). Since stacks of small trees are bulky (with solid mass accounting for about 25-35% of total volumes), only 30-60% of a forwarder's load capacities is normally used (Nordén 1991). Hence, the productivity of off-road transport is generally low, especially over long hauling distances. Further, parts of the top, such as fine branches and needles, are rich in minerals (Ringman 1996) and their extraction can lead to the removal of significant amounts of nutrients from the forest. This can potentially reduce subsequent biomass production in the stand, especially on sites with low fertility (Jacobson et al. 1999). In addition, properties of the raw material used as fuel wood (e.g., moisture and ash contents, chemical composition, bulk density, presence of microbes, and heating values) are all important factors to take into account (Nurmi & Hillebrand 2007), and it is desirable to have low contents of ash (nutrients) and inorganic materials (contamination) during its combustion process (Nordin & Levén 1997). Therefore, in harvesting operations it would often be desirable to compress trees and to leave as much as possible of the foliage and fine branches evenly distributed in the stand, before transporting the material to roadside, in order to reduce losses of nutrients from the stands, improve the efficiency of off-road transport, and enhance the harvested materials' fuel properties (i.e. ash content).

An obvious way to increase forwarder payloads is to enlarge the load-space by widening and/or elongating it (Brunberg 1999). This may be advantageous for purposes such as forwarding loose logging residues in clear cuttings. However, it is not suitable for thinning since strip-roads are kept narrow and the remaining trees are likely to be damaged if large/wide loads are transported along them. Alternatively, as demonstrated by Nordén (1984), load densities could be increased by 35-60% by compressing (load compression) small diameter trees harvested in early thinnings. Similar approaches have also been tested in Finland (Kallio & Leinonen 2005). Bundling whole trees (full tree; tree above felling cut) or parts of trees at high density before leaving the stand facilitates handling and offers logistical advantages compared to the use of separate systems for round wood and fuel wood, i.e. transporting the former in conventional trucks, but loose tree parts and chips in specially designed trucks (Richardson et al. 2002, Johansson et al. 2006).

Using both conventional and prototype off-road bundling machines, it has been shown that bundles of small Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst), and birch (*Betula pubescens* Ehrh.) trees (diameter at breast height over-bark (dbh), ranging from 1.7 to 10.4 cm) with densities of 236-537 kg×m^{-3} green weight (GW) can be obtained (Jylhä 2004, Pettersson & Nordfjell 2007). The bundling process may also significantly reduce the amount of foliage and fine branches attached to the handled material, especially if the raw material has been stored before bundling, since dried needles are less firmly attached to branches than fresh ones (Jirjis & Norden 2005, Röser et al. 2008). However, off-road bundling machines are expensive and generally have low productivity (Richardson et al. 2002). In order to improve the productivity of bundling, several factors must be considered. For example, substantially higher forces are required to produce high-density bundles than to produce medium-density bundles; Nordfjell and Liss (2000) found that forces of 16 kN and 53 kN were needed to compress fresh, small (dbh, 7.5 cm, height, 8.0 m) Scots pine, Norway spruce, and birch trees into bundles with bulk densities of 270-460 kg×m^{-3} and 520-780 kg× m^{-3}, respectively. Compressed bundles dry almost as well as non-compressed bundles and require less time to chip (Nordfjell & Liss 2000). In addition, according to Danielsson et al. (1977), less force is required to compress fresh, small Scots pine and Norway spruce trees than materials that have been stored over a season, and storage of whole trees either in-stand or at roadside, especially over the summer period, significantly reduces the moisture content (MC%-wet-basis) (Nurmi & Hillebrand 2007).

Systems involving the use of a single machine to both fell and bundle trees simultaneously (i.e., a bundle harvester) and a forwarder to transport bundles to roadside might be preferable to systems requiring the use of more machines. However, use of a prototype bundle harvester for first thinnings proved to have low productivity in a field study by Jylhä and Latila (2007). Thus, new systems are required to increase productivity and reduce the removal of nutrients from harvested stands. Developmental efforts to meet the latter objective should focus on the upper parts of tree crowns since most nutrients are concentrated in these parts. The crown mass to stem mass ratio of trees decreases as they age (Hakkila 1991). In a discussion of the possibility of using multi-stem delimbers to rationalize the delimbing process of small diameter trees, Dahlin (1989) concludes that cradle type delimbers provide the greatest flexibility in construction and can be used in cases where portable (off-road), lightweight, and compact bunch delimbing systems are required. However, a machine that simultaneously compresses, debranches, bucks, and loads trees requires more power than standard machines, and the more tools that are attached, the heavier the machine becomes.

Two series of experiments are described here. The objective of the first experiment was to evaluate the utility of experimental technical devices for compressing and semi-debranching (compression processing) bunched, young harvested Scots pine trees (with 2-5 trees per bunch). The objective of the second series experiment was to explore the potential advantages, disadvantages, and parameters of compressing forwarder loads of young Scots pine and birch trees.

The net energy contents of the processed and compressed materials were derived from functions found in literature, and no laboratory measurements of these properties were made.

Material and Methods

In this paper, a bunch is defined as two or more whole trees stacked together that have not been subjected to any external mechanical forces, and a bundle is defined as a bunch of trees that has been compressed, bucked and stacked.

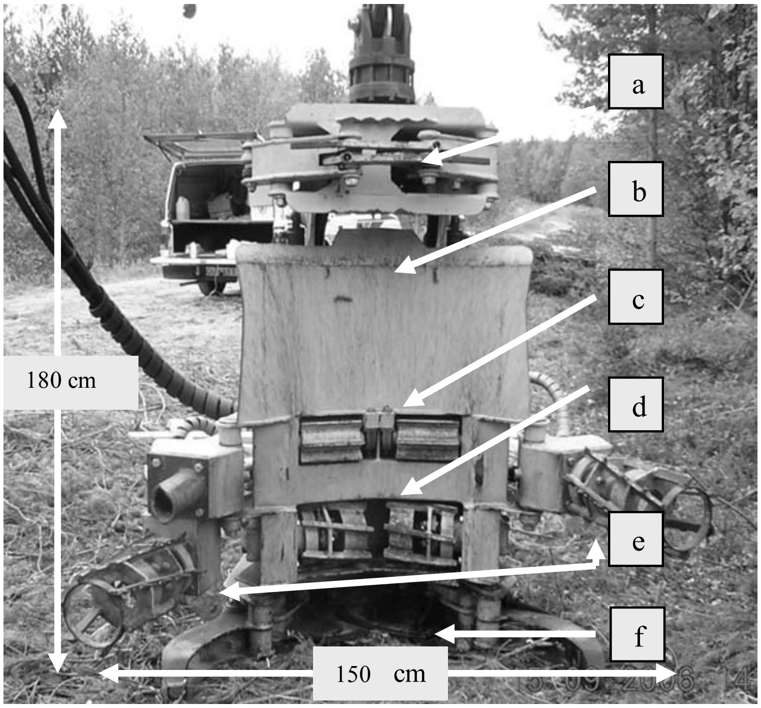

Figure 1. The experimental unit for compressing and semi-debranching tree bunches from young stands: (a) two grapple arms for accumulation on the top; (b) debranching supporting plate; (c) two "support" rollers on the body; (d) two feed rollers attached to the body; (e) two horizontal front feed rollers attached to grapple arms and at the bottom; and (f) knives for cutting the trees/bunches. The height and width (open) of the unit are 180 cm and 150 cm, respectively.

Compression and Semi-Debranching of Tree Bunches

An experimental boom-tip mounted unit for compressing and semi-debranching tree bunches was designed, constructed, and mounted on a conventional medium-sized harvester (~ 12 t), with four aggressive feed rollers to break and flatten branches, and reduce foliage and fine branches during processing (Figure 1). The mass of the unit was approximately 1000 kg, the diameter and length of the two front feed rollers were 25 and 46 cm, respectively, the corresponding dimensions of the body-attached feed rollers were 25 and 24 cm, respectively, and the calculated feeding speed was 5.7 $m \times s^{-1}$. The force with which a bunch was gripped by the front feed rollers/grapple arms during processing (calculated) was 9.8 kN at the mid-point of the roller.

The first part of the study was conducted in August 2006, in a forest stand located in Vindeln, Sweden (N 64º 10', E 19º 37', 170 m a.s.l.). The annual growth potential of the stand was 3.7 $m^3 \times ha^{-1}$ and it was dominated by Scots pine in terms of volume, but contained substantial numbers of Norway spruce and small birch trees. On average, the stand had 15940 $trees \times ha^{-1}$ (21% pine, 14% spruce, and 65% birch), a basal area of 39.8 $m^2 \times ha^{-1}$, a dbh of 4.9 cm, and a height of 5.7 m. All trees taller than 1.3 m were measured. Compression processing took place under controlled conditions at roadside, but the intent of the prototype system is to work on site.

Only Scots pine trees were used in the experiment, which had a 2×2×2 randomized factorial design, including:

Two types of raw materials, fresh (*Fresh*) and stored in-stand over winter (*Stored).*

Two size classes, represented by: (i) trees with dbh ranging from 5 to 8 cm (*5-8cm trees*), bunched in sets of five; and (ii) trees 12 to 15 cm (*12-15cm trees*), bunched in pairs.

Two treatments, processed (*Proc.*) and control (*C*) bunches.

Trees were randomly selected for each bunch and were then manually felled and gathered, their dbh, height, and height-to-first-living-branch were measured, and their GW were determined using one of three dynamometers, scaled

Table 1. Characteristics of fresh Scots pine trees used in the single bunch* compression processing (compression and semi-debranching) experiments, *Fresh* = materials processed immediately after felling and *Stored* = materials processed after in-stand storage over winter. GW = green weight, s.d. = standard deviation and n = no. of trees.

	Fresh		***Stored***	
Properties	***5-8cm* (n=120)**	***12-15cm* (n=40)**	***5-8cm* (n=50)**	***12-15cm* (n=20)**
Dbh (cm)	6.6^b	13.4^a	6.5^b	13.3^a
Height (m)	6.9^c	9.1^b	7.2^c	9.7^a
Height of first living branch (m)	3.1^b	3.2^{ab}	3.3^a	3.4^a
GW of bunched trees before processing (kg), (s.d.)*	95.1^b (7.5)	180.0^a (20.2)	92.9^b (14.6)	192.8^a (31.3)

*Bunches; *5-8cm trees* (5 trees per bunch), *12-15cm trees* (2 trees per bunch). Different superscript letters in rows indicate significant differences ($p \leq 0.05$) according to Tukey's test.

Figure 2. The compression and semi-debranching sequence of a bunch processed from the butt-end (a) to the top-end (d).

from 0–100, 0–250, and 0–500 kg (Table 1). In August 2006, 64 fresh bunches were made in total, 20 of which were randomly sampled and left in the stand for storage over winter, from August to June (~ 10 months) (Table 1). Experiments on fresh bunches and stored bunches were performed in August 2006 and June 2007, respectively. Bunches to be stored were placed on the ground in the stand at the felling site. After storage the proportions of their needles and fine branches that still remained were visually estimated according to a five-degree scale (0, 25, 50, 75, and 100%), and their color (green or brown) was also visually estimated.

Each bunch destined for the *Proc.* treatment was transported to roadside with a 2 t forwarder. The GW of the bunch was then measured and it was positioned in such a way that the harvester could grasp it at the butt-end and process it at full feeding speed, from the butt-end to the top-end, until the entire bunch had been passed through the experimental unit (Figure 2a-d). After processing the GW of the bunch was measured again and (for stored bunches) the broken-off mass of large branches (including attached fine branches and needles) was also measured. The broken-off mass of fine branches and needles were calculated as the difference in GW of total mass losses and the mass losses of large branches.

The volume of each bunch was measured as the bundled bulk volume (m^3): *5-8cm trees* bunches were bucked at half length, and then stacked on a flat surface by placing three of the butt-end parts side by side in the bottom, and the other two butt-end parts side by side on top of them. The top parts were then placed, one by one, on top of the butt-ends as tightly and evenly distributed as possible with the cut part/ stem pointing in the same direction as the butt-end parts. The bunch was then bundled by tying a piece of inelastic plastic string around it at three specific positions: 30 cm from the butt-end, in the middle, and 30 cm from the top-end. One by one, the strings were pulled tight with a force of 98 N and were fastened, then cut off. The strings were then measured to determine the average circumference of the bundle. The length of the bundle was also measured. Bundles of category *12-15cm trees* were made according to the same method as for *5-8cm trees* bunches, but only contained two butt-ends at the bottom and two top parts on top of them.

In total 24 bunches (three per treatment) were randomly selected from the bundled bunches and then chipped using a tractor-mounted chipping device. Samples were taken from a running stream of chips, and divided into two sub-samples per bunch, which were stored in closed plastic buckets (10 l each) and subsequently prepared in the laboratory according to Swedish standard methods to determine ash and dry matter (DM) contents (ash content SS 187171:1, DM SS 187170:3).

Table 2. Characteristics of forest stands used in the compression of forwarder loads investigation.

	Study area	
Stand characteristics	***Bergsbyn***	***Vikmyran***
Age (years)	38	33
Stand density (trees×ha^{-1})	2333	2514
Proportions of pine:spruce:birch (% of trees)	10:0:90	100:0:0
Dbh (cm)	10.9	12.2
Height (m)	12.7	9.9

The net calorific values as received (*q net p.m.*) were determined from the formula $q\ net\ p.m. = q\ net\ p. - 2.45 \times (MC \times (100-MC)^{-1})$ (MJ×kgDM^{-1}), where *q net p.* is the net calorific value, the constant *2.45* is the amount of energy needed to vaporize water at 20Cº (MJ×kgDM^{-1}). The *q net p.* value of Scots pine and birch was set to *19.59* and *19.04* MJ×kgDM^{-1}, respectively (Ringman 1996). The *net energy content* (E_{net}) was then determined from the formula $q\ net\ p.m. \times kgDM \times 3600^{-1}$ (MWh), where the constant *3600* is used for converting MJ to MWh.

Compression of Forwarder Loads

This part of the study was carried out at two sites in the municipality of Skellefteå in the northern part of Sweden — Vikmyran (N 64º 38', E 21º 4', 53 m a.s.l.) and Bergsbyn (N 64º 42', E 21º 7', 5 m a.s.l.) — where compression parameters of loads of Scots pine (*Pine*) and birch (*Birch*) trees, with dbh ranging from 5 to 15 cm, were evaluated in July 2006 and August 2006, respectively (Table 2). The experiments followed a randomized design with two treatments: compressed (*Compr.*) and control (*C*) loads. The treatments were paired and their order was randomized. Five loads per tree type (*Pine & Birch*) and treatment (*Comp. & C*) were made, hence in total 20 loads were examined.

A small prototype combined feller buncher and forwarder (Vimek 606 TT Biocombi (Vimek AB, Vindeln, Sweden)), with a mass of 2860 kg and 180 cm width was used (Figure 3). The forwarder's load space cross-sectional area was 2.0 m^2, the length of the load-bed was 3 m (from the bulkhead to rear stakes), and the load capacity was 3000 kg. The machine, which was designed to fell, buck, and load trees one by one, had a combined felling and grappling head at the tip of the boom and a device for compressing the trees on the load-bed. Trees were compressed by moving the four (two on each side) jointed, hydraulically powered stakes, from the outward to the inward position, thereby compressing loaded trees. Each of the jointed stakes was 112 cm long (seen from behind) and could be moved from an orientation (relative to vertical) 34º away from the load-space to 25º into the load-space. The maximum calculated compression forces delivered at half-stake length (56 cm) in the outward and inward orientations were approximately 4.3 and 1.2 kN, respectively. The mass (GW) of each load was measured using a mobile weighing system (Telub 20T) by separately weighing the front and rear parts of the forwarder, summing them, then deducting the machine's tare weight, obtained by re-weighing it directly after unloading.

The trees for each load were selected by the machine operator who thinned trees from below, to a target stem density of about 1500 trees×ha^{-1}. The dbh of each harvested tree was measured, and it was then felled and bucked (if necessary) to a maximum length of 5.5 m. Trees were then loaded

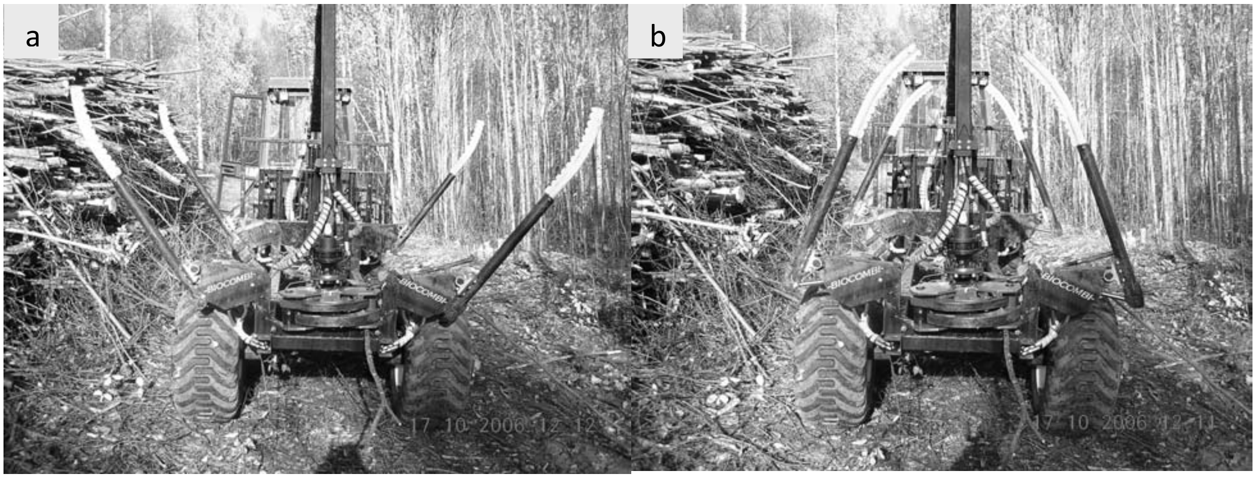

Figure 3. Rear view of the prototype Vimek 606 TT Biocombi (Vimek AB, Vindeln, Sweden) designed for compressing loads of whole trees and tree parts: a) stakes in outward position (34º); and b) stakes in inward position (25º).

Table 3. Properties of Scots pine bundles in the investigation of compression processing (compression and semi-debranching) of bunched *Fresh* and *Stored* trees of two size-classes (*5-8cm trees* & *12-15cm trees*). *Proc.* = processed and *C* = controls; MC = moisture content %-wet-basis; DM = dry matter; GW = green weight; E_{net} = net energy content; n = no. of bunches; nt = not tested.

	Fresh				***Stored***			
	5-8 cm trees		***12-15 cm trees***		***5-8 cm trees***		***12-15 cm trees***	
	Proc.	***C***	***Proc.***	***C***	***Proc.***	***C***	***Proc.***	***C***
Properties	***n=3***	***n=3***	***n=3***	***n=3***	***n=3***	***n=3***	***n=3***	***n=3***
MC (%)	55.1^{a}	55.5^{a}	57.7^{a}	58.1^{a}	45.5^{b}	48.8^{b}	45.9^{b}	45.5^{b}
Average MC[1] (%)	56.6				46.4			
Ash content (% of DM)	0.50^{b}	0.77^{a}	0.40^{b}	0.80^{a}	nt	0.60^{ab}	0.47^{b}	0.53^{bc}
Ash losses (%)[*]	*35.1*	-	*50.0*	-	-	-	*11.3*	-
	n=14	***n=10***	***n=10***	***n=10***	***n=5***	***n=5***	***n=5***	***n=5***
Length (m)	3.7^{c}	3.9^{c}	4.5^{ab}	4.8^{a}	3.8^{c}	4.1^{bc}	4.6^{ab}	5.0^{ab}
Diameter (mm)	320^{c}	434^{b}	394^{b}	654^{a}	286^{c}	394^{bce}	359^{be}	657^{a}
Diameter reduction (%)[*]	*26.3*	-	*39.8*	-	*27.4*	-	*45.4*	-
Bulk volume (m^3)	0.29^{a}	0.580^{a}	0.550^{a}	1.651^{b}	0.243^{a}	0.498^{a}	0.477^{a}	1.712^{b}
Mass (GW) (kg))	85.5^{c}	93.0^{c}	154.0^{b}	178.5^{a}	54.6^{d}	78.1^{c}	103.9^{c}	146.7^{a}
Mass losses (%)[#]	*11.4^{c}*	-	*15.2^{ab}*	-	*12.3^{bc}*	-	*18.4^{a}*	-
Bulk density ($kg \times m^{-3}$)	290^{a}	162^{bcd}	298^{a}	114^{cde}	225^{b}	160^{bde}	225^{b}	87^{e}
Bulk density increase (%)[*]	*79.0*	-	*161.4*	-	*40.6*	-	*158.6*	-
DM (kg)	37.1^{a}	40.4^{a}	66.8^{c}	77.5^{b}	29.3^{a}	41.9^{a}	55.7^{c}	78.6^{bc}
Dry density ($kg \times m^{-3}$)	125.7^{a}	70.5^{b}	129.1^{a}	49.6^{b}	120.4^{a}	112.9^{a}	120.8^{a}	65.2^{b}
E_{net} (kWh)	169^{c}	184^{c}	304^{b}	353^{a}	142^{c}	203^{c}	270^{b}	382^{a}
E_{net} density ($kWh \times m^{-3}$)	573^{a}	321^{bc}	588^{a}	226^{c}	584^{a}	417^{b}	586^{a}	227^{c}

[1] Used for further calculations based on MC. [*] Comparison of *Proc.* and *C* treatments in respective raw material and size-class. [#] Compared to the initial mass (GW) of bunches before processing. Different superscript letters in rows indicate significant differences between treatments ($p \leq 0.05$) according to Tukey's tests.

with their butt-ends pointing toward the bulkhead. In the *C* treatment, the four stakes were positioned and locked at the normal vertical position throughout each loading cycle, but in the *Comp.* treatment they were oriented in the outward position (Figure 3a) when loading and moved towards the inward position between loading cycles for compression processing (Figure 3b). Each load was stacked to a level of the top-ends of the stakes (in the normal position). At full load the length and mass (GW) of the load were measured.

Two randomly selected trees from each study area were sampled to measure their MC by cross-cutting the stem-wood of each whole tree into 2 l pieces, which were then placed and stored in plastic bags for about 12 hours. Samples were then dried at 105ºC for 48 hours in a ventilated oven.

Statistics

The effects of the treatments on the measured variables were assessed by analysis of variance using a general linear model, calculated by Minitab 15 (Minitab Ltd.). Differences were considered significant if p≤ 0.05. In the analysis of the

Table 4. Properties of trees and loads of *Pine* and *Birch* trees subjected to each of the treatments (compression *Compr.* & control *C*) in of the investigation of load compression with the prototype Vimek 606 TT Biocombi (Vimek AB, Vindeln, Sweden). The experimental design was a one-way layout, one for each species, *Pine* and *Birch.* MC = moisture content %-wet-basis; DM = dry matter; E_{net} = net energy content; Standard deviation (s.d.) values within brackets; n = number of loads.

Properties	***Pine***		***Birch***	
	Compr.* *(n=5)	***C.* *(n=5)***	***Compr.* *(n=5)***	***C.* *(n=5)***
Trees				
No. per load	45^{a}	37^{a}	42^{a}	38^{a}
Dbh (cm)	9.3^{a}	9.3^{a}	10.0^{a}	9.5^{ab}
MC (%)	50.1 (3.2)		38.2 (2.4)	
Loads				
Length (m)	4.5^{a}	4.5^{a}	5.2^{a}	5.2^{a}
Mass (GW) (kg)	2166^{a}	1900^{a}	2146^{a}	1606^{b}
Bulk volume (m^3)	10.1^{a}	10.3^{a}	13.7^{a}	13.7^{a}
Bulk density ($kg \times m^{-3}$)	213^{a}	184^{a}	156^{a}	118^{b}
Bulk density increase (%)	*15.8*	-	*32.2*	-
DM (kg)	1081 (161)	948 (111)	1326 (183)	993 (158)
E_{net} (kWh)	5140 (768)	4510 (529)	6460 (888)	4830 (769)
E_{net} density ($kWh \times m^{-3}$)	509 (56)	438 (54)	471 (63)	353 (66)

Different superscript letters in rows within the species (*Pine* or *Birch*) columns indicate significant differences at the 5 % probability level according to Tukey's tests.

data acquired from the bunch compression investigation a full factorial model with three fixed main effects was used and differences between mean values obtained for the eight treatment combinations were analysed using Tukey's simultaneous test of means, while in the analysis of data from the load compression investigation a one-way layout was used.

Results

Compression and Semi-debranching of Tree Bunches

Processing *Fresh 5-8cm trees* and *12-15cm trees* bundles resulted in significant increases in bulk density, of up to 80 and 160%, respectively (Table 3). This corresponded with significant decreases in bundle diameter (up to 26 and 40%, respectively) compared to controls. The processing caused a significant reduction in mass of *12-15cm trees* bundles, but not of *5-8cm trees* bundles. For *Stored* bundles the effects of processing were not as clear as those for fresh material, and the changes in bundle diameter ($p = 0.06$) and bulk density ($p = 0.15$) of *5-8cm trees* bundles were not significant. Processing resulted in significant mineral losses from *Fresh 5-8cm trees* and *12-15cm trees* bundles, with reductions of up to 35% and 50%, respectively, in ash contents. No corresponding differences were observed for *Stored* materials, but the value for *Proc. 5-8cm trees* was excluded from analysis since a heavy rain shower caused contamination during handling.

High proportions of needles remained attached to the trees after storing type *5-8cm trees* and *12-15cm trees* bunches in-stand, ranging from 50 to 100% and 75 to 100%, respectively; and their proportions of brown needles ranged from 25 to 75% and 25 to 50%, respectively. The proportions of needle and fine branch and large branch masses (GW) lost during processing *Stored 5-8cm trees* bundles were found to be 61% and 39%, respectively, while corresponding values for *12-15cm trees* bundles were 65% and 35%, respectively. During in-stand storage the DM losses of *5-8cm trees* and *12-15cm trees* bundles were small; reductions of only 3.1 and 1.0 % were found, respectively, but their MC values dropped almost 20% (Table 3). The subsequent processing did not affect their MC and their proportional losses of DM were similar to those of fresh material. The highest reduction of net energy content due to processing was found on *Stored* bundles (~ 30%). However, the net energy density increased significantly (up to ~ 160%).

Compression of Forwarder Loads

Compression significantly increased (by more than 30%) the bulk density of *Birch* loads (Table 4), and had a positive (but not statistically significant) effect on the bulk density of *Pine* loads ($p=0.087$). Compressed loads of both *Pine* and *Birch* reached almost 75% of the load capacity of the forwarder, while corresponding values for control loads were only about 60% and 55%, respectively. In addition, the load (bulk) density and net energy density of compressed *Pine* loads were 37% and 8% higher, respectively, than those of compressed *Birch* loads (Table 4: 213 v. 156 $kg \times m^{-3}$ and 509 v. 471 $kWh \times m^{-3}$), but the net energy content per load was about 25% higher for *Birch* loads (5140 v. 6460 kWh).

Discussion

Compression and Semi-debranching of Tree Bunches

The bulk densities of *Fresh Proc. 5-8cm trees* and *12-15cm trees* bundles were in accordance with densities obtained by Nordfjell and Liss (2000), who used compression forces of 16 kN to bundle trees harvested in first thinnings, and with densities obtained by bundling small sized trees with conventional bundling machines (Pettersson & Nordfjell 2007). In the present study the calculated compression forces applied during processing (i.e., breaking and flattening branches) was 9.8 kN. The results demonstrate that high-density bundles can be made by breaking and flattening branches using a feeding process with relatively low compression forces.

The mass losses (GW) due to processing were about 11 and 15% for *Fresh 5-8cm trees* and *12-15cm trees* bunches, respectively, with a significant mass loss for *12-15 cm trees* bunches. Corresponding significant mass losses for *Stored 5-8cm trees* and *12-15cm trees* bunches were 12 and 18%, respectively. The relative contributions of losses of needles and fine branches and large branches to the total mass losses of *Fresh* materials were not measured. However, the broken-off materials clearly consisted of both relatively large branches with all needles still attached, and large numbers of fine branches with needles. The mass broken-off from both fresh and stored materials was considerably higher than the maximum possible mass of the needles, as calculated with functions by Marklund (1988). This indicates that some of the branches were removed during processing. Thus, it seems to be difficult to remove needles, at least in fresh conditions, without removing some of the branches to which the needles are attached. In comparison to results obtained by leaving the top-ends in thinnings (Hakkila 1991, Jylhä 2004), processing both *Fresh* and *Stored* materials leaves greater amounts of foliage at the felling site. The amount that could be left in the stand following compression processing also seems to be affected by the size of the processed trees. Despite a 16% mass loss (GW) from *5-8cm trees* bunches during in-stand storage, the bulk density of *Fresh* and *Stored* control bundles reached similar values. The difference between *Fresh* and *Stored* bundles were not so clear for *12-15cm trees* bunches, even though mass losses of 24% occurred during their storage, possibly because they were compacted less by snow during in-stand storage than the smaller bunches. The results also show that more material (GW) was left in-stand of the *12-15cm trees* bundles than the smaller, *5-8cm trees* bundles (~ 30% and 50% more for the *Fresh* and *Stored* bundles, respectively). Thus, it seems to be easier to break and scrape off foliage from trees stored in-stand than from fresh trees, especially for larger trees. However, there were no clear differences in ash/mineral nutrients left in-stand between the processed fresh and stored materials. Thus, there seem to be no clear advantages of storing trees/bunches in-stand over winter before compressing processing them, from a nutrient-balance perspective.

The studied experimental unit has not been developed for use in operational forestry, but its components, such as those used for compression processing (compressing and semi-debranching) could be adjusted to fit a conventional system. It may also be possible to improve the feed rollers to enable more of the needles and fine branches to be removed, while only partly breaking and flattening larger branches. In practice, the equipment required for compression processing could be attached to a harvester head or the boom-tip of a forwarder crane. Alternatively, it could be mounted as a separate unit: e.g., attached to the load space of a forwarder.

Compression of Forwarder Loads

In this investigation compression forces of 4.3 kN were applied to forwarder loads, which resulted in 16-32% increases in load density with a significant increase for birch loads. The results indicate that birch trees are easier to compress than pine trees. Increases in bulk densities of 35-60% have been found in previous studies (Nordén 1984) for loads containing trees harvested in first thinnings, but compressed using a similar compression device with greater than 10 times the compression force. Thus, further compression than that observed in the present study could presumably be easily achieved simply by increasing the compressing forces, since the forces applied were relatively low. The net energy content per load was higher for compressed loads of birch than for compressed loads of pine, even though the load density of the latter was higher. This is because pine trees have a higher MC percent and lower solid density. Hence, since similar payloads were obtained for compressed pine and birch trees, their off-road transport costs should be similar, and the findings indicate that the studied technique could make off-road transport of compressed whole trees and tree parts cost-effective. Such techniques should therefore be of interest in many fuel wood supply systems. Further, to our knowledge, no attempts have been made to determine the "optimal" compression forces when using similar techniques to optimize the densification of loads comprising trees of different species and sizes. Such studies would greatly facilitate the development of optimized load compression technology to improve the efficiency of off-road and road transport of whole trees and tree parts.

Conclusions

The results show that the bulk and net energy density of both fresh and stored materials from young trees of 5-8 and 12-15 cm dbh classes can be increased about 40-80 and 160%, respectively. The processing generates two assortments of debranched material: relatively large branches and small branches, both with needles attached. The compression and semi-debranching of fresh bunches should result in mass losses of about 10 to 15%, depending on the size of the young trees, with reductions in nutrient removal of up to 50%. It should also be feasible to develop operational systems for compressing and semi-debranching bunches from young stands that offer significant improvements in productivity in terrain and road transport of tree parts and allow substantial proportions of the ash-rich needles and fine branches to be left in the stand. Using the tested load-compression technique, payloads of whole trees and tree parts can be significantly increased, and thus it offers a cost-effective way to improve the productivity of off-road transport. If both tested techniques were combined during the harvesting of young trees the benefits could be substantial.

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