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Operational Efficiency and Damage to Sawlogs by Feed Rollers of the Harvester Head

Yrjö Nuutinen, Kari Väätäinen, Antti Asikainen, Robert Prinz and Jaakko Heinonen

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In mechanical cutting, deep damage caused by feed rollers can reduce the yield of good quality timber for the sawmill and plywood industries. Additionally the feeding and energy efficiency of feed rollers are important for the profitability of harvester cutting. The objectives of this study were to compare the damages to sawlogs, as well as the time and fuel consumption of stem feeding with six different steel feed rollers during the processing of stems using a single grip harvester. This study tested two rollers with big spikes, two rollers with small spikes, one roller with studs in v-angle and one roller with adaptable steel plates in the ring of the roller. A highly detailed, and accurate processing and fuel consumption projection was recorded using the harvester's automated data collector on a log and stem level. The roller adaptable plate averaged, for unbarked sawlogs, the lowest damages of 3.7 mm. While the damages of the roller with big spikes were the deepest with an average of 7.8 mm. For medium stems, volume of 0.35 m^3, the range of differences between the maximum and minimum effective feeding time per roller was 6–19%, which would increase the effective time consumption of cutting by 1–3%. Corresponding differences in fuel consumption during total stem processing were in the range of 7–15%. According to this study it can be concluded that the traditional rollers with spikes were most effective in processing and fuel consumption, but at the same time they caused the deepest damages to the sawlogs. The roller type with adaptable steel plates was the most effective for small stems, additionally it also caused the least damage to the sawlogs.

Keywords single grip harvester, feed roller, productivity, timber damages, work study
Addresses Finnish Forest Research Institute, Joensuu Research Unit, P.O. Box 68, FI-80101 Joensuu, Finland **E-mail** yrjo.nuutinen@metla.fi
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1 Introduction

Throughout the world roundwood harvesting with single grip harvesters has increased significantly. The increase has been rapid, especially in this decade in Europe (Asikainen et al. 2009). In Finland logging operations are based on the cut-to-length -method (CTL) with cutting of timber predominantly being carried out using single grip harvesters. Single grip harvesters are advanced logging processors provided with a tree-harvesting unit, a so called harvester head. Harvester head fells, delimbs, cuts and measures the trees. A modern single grip harvester cuts timber to desired lengths with a high accuracy, but the log defects that result during processing (delimbing and cutting) are considerably greater than with manual harvesting. Harvesters equipped with a chainsaw harvester head and feed rollers can mostly cause three types of damage to the timber: checks in the ends of the bucked logs (Eronen et al. 2000, Granlund and Hallonberg 2001), bark losses in processing (Liiri et al. 2004) and damage to the wood surface of the logs, which is caused by the feed rollers. In Finland, in 2006, mechanized harvesting represented 98% of the total fellings of 50.8 million m^3 (Finnish Forest Research Institute 2007) thus the risk of feed roller damage to the timber must not be underestimated. Furthermore, the efficiency, reliability and costs play an important role when choosing feed rollers for use. This is because, for example, in clear cuttings processing itself represents 50% (Rieppo and Örn 2003, Väätäinen et al. 2005) while stem feeding time during processing accounts for 15% of the total harvesting time (Väätäinen el al. 2005).

Single grip harvesters mostly have a roller feeding mechanism. Currently there are a variety of feed rollers on the market, manufactured totally from steel or alternatively rubber-tyre rollers. Some harvester head manufacturers offer a harvester head with metal chain tracks for the feeding mechanism. Nilsson (1996) has successfully described the functionality of the feed roller for use in tree harvesting (Fig. 1): "When a tree is felled the tree trunk is inserted between feed rollers which clamp around the trunk on opposite sides thereof. The trunk is then trimmed by feeding the trunk through the harvester head with the aid of the feed rollers while limbing knives remove knots and branches from the trunk. In order to achieve a fully satisfactory trimming result, it is important that the feed rollers grip the trunk satisfactory. The steely feed rollers are equipped with studs, spikes or ribs which purpose is to penetrate through the bark and grip or bite into the surface wood of the log. The shape and length of them is important, so as to eliminate the risk of the slipping of the rollers". Also important is the optimal force with which the feed rollers clamp the log. This is achieved by setting the pressing force of the hydraulic cylinders, which clamp the feed rollers against the log, at the right level. Too low feed roller pressure causes bark loosening and damage on the wood surface as rollers slip. Too high pressure causes deep stud damage to the logs and also the log feeding can get stuck.

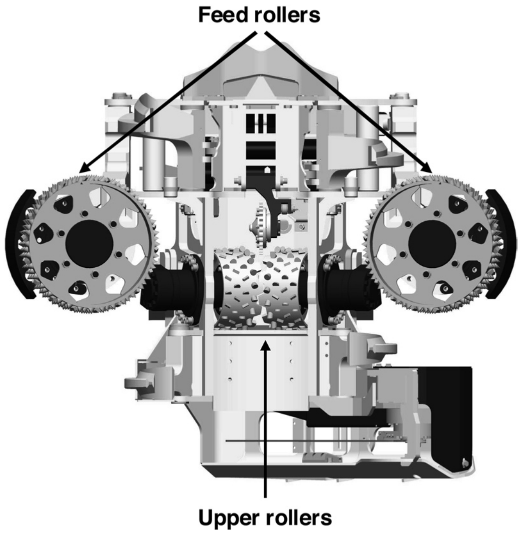

Fig. 1. Harvester head of a single grip harvester, perspective from underneath (Fig. Waratah Om).

The era of single grip harvesters started at the beginning of the 1980s when the first harvester head of this type was developed in Sweden by Sandahl and Pedersen (SP 21) and in Finland by Mononen (Finko) (Konttinen and Drushka 1997). Feed rollers' damage has existed since the introduction of the first steel rollers in the 1970s. During the period 1970 to 2000 numerous studies have been conducted about mechanical cuttings including those evaluating the metal or rubber feed roller mechanisms (Grönlund and Wiklund

1973, Lekander 1974, Mikkonen and Ylä-Hemmilä 1977, Mikkonen 1977, Melkko 1978, Mikkonen et al. 1979, Ylä-Hemmilä 1979, Mäkelä and Pennanen 1980, Nissi 1983, Helgesson and Lycken 1988, Mäkelä 1993, Lee and Gibbs 1996). However, these studies have mostly concentrated on the productivity and the terrain capacity of the harvesters and have presented limited results concerning feed rollers. The studies have concluded that the rubber rollers caused significantly less wood damage than metal rollers, however, their traction, especially in the sap wood season, was much worse (Mikkonen, et al. 1979, Ylä-Hemmilä 1979, Mäkelä 1993). Feed rollers have not been found to cause any significant timber value or material losses. In some studies blue stain infections have been found to lower timber quality as a secondary infection in the surface of wood damaged by feed rollers.

Recent studies, since 2000, relating to feed rollers have been made by Skogforsk (Sweden). Brunberg et al. (2006) carried out controlled studies on three types of steel feed rollers, to ascertain their productivity levels as well as damage caused by rollers. They found that feed rollers equipped with steel spikes caused the greatest damage, however, they also were more productive, though this did not compensate for the 3% reduction in value caused by the roller damage to the timber. Feed rollers with protective spacers and damper plates reduced the amount of damage considerably. Hallonborg et al. (2004) tested rubber-tyred rollers and steel rollers. The steel rollers exerted much better traction, however, the studs also caused much more damage to the timber. Jönsson and Hannrup (2007) found that the incidence of feed roller damage in Sweden has increased from 2001 to 2006. The main cause of this was the reintroduction of steel studs on the harvester feed rollers.

Deep damage caused by the feed rollers can reduce the yield of good quality timber for the sawmill and plywood industries. The biggest problems may be found at the tops of the veneer logs, especially for birch. Damage to the surface of the wood can create a breeding ground for blue-stain (Grönlund and Wiklund 1973, Mikkonen 1977, Mäkelä and Pennanen 1980, Kärkkäinen 2003) and if the effect of climate change increases then the blue-stain problem may worsen. Study results of Helgesson and Lycken (1988) and Lee and Gibbs (1996) showed that levels of blue-stain were significantly greater with machine harvested logs than when harvested with a chainsaw, this they found to correlate with the amount of bark loosened during harvesting. The use of spiked steel rollers resulted in more stain than when rubber rollers were used. The maximum recorded blue stain area was 10% of the wood surface. Barking and feed roller damage on the surface of the wood have been found to increase the drying of timber in the roadside storages which especially lowers the quality of the mechanical paper making process of spruce. On the other hand, Swedish and Finnish experiments (Lekander 1974, Mäkelä and Pennanen 1980) of mechanically harvested rough and smooth barked logs, that were marked by the teeth of feed rollers, found that they were free, or nearly so, from bark-beetle attacks. The effect is possibly due to drying-out of the bark between the tooth-marks caused by the rollers.

Previous studies concerning feed rollers have concentrated on damage and their impact on timber value, rollers' traction and operating and capital costs. No methodical comparisons have been conducted concerning the efficiency of different feed rollers which analyzes the volume of processed timber in a certain period of time. The time consumption material of this study was recorded using the automated data collector of a harvester which enabled highly detailed processing and fuel consumption comparison at a stem level between different roller types.

The feed rollers chosen in this study represent the most used steel roller types available on the market which are today dominating harvester cutting in Finland. *The objectives of this study were to compare the damages to sawlogs and the time and fuel consumption of stem feeding with six different steel feed rollers during the processing of stems using a single grip harvester.*

2 Material and Methods

2.1 Performance Study of Feed Rollers

In the study six different types of steel feed rollers were tested (Fig. 2): two small spike roll-

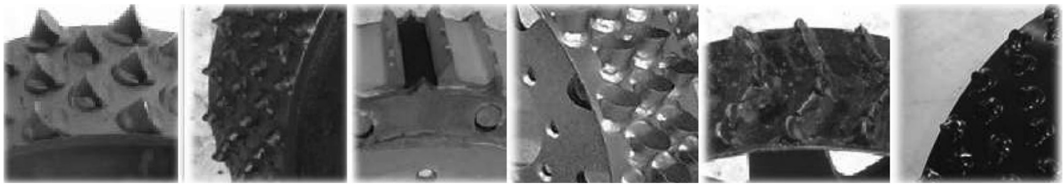

Fig. 2. The types of the six tested feed rollers. (Photos Kari Väätäinen and Heikki Tuunanen).

Table 1. The technical information of the studied feed rollers.

	Length of the spike or stud, mm			Roller's smallest diameter, mm	Acute angle of spike/stud, degrees	Depth of spike groove, mm	Diameter of spike/stud, mm
	Outer circle	Inner circle	Average				
Big spike 1	24	18	21	464	60	-	22
Small spike 1	14	14	14	464	60	-	16
Adaptable plate	15	15	15	470	-	4	-
Big spike 2	28	28	28	478	60	-	30
V-type stud	14	14	14	464	60/90	3.5	16
Small spike 2	14	14	14	464	60	-	16

ers (small spike 1 and small spike 2), two big spike rollers (big spike 1 and big spike 2), one roller with studs in V-angle (v-type stud), and one roller with adaptable steel plates on the ring of the roller (adaptable plate). Table 1 presents the technical information of the studied feed rollers. The performance study of feed rollers was conducted with a John Deere 1270 D Eco III harvester (equipped with a John Deere 758 head) by two experienced operators on 12–19th March 2007 in eastern Finland in four separate clear cutting areas. The sites were approximately 50 km north-east of the city of Joensuu, near the village of Sarvinki (62°41.672´N, 30°16.289´E). The base machine and the harvester head alike are designed for second thinnings and clear cuttings (John Deere 2008b). Before the start of the study, the cylinder pressure of each feed roller type was separately adjusted to within the optimal operating levels to ensure that the functioning of each roller type was suitable for cuttings. For controlling the cylinder pressure of the rollers, the penetration of the studs of the upper rollers into the wood surface was measured and compared (Fig. 1, Table 4). The harvester head's upper rollers were the same during the whole study. The damage caused by the feed rollers on the study logs were measured immediately after processing, before forest haulage. Because the temperature during the testing cuttings was in the range of 0 °C…+5 °C the study logs were not frozen. The proportion of tree species of the processed study stems was pine (*pinus sylvestris*) 12%, spruce (*Picea abies*) 49% and birch (*Betula pendula*) 39%. The average mercantile stem volume of the processed stems, per studied feed roller, was in the range of 0.21–0.38 m^3. The proportion of the processed stems mercantile volume which was less or equal to 0.4 m^3 per roller varied in the range of 62–81%.

2.2 Analysis of the Damage to the Logs

Depths of the roller damage and bark thickness of the study logs were measured from zones on the butt, in the middle and in the top of the logs by using an electronic penetration calliper (Fig. 3). Additionally the log diameter was measured in the same zones. From each measuring zone 3–4 damage depths, without bark, were taken, thus 9–12 penetrations were measured for each log.

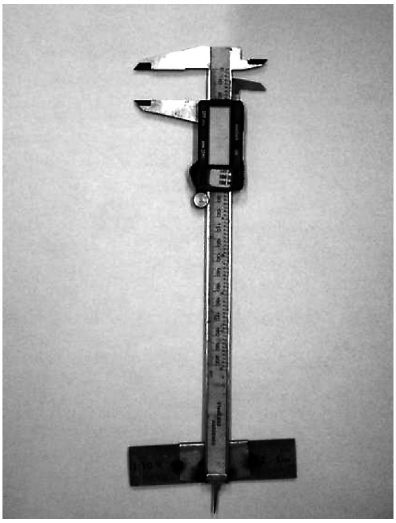

Fig. 3. Electronic penetration calliper for measuring the damage to the saw logs. (Photo Yrjö Nuutinen).

The length of each measuring zone was 20–30 cm. The measuring zones were first checked if they were unbarked or barked by delimbing knives of the harvester head. This was important because delimbing knives can bite into the surface wood before the feed rollers and, therefore, bark is not covering and protecting the wood surface from the rollers. Before measuring the damage, bark was mechanically removed from the stems by billhook without breaking the surface wood of the log. The thickness of the bark was measured separately at the same height of the log as the damage depths. A total of 20 logs, 6–7 pine, spruce and birch logs, were measured per roller type.

The damage caused by the roller v-type stud were measured for a second time (v-type stud reference) in the thinning stand where the average mercantile stem volume of the processed stems was 0.10 m^3, and 90%, of the processed stems were maximum mercantile volume of 0.2 m^3.

The spike of the penetration calliper (Fig. 3) did not always reach the bottom of the damage or penetrated too deep into the wood which would result in a measuring error. The possible error was checked by one control measurement in each measuring zone. Before the control measurement the damaged wood was removed until the bottom of the hole was clearly seen. Errors of the original measurements were corrected by regression analysis for each tree species. A total of 139 logs were measured for this study, with a total of 1416 damage depth measurements and 467 control measurements being taken. The diameter information of the study logs is presented in Table 2.

2.3 Analysis of Effective feeding time and the Fuel Consumption

In this study, machine functions and work elements of interest were feeding time during processing and fuel consumption during feeding. Processing time begins immediately after the final felling cut of the previous tree and ends when the operator lifts the harvester head to an upright position after the final cross-cut of the stem. Processing time includes delimbing and crosscutting of stem and pause times. Processing time and fuel consumption during processing of the 7400 studied stems were collected by using the TimberLink monitor-

Table 2. The diameters (mm) in the middle of 139 damage measurement study logs: average, minimum and maximum.

Roller	Pine	Spruce	Birch
Big spike 1	229 [186–300]	255 [183–335]	256 [203–342]
Small spike 1	272 [204–342]	258 [173–432]	266 [225–314]
Big spike 2	236 [182–323]	266 [189–351]	248 [205–302]
Adaptable plate	249 [179–337]	262 [188–352]	269 [200–391]
Small spike 2	299 [178–415]	255 [183–346]	259 [224–326]
V-type stud	245 [170–345]	256 [185–350]	241 [195–276]
V-type stud reference	219 [180–267]	233 [173–340]	215 [182–265]

ing system of the harvester functions developed by John Deere. TimberLink has been available as an option on all new John Deere harvesters since November 2005. It is a software which collects and processes data about the machine's condition and performance (John Deere 2008a).

For the time consumption models the working time of effective feeding was separated from the processing time. Effective feeding time excludes pause and cutting times. It is the pure feed time and it enables the study and comparison of the efficiency of the rollers without the operator effect. Fuel consumption was analyzed during the processing time. Effective feeding time and fuel consumption during the processing time were modelled using roller type and log amount per stem as categorical and mercantile stem volume as covariant variables. Figures presented in the results express the predicted values of regression models. Using the models, the estimates of each roller type and tree species were calculated for three mercantile stem volumes: small stems of volume 0.05 m^3, medium stems of volume 0.35 m^3 and large stems of volume 0.65 m^3. In this study mercantile stem volume is defined as industrial timber excluding the uncommercial top of the stem.

Independent modelling variables were formed so that they correlated maximally between dependent variables (effective feeding time and fuel consumption during processing time). To ensure the reliability of the models the final data to be analyzed was filtered and harmonized from the base data as follows:

– Fuel consumption per stem, which was recorded during the total processing time, was included in the modelling material only if the subtraction of the total feeding (processing) per stem and effective feeding per stem was less or equal to 2 seconds. This ensured that the fuel consumption corresponded with effective feeding time adequately.
– Stems which had more than 4 logs were excluded.
– Spruce and pine stems were selected with a mercantile volume of under 0.8 m^3, while for birch stems those with a mercantile volume of under 0.7 m^3 were chosen.
– Stems whose effective feeding time and fuel consumption values deviated more than three times the standard deviation from the arithmetic average were excluded (Ranta et al. 1994).

Table 3. The number of studied stems for fuel consumption and effective feeding time.

	Fuel consumption			
	Pine	Spruce	Birch	Total
Big spike 1	30	298	243	571
Small spike 1	73	261	53	387
Big spike 2	142	268	125	535
Adaptable plate	5	64	25	94
Small spike 2	174	699	1050	1923
V-type stud	79	589	189	857
Total	503	2179	1685	4367
	Effective feeding time			
	Pine	Spruce	Birch	Total
Big spike 1	30	301	246	577
Small spike 1	73	263	54	390
Big spike 2	143	269	129	541
Adaptable plate	5	64	25	94
Small spike 2	189	713	1082	1984
V-type stud	81	593	191	865
Total	521	2203	1727	4451

The total number of analysed stems was 4451, for effective feeding, and 4367 for fuel consumption during processing (Table 3).

Effective feeding time, seconds/stem, was calculated as a sum of effective feeding time of each log. Fuel consumption, l/mercantile-m^3/stem, was calculated by using the total fuel consumption [l/h] per stem during processing and the total sum of log volume [m^3] per processed stems. The following elements of recorded TimberLink data were used in the modelling:

Stem level:
– Roller: roller type.
– Stem number.
– Total fuel consumption per mercantile stem: recorded during total processing time. [0.0 l/h].
– Tree type: the harvester operator sets the tree type code.

Log level:
– Roller type.
– Stem number.
– Log number.
– Effective feeding time: harvester head is feeding the log forward or backwards, excluding bucking and pause times. [0.000 s].

– Volume: log volume, is recorded when the bucking starts. Log diameters are recorded as the rollers feed the log forward. [0.000 m^3].

3 Results

3.1 Damage to the Saw Logs

The roller adaptable plate averaged, for unbarked logs, the lowest damage of 3.7 mm, whereas damage caused by the roller big spike 1 were the deepest; with an average of 7.8 mm. The average of all rollers was 5.8 mm. Small spike 1 had the lowest damages of 1.79 mm, on average, for unbarked birch logs, while adaptable plate had the lowest values for pine (4.2 mm) and for spruce (4.3 mm) (Fig. 4). For the adaptable plate roller, 47% of the damages were in the depth of 3–5 mm while for the roller big spike 1 damages over 8 mm were dominant (54%). The damages of other rollers were mostly in the damage depth class of 5–8 mm (Fig. 5). The penetration of upper rollers were in the range of 5.1–6.9 mm, where big spike 1 had the highest value (Table 4).

The damages of different feed roller types on the unbarked sawlogs averaged, for birch, 1.79–6.0 mm, for spruce 4.3–8.7 mm and for pine 4.2–8.7 mm. The average damage depth of birch, for unbarked logs, was 3.7 mm and 5.8 mm for spruce and 5.5 mm for pine. The average bark thickness of birch, 8.6 mm, was 2.2 mm more than for pine and spruce. The damage caused by roller v-type stud to birch logs averaged 2.6 mm while the bark thickness for birch was, on average, 8.3 mm. Respective values of the reference measurements, in the thinning stand for v-type stud, were 5.2 mm and 6.2 mm (Fig. 4). For all rollers, and for unbarked logs, the proportion of damage of 5–8 mm was, on average, 39% while for over 8 mm the deep damages averaged 10% (Fig. 5). Respectively, values of barked logs were 25% and 61%.

3.2 Effective Feeding Time

The following model was estimated for the natural logarithm of effective feeding time of each tree species:

$$\begin{aligned}\ln(\text{Effective feeding time}) &= \text{Intercept} + \text{Roller}_i + \text{Logs per stem}_j \\ &+ b_1 * \ln(\text{Mercantile stem volume}) \qquad (1)\\ &+ b_{2j} * \text{Logs per stem}_j * \ln(\text{Mercantile stem volume}) \\ &+ b_{3i} * \text{Roller}_i * \ln(\text{Mercantile stem volume}) + \varepsilon\end{aligned}$$

where

ln(Effective feeding time) = natural logarithm of the effective feeding time,

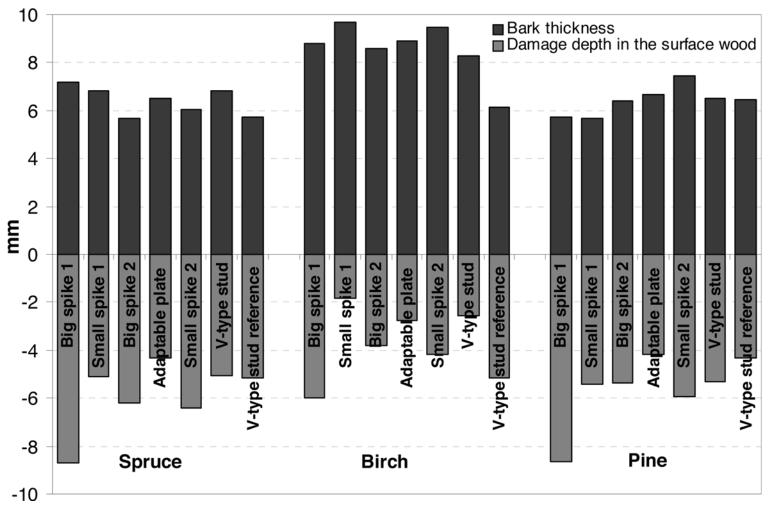

Fig. 4. Feed roller damages and bark thickness of spruce, pine and birch for unbarked saw logs.

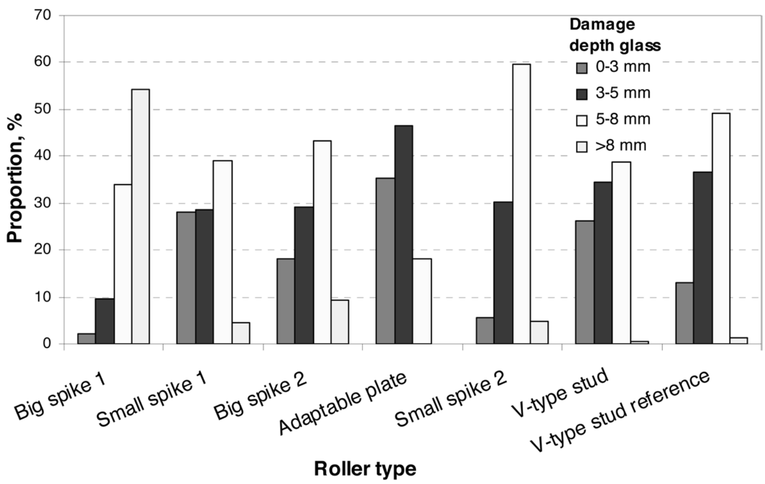

Fig. 5. Damage depth classes of feed rollers for unbarked saw logs.

Roller_i = roller type, $i = 1,2,3,4,5,6$,
Logs per stem_j = the number of logs per stem, $j = 1,2,3,4$,
ln(Mercantile stem volume) = natural logarithm of the mercantile stem volume and
ε = residual term.

It was assumed that the residuals are independent and normally distributed and their variance is homogenous. The statistical coefficients of Model 1 are presented in Table 5.

Example regarding the combination of the estimated effective feeding time using Model 1:

Roller = big spike 2, Logs per stem = 3, Tree species = spruce, Mercantile stem volume = 0.35 m^3,
ln(Mercantile stem volume) = –1.0498
ln(Effective feeding time) = 2.363 + 0.028 + (–0.134) + [0.245 + 0.025 + 0.010] * –1.0498 = 1.9631
exp(1.9631) = 7.12 seconds/stem

Fig. 6 shows the estimated effective feeding time of spruce and birch. Due to the insufficient amount of data for pine (Table 3), estimated values of feeding time (Fig. 6) and fuel consumption (Fig. 8) per stems were not presented. Effective feeding time was mostly dependent on mercantile stem volume and secondly on the amount of logs per stem. The effective feeding time of pine and spruce did not differ significantly from each other where the average time consumption for the smallest one log stems, of 0.03 m^3, was less than 2 seconds, while for the biggest 4 log stems of 0.8 m^3 it was 9–11 seconds per stem. For birch the estimated value of effective feeding time was clearly the longest, up to 13 seconds for the biggest 4 log stems of 0.7 m^3 (Fig. 6).

For small stems of 0.05 $m^3$when the amount of logs increased from 1 to 2, the effective feeding time increased the most; by about 60%. For big birch stems of 0.65 m^3, when the amount of logs increased from 3 to 4, the increase was 25% (Fig. 7), while for spruce the increase was 16% and for pine 15%.

Table 4. The penetration of upper rollers compared to feed rollers, mm, on unbarked saw logs. Small spike 2 had no upper roller measurements.

Feed roller type	Upper roller penetration, mm	Feed roller penetration, mm
Big spike 1	6.9	7.8
Small spike 1	5.1	4.2
Big spike 2	5.4	5.2
Adaptable plate	5.4	3.7
Small spike 2	-	5.5
V-type stud	6.0	4.8
V-type stud reference	5.7	4.4

Table 5. Statistical information of regression Model 1 for effective feeding time, sec/stem. Dependent variable: natural logarithm of the effective feeding time. Independents: roller type and log amount per stem as categorical and natural logarithm of the mercantile stem volume as covariant variables. B = Regression coefficient. Sig. = significance for the coefficient or an effect.

Parameter		Pine N = 521, R^2 = 0.919			Birch N = 1727, R^2 = 0.876			Spruce N = 2203, R^2 = 0.905	
	B	Std. Error	Sig.	B	Std. Error	Sig.	B	Std. Error	Sig.
Intercept	2.397	0.038	0.000	2.694	0.049	0.000	2.363	0.026	0.000
Roller			0.322			0.000			0.001
[Roller = Big spike 1]	–0.072	0.066	0.274	–0.232	0.055	0.000	0.064	0.028	0.021
[Roller = Small spike 1]	0.042	0.048	0.382	–0.032	0.077	0.679	–0.018	0.033	0.577
[Roller = Big spike 2]	0.057	0.043	0.189	0.054	0.055	0.325	0.028	0.034	0.411
[Roller = Adaptable plate]	0.070	0.123	0.569	0.136	0.142	0.336	0.145	0.060	0.015
[Roller = Small spike 2]	0.057	0.048	0.242	–0.094	0.042	0.024	0.079	0.024	0.001
[Roller = V-type stud]	0 [a)]			0 [a)]			0 [a)]		
logs per stem			0.000			0.000			0.000
[logs per stem = 1]	–1.323	0.134	0.000	–1.213	0.070	0.000	–0.907	0.061	0.000
[logs per stem = 2]	–0.495	0.082	0.000	–0.725	0.063	0.000	–0.549	0.051	0.000
[logs per stem = 3]	–0.138	0.052	0.008	–0.266	0.058	0.000	–0.134	0.038	0.000
[logs per stem = 4]	0 [a)]			0 [a)]			0 [a)]		
ln(Mercantile stem volume)	0.265	0.032	0.000	0.418	0.037	0.000	0.245	0.019	0.000
*logs per stem * ln(Mercantile stem volume)*			0.000			0.000			0.000
[logs per stem = 1] * ln(Mercantile stem volume)	–0.170	0.043	0.000	–0.193	0.040	0.000	–0.052	0.023	0.026
[logs per stem = 2] * ln(Mercantile stem volume)	–0.071	0.039	0.069	–0.187	0.040	0.000	–0.077	0.025	0.002
[logs per stem = 3] * ln(Mercantile stem volume)	–0.001	0.038	0.988	–0.104	0.041	0.010	0.025	0.025	0.330
[logs per stem = 4] * ln(Mercantile stem volume)	0 [a)]			0 [a)]			0 [a)]		
*Roller * ln(Mercantile stem volume)*			0.225			0.000			0.000
[Roller = Big spike 1] * ln(Mercantile stem volume)	–0.017	0.034	0.619	–0.083	0.021	0.000	0.039	0.011	0.001
[Roller = Small spike 1] * ln(Mercantile stem volume)	0.023	0.031	0.468	–0.057	0.035	0.100	–0.002	0.013	0.862
[Roller = Big spike 2] * ln(Mercantile stem volume)	0.024	0.027	0.375	0.001	0.024	0.977	0.010	0.013	0.457
[Roller = Adaptable plate] * ln(Mercantile stem volume)	0.203	0.171	0.236	0.106	0.110	0.334	0.090	0.035	0.010
[Roller = Small spike 2] * ln(Mercantile stem volume)	0.040	0.026	0.126	–0.023	0.018	0.194	0.051	0.009	0.000
[Roller = V-type stud] * ln(Mercantile stem volume)	0 [a)]			0 [a)]			0 [a)]		

[a)] This parameter is set to zero because it is redundant.

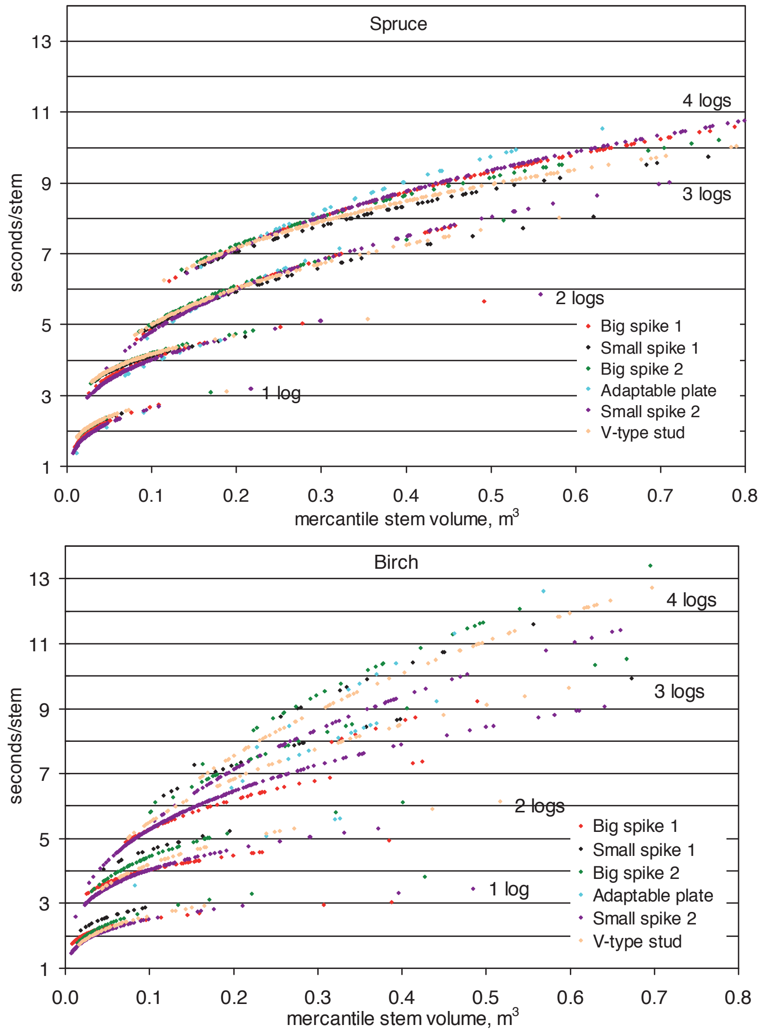

Fig. 6. Estimated effective feeding time of spruce and birch (Model 1).

The maximum difference between feed rollers regarding effective feeding time, when comparing the minimum value to maximum value, was biggest for birch: for small stems 29%, for medium stems 19% and for large stems 24%. For spruce the difference was smallest and varied between 6–11%. The feed rollers had also statistically significant influence on the effective feeding time averages of the rollers for birch and spruce (Table 5).

For pine, spruce and birch small stems, of volume of 0.05 m^3, the adaptable plate roller had the shortest effective feeding time; the difference compared to the slowest roller type was, for spruce stems of 2 logs, 11% (compared to big spike 2), 29% (compared to small spike 1) for birch and 41% (compared to v-type stud) for pine. For medium stems, of volume 0.35 m^3, the differences between rollers decreased: For spruce stems of 4 logs the fastest roller (small spike 1) was 6% faster than the slowest (adaptable plate). While for pine the most effective, adaptable plate, was 16% faster than the slowest, big spike 2. For birch big spike 1 was 19% faster than the slowest,

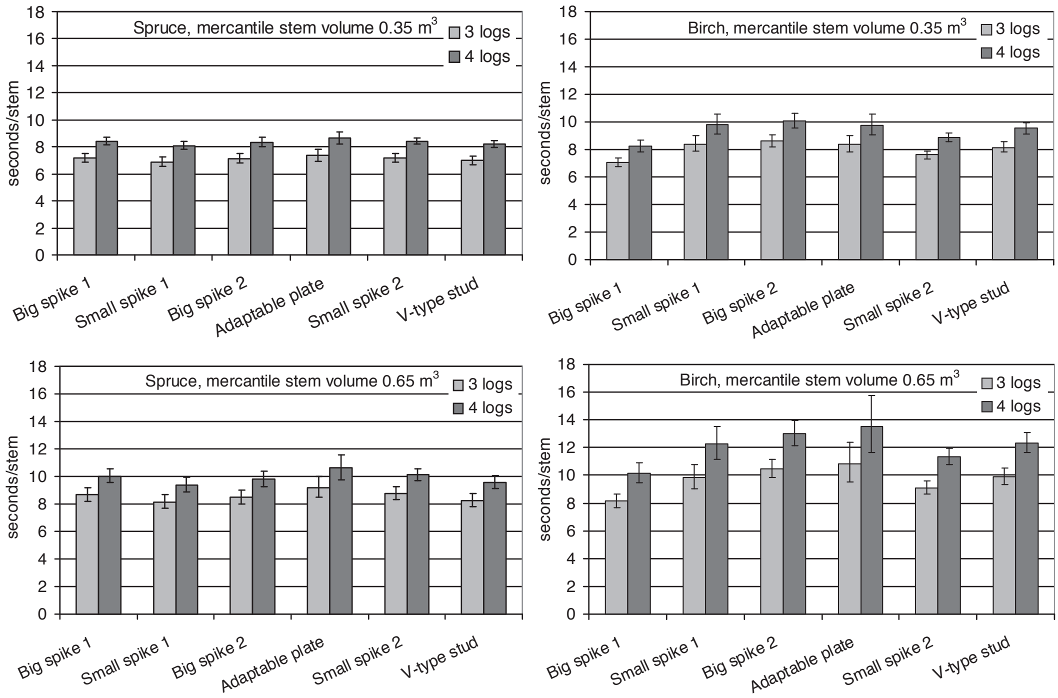

Fig. 7. Estimated effective feeding times of feed rollers for medium (0.35 m^3) and large (0.65 m^3) spruce and birch stems, sec/per stem. Line segments identify the 95% confidence levels (Model 1).

big spike 2. When processing large spruce stems, of stem volume 0.65 m^3, the fastest roller (small spike 1) was, for 4 log stems, 11% faster than the slowest, adaptable plate. Time consumption of roller big spike 1 was the smallest for large pine and birch stems: the difference was 11% for 4 log pine stems compared to the slowest, big spike 2, and compared to adaptable plate 24% for birch (Fig. 7).

3.3 Fuel Consumption

The following model was estimated for the natural logarithm of fuel consumption during processing of each tree species:

$$\begin{aligned} \ln(\text{Fuel consumption during processing}) &= \text{Intercept} + \text{Roller}_i + \text{Logs per stem}_j \\ &+ b_1 * \ln(\text{Mercantile stem volume}) \\ &+ b_{2j} * \text{Logs per stem}_j * \ln(\text{Mercantile stem volume}) \\ &+ b_{3i} * \text{Roller}_i * \ln(\text{Mercantile stem volume}) + \varepsilon \end{aligned} \tag{2}$$

where

ln(Fuel consumption during processing) = natural logarithm of the fuel consumption during processing,

Roller_i = roller type, $i = 1,2,3,4,5,6$

Logs per stem_j = the number of logs per stem, $j = 1,2,3,4$

ln(Mercantile stem volume) = natural logarithm of the mercantile stem volume and

ε = residual term.

It was assumed that the residuals are independent and normally distributed and their variance is homogenous. The statistical coefficients of the model 2 are presented in Table 6.

Example regarding the combination of the estimated fuel consumption during processing using Model 2:

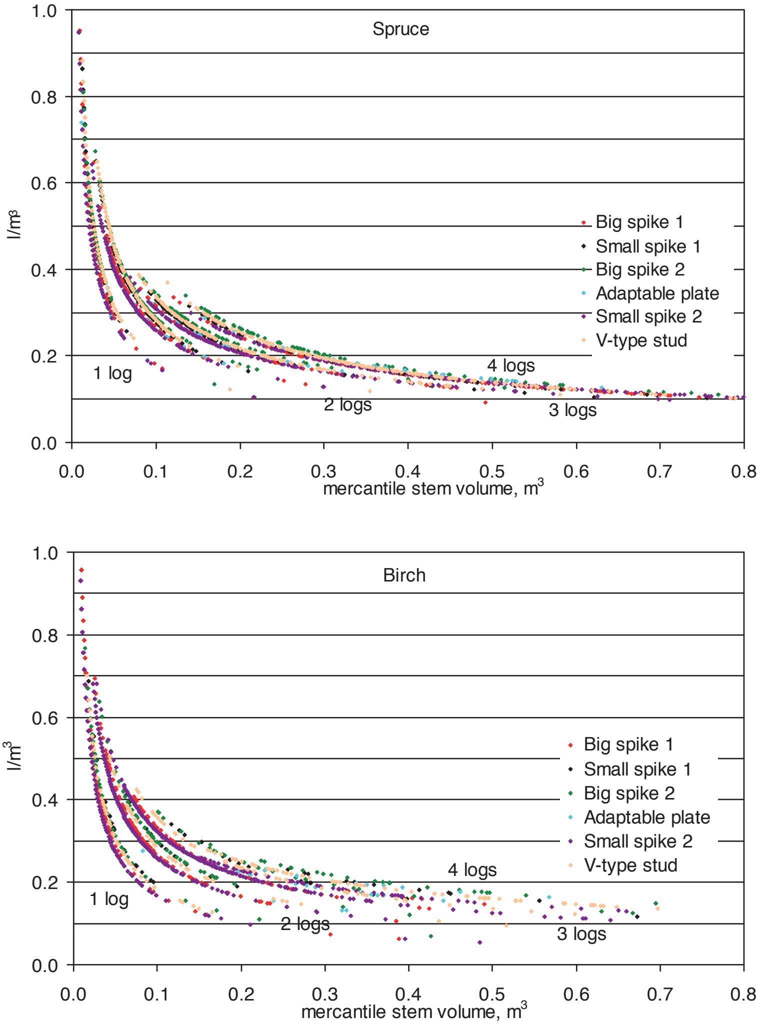

Fig. 8. Estimated fuel consumption during processing time for spruce and birch (Model 2).

Roller = big spike 2, Logs per stem = 3, Tree species: spruce, Mercantile stem volume = 0.35 m^3,
ln(Mercantile stem volume) = –1.0498
ln(Fuel consumption during processing) = –2.438 + 0.071 + (–0.103) + [–0.665 + 0.034 + 0.023] * –1.0498 = –1.8317
exp(–1.8317) = 0.16 l/m^3

Fig. 8 shows the estimated fuel consumption during processing of spruce and birch. Fuel consumption per processed stem was in the range of 0.1–0.6 l/m^3 depending on the mercantile stem volume. Fuel consumption of pine, birch and spruce starts to increase rapidly when the stem volume decreases under 0.2 m^3/stem. Birch had the highest fuel consumption level.

For small stems, of 0.05 m^3, when the number of logs increased from 1 to 2 the fuel consumption, during processing, increased at most by about 50%. For large birch stems, of 0.65 m^3, when the amount of logs increased from 3 to 4 the fuel consumption increase was 25%, while for spruce it was 13% and 15% for pine (Fig. 9). The maximum differences between fuel consumption of the feed rollers, when comparing the minimum

Table 6. Statistical information of regression Model 2 for fuel consumption during processing, l/m^3. Dependent variable: natural logarithm of the fuel consumption during processing. Independent variables: roller type and log amount per stem as fixed factors and natural logarithm of the mercantile stem volume as covariant. B = Regression coefficient. Sig. = significance for the coefficient or an effect.

Parameter	Pine N = 503, R^2 = 0.913			Birch N = 1685, R^2 = 0.830			Spruce N = 2179, R^2 = 0.880		
	B	Std. Error	Sig.	B	Std. Error	Sig.	B	Std. Error	Sig.
Intercept	–2.491	0.040	0.000	–2.170	0.053	0.000	–2.438	0.027	0.000
Roller			0.472			0.014			0.088
[Roller = Big spike 1]	0.033	0.071	0.638	–0.111	0.059	0.059	0.001	0.029	0.975
[Roller = Small spike 1]	0.078	0.052	0.131	0.019	0.083	0.819	–0.021	0.034	0.535
[Roller = Big spike 2]	0.085	0.047	0.067	0.098	0.059	0.098	0.071	0.035	0.044
[Roller = Adaptable plate]	0.063	0.130	0.630	0.156	0.151	0.302	0.105	0.062	0.092
[Roller = Small spike 2]	0.090	0.052	0.086	–0.066	0.045	0.146	0.034	0.025	0.167
[Roller = V-type stud]	0 a)			0 a)			0 a)		
logs per stem			0.000			0.000			0.000
[logs per stem = 1]	–1.316	0.143	0.000	–1.204	0.075	0.000	–0.869	0.064	0.000
[logs per stem = 2]	–0.479	0.091	0.000	–0.633	0.069	0.000	–0.419	0.055	0.000
[logs per stem = 3]	–0.135	0.056	0.016	–0.244	0.062	0.000	–0.103	0.040	0.010
[logs per stem = 4]	0 a)			0 a)			0 a)		
ln(Mercantile stem volume)	–0.671	0.034	0.000	–0.488	0.040	0.000	–0.665	0.020	0.000
logs per stem * ln(Mercantile stem volume)			0.000			0.000			0.003
[logs per stem = 1] * ln(Mercantile stem volume)	–0.189	0.046	0.000	–0.242	0.044	0.000	–0.055	0.024	0.025
[logs per stem = 2] * ln(Mercantile stem volume)	–0.062	0.042	0.144	–0.186	0.044	0.000	–0.027	0.026	0.305
[logs per stem = 3] * ln(Mercantile stem volume)	0.004	0.040	0.912	–0.113	0.044	0.011	0.034	0.027	0.198
[logs per stem = 4] * ln(Mercantile stem volume)	0 a)			0 a)			0 a)		
*Roller * ln(Mercantile stem volume)*			0.029			0.277			0.000
[Roller = Big spike 1] * ln(Mercantile stem volume)	0.044	0.037	0.230	–0.017	0.023	0.451	0.028	0.012	0.017
[Roller = Small spike 1] * ln(Mercantile stem volume)	0.047	0.034	0.165	–0.012	0.038	0.753	0.000	0.013	0.997
[Roller = Big spike 2] * ln(Mercantile stem volume)	0.039	0.030	0.188	0.024	0.026	0.342	0.023	0.014	0.100
[Roller = Adaptable plate] * ln(Mercantile stem volume)	0.138	0.181	0.448	0.127	0.117	0.279	0.076	0.036	0.035
[Roller = Small spike 2] * ln(Mercantile stem volume)	0.088	0.029	0.002	0.015	0.019	0.440	0.053	0.009	0.000
[Roller = V-type stud] * ln(Mercantile stem volume)	0 a)			0 a)			0 a)		

a) This parameter is set to zero because it is redundant.

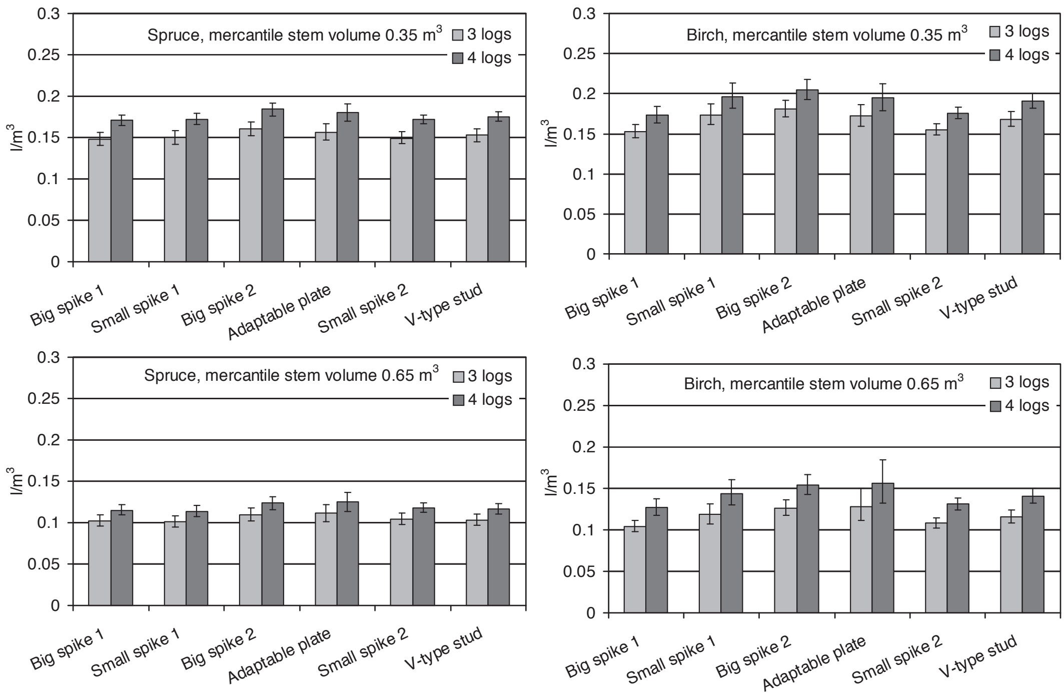

Fig. 9. Estimated fuel consumptions of feed rollers during processing for medium (0.35 m^3) and large (0.65 m^3) spruce and birch stems, l/m^3. Line segments identify the 95% confidence levels (Model 2).

value to maximum value, were found for birch with a range of 15–25%, depending on the mercantile stem volume. The respective differences for pine were 6–30% and for spruce 7–12%. The feed rollers only had statistically significant influence on the fuel consumption averages of the rollers during processing for birch (Table 6).

Fuel consumption for the adaptable plate roller was lowest for small stems, of volume 0.05 m^3: for small, 2 log, stems the difference compared to the highest value was 12% for spruce (compared to big spike 2), 24% for birch (compared to small spike 1) and 30% for pine (compared to v-type stud). For medium stems, of volume 0.35 m^3, and large stems, of volume 0.65 m^3, the differences between rollers decreased. Adaptable plate had the smallest fuel consumption also for the medium pine stems: for stems of 4 logs the difference was 12% compared to the highest value of big spike 2. For medium spruce stems, the difference between the lowest value of big spike 1 and the highest value of big spike 2 was 7%. Furthermore, for medium size birch stems, roller big spike 1 was the most effective roller with 15% difference compared to the highest value of big spike 2. For large spruce stems (of volume 0.65 m^3) of 4 logs the least fuel consuming roller was small spike 1, for pine v-type stud and for birch big spike 1 with differences of 9%, 6% and 19% compared to the ones consuming the most fuel (Fig. 9).

The influence of different feed roller types on fuel consumption can be demonstrated by fuel consumption of each roller type for processed volume of 30000 m^3 which represents one year cutting performance of a harvester in Finland (Table 7). The fuel consumptions were estimated (Model 2) using the coefficients of Table 6. In the calculations the proportion of spruce and birch was assumed to be 6:4, with the mercantile stem volume for spruce being 0.112 m^3 and 0.065 $m^3$for birch, which were the median volumes of the study material. All stems were processed into two logs. The lowest total fuel consumption,

Table 7. The estimated (Model 2) fuel consumptions (l) during processing of different feed rollers for total harvester cutting of 30 000 m^3. The stem volume for spruce 0.112 m^3 and for birch 0.065 m^3, two logs per each processed stem.

Feed roller type	Birch, 12 000 m^3	Spruce, 18 000 m^3	Total, 30 000 m^3
Big spike 1	4355	4255	8610
Small spike 1	4748	4549	9296
Big spike 2	4735	4833	9568
Adaptable plate	3878	4266	8143
Small spike 2	4102	4364	8466
V-type stud	4538	4814	9352

8143 l, for the adaptable plate roller was 15% less than the maximum value of big spike 2. For birch the lowest value, adaptable plate, was 18% less than the highest fuel consumption of small spike 1. For spruce the least consuming roller was big spike 1 with 12% difference compared to the most, big spike 2.

4 Discussion

In this study the field work was done in late winter, when the air temperature was above 0 °C. Bark peeling is at its highest during the sap season when it is approximately three times higher compared to the rest of the year which would increase the feed roller damage. In winter when the air temperature is below freezing the barking is lowest which protects the surface wood against roller damage (Liiri et al. 2003, 2004). The base machine and the harvester head were well suited to the size of the processed timber and the terrain conditions of the performance study conducted in clear cuttings. The cylinder pressures for each feed roller type were set at a level where cutting could be conducted efficiently. This was necessary because each roller type has its own optimal level of log feeding pressure, which varies according to their technical characteristics. Also the pressures must be adjusted when changing each feed roller to another harvester head type. In our study the harvester and the head was the same for all tested rollers. The stud penetration of the upper feed rollers did not differ significantly during the processing for each of the studied feed rollers (Fig. 1, Table 4). Only the stud penetration of upper rollers during the performance study of big spike 1 was a bit deeper, which indicated higher pressures than the other rollers.

The number and dimensions of the logs, for damage measurements, were comparable for rollers and tree species (Tables 2, 3). Furthermore, the errors of depth measurements on the logs were calibrated with control measurements. The recorded TimberLink study data for highly detailed processing and fuel consumption projection provided accurate data for analyses. Additionally the amount of recorded stems gave reliable data for estimating the models. However the amount of pine stems was statistically insufficient for analyzing the roller with adaptable plates (Table 3). Study data was gathered from one single grip harvester operated with two operators in limited study conditions. A well known fact is the substantial influence of the main working factors, such as operator, machine and environment, on the general work output, particularly in mechanised loggings (Väätäinen et al. 2005, Kariniemi 2006, Ovaskainen 2009). Therefore generalisation of the study results' absolute values, such as effective feeding time and fuel consumption during processing per each feed roller type, is relatively limited. Nevertheless, the proportional differences among feed rollers by the studied features could be generalised to the practice more reliably.

According to this study it can be concluded that the traditional rollers with spikes were the most effective in processing and fuel consumption, but at the same time they caused the deepest damage to the sawlogs. Roller type with adaptable steel plates was the most effective for small stems, in addition it caused less damage to the logs. Big spike 1 was the most effective roller for medium and large birch stems as well as for large pine stems. However, at the same time the damage caused by big spike 1 to the sawlogs were the deepest. Small spike 1 was the most effective for medium and big spruce stems. Small spike 2 was the second most effective for birch stems for all stem sizes. The depth of damage caused by small spike 2 was the second deepest for pine and spruce, after big spike 1. The thickness of bark had a direct influence on the damage to the logs: due to its thicker bark the damage to birch logs were lower than for pine and spruce. This was clearly recognizable for the roller v-type stud in the thinning stand (v-type stud reference) for birch, where the damage compared to clear cut stand, were, on average, 2.6 mm deeper and the bark thickness 2.1 mm less (Fig 4).

The damage caused by big spike 1 was as a result of the simultaneous influence of high spike length (Table 1) and big roller pressure (Table 4). Despite of the second highest pressure force (Table 4) of v-type stud the damage was almost at same level as the lowest damage of adaptable plate and small spike 1. Roller v-type stud, with its studs at a v-angle, had the smallest studs compared to other rollers. This indicates that the deepness of the damage is dependent simultaneously on the shape and the length of the spikes or studs and the force with which they penetrate the surface wood.

The effective feeding time differences between feed rollers will have a significant influence on the total cutting time: for medium stems, of mercantile volume 0.35 m^3, the range of differences between the maximum and minimum of the estimated effective feeding time per roller was 6–19% which would increase the effective time consumption of cutting by 1–3%. Similarly there were significant differences between maximum and minimum fuel consumptions of the feed rollers' estimated consumption levels. Most of the time fuel consumption increased simultaneously with the increase of effective feeding time: the slowest rollers had the highest fuel consumption. Also fuel consumption per m^3 increased when processing smaller stems. In the comparison of the feed rollers' fuel consumption for stem processing of annual cutting of a harvester (Table 7) the difference between the lowest fuel consumption and the highest was 15%. The difference converted into total cutting in Finland in 2006 of 50.8 million m^3 (Finnish Forest Research Institute 2007) would be 2 413 000 l of fuel, costing about 2 million € (fuel price of January 2009). Rieppo and Örn (2003) found that in Finland a 5% decrease in fuel consumption significantly reduces, by 5 million €, the cost of logging operations and long distance transport. The results of the study also showed that the proportion of processing is over half of the fuel consumption of the cutting work as a whole.

Brunberg et al. (2006) tested three types of feed rollers which were similar to the ones used in this study: v-type stud, small spike 2 and adaptable plate. The average damage on the processed logs in the measurements by Brunberg et al. (2006) were, on average, 19% less for pine and 42% less for spruce than in this study. In both performance studies roller pressures were adjusted to within the operable level for each feed roller type. In the study of Brunberg et al. (2006) the measuring technique was different than the one used in this study. The measuring of the damage was conducted in both studies when the logs were not frozen. However, the study of Brunberg et al. (2006) was conducted in May, in the sap season, when the level of barking is at its highest. In this study the field work was made in late winter with the air temperature being just above freezing point. The differences between the studies could be partly explained by the different bark thickness on the studied logs, information of which was not available in the study of Brunberg et al. (2006). The probable main reasons for this kind of significant and systematic differences were the different cylinder pressures of the feed rollers, the peeling level of bark caused by delimbing knives and the influence of different measuring techniques.

The biggest differences were found when comparing the results of the adaptable plate roller where the damage measured by Brunberg et al. (2006) was 36% lower for pine and 53% lower for spruce. In our study the damage to pine were, on average, 8% lower than for spruce. However, in the study of Brunberg et al. (2006) the damage to spruce was 22% lower than for pine. The results of Brunberg et al. (2006) agreed with our results that the rollers with spikes caused the deepest damage to the logs, however, at the same time their performance was slightly higher (2%) than for the other roller types. Additionally the damage caused by the adaptable plate roller was found to be clearly the lowest.

In the study of Hallonborg et al. (2004) the damage levels of the spiked rollers were at the same level than in our study. In autumn 2003, they tested four different types of feed roller for single grip harvesters: two rubber tyred rollers and two steel rollers. The productivities of both steel rollers were at the similar levels and were approximately 30% higher than for the rubber tyred rollers. The steel rollers exerted heavy traction but the spikes also damaged the timber, on average, to a depth of more than 5 mm. 89% of the damage of the steel roller type with spikes of 15 mm were deeper than 5 mm. In our study roller type small spike 1, with 14 mm spikes, had 44% of its damage of more than 5 mm and small spike 2, also with 14 mm spikes, 65%.

Athanassias et al. (1999) found that the fuel consumption of single grip harvesters in Sweden for thinnings and clear cuttings was, on average, 1.167 l/m^3. The material of their study represents approximately 5% of the total volume cut in Sweden in 1996. In the study of Rieppo and Örn (2003) the average fuel consumption in Finland of volume cut of 64 000 m^3 of single grip harvesters was, on average, 0.87 l/m^3. Furthermore, in the study of Rieppo and Örn (2003) the fuel consumption of a single grip harvester increased from 0.71 l/m^3 to 1.15 l/m^3 (+62%) when the stem volume lowered from the volume class 0.25–0.45 m^3 to class 0.1–0.25 m^3. In our study, the fuel consumption started to rapidly increase when the stem volume decreased to under 0.2 m^3/stem. In the study of Rieppo and Örn (2003) the average fuel consumption of medium size harvester in clear cuttings, with an average stem volume of 0.45 m^3, was 0.64 l/m^3.

The results of our study showed that the efficiency of different feed roller types varies depending on the size and tree species of processed stems. This should be taken into account case by case when choosing the optimal feed rollers in different cutting types, varying from first thinnings with small size trees to big sized final fellings.

Firm bark cover in processed logs diminishes the stud damage of steel feed rollers during processing. Bark thickness varies between tree species, in different parts of the stems and according to tree size. Therefore appropriate adjustments of the harvester head are essential for minimizing the damage to the timber. Liiri et al. (2004) found that keeping delimbing knives sharp and using optimal compression pressures in knives and rollers will lead to lower barking in cuttings. Also the harvester operators' craftsmanship was found to have a significant influence in lowering the barking. In order to minimize the damage caused by the feed roller the pressure levels of the rollers and knives should be as low as possible without causing any restrictions to the work.

This study revealed the importance of improving the cost- and energy efficiency of feeding work element. Study results confirmed and complemented the previous knowledge about feed roller damage on the surface wood of sawlogs. More exact research information would be needed regarding the placement of the damages in different parts of the stems. The deepest damage in the top of the log is a bottleneck for the saw log industry. The acceleration period at the beginning of stem feeding causes the most roller pressure against the butt of the log therefore is the largest risk area for the most damage. Moreover, the degree of damage should be clarified in different seasons when the peeling and elasticity of bark varies.

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