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ORIGINAL PAPER

In-stand debarking with the use of modified harvesting heads: a potential solution for key challenges in European forestry

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Abstract

Modern forestry is increasingly confronted with challenges that appear with intensive forest management and the progression of the effects of climate change. The forestry sector is able to react to the changing conditions by adapting management plans, forest structure or planting tree species with a higher stress resistance. However, during stand management activities, silvicultural treatments and harvesting operations can have an impact on the further development of the remaining forest ecosystem. In Germany, the most widely used harvesting system for thinning operations is a single-grip harvester used for felling and processing trees followed by a forwarder for timber extraction from the machine operating trails to roadside. In this research project, debarking rollers and other modifications designed for Eucalyptus harvesting heads were tested on conventional harvesting heads for the first time to assess the possibility of adding debarking to mechanized forest operations under Central European conditions. Seven field tests with varying tree species, diameters and age classes, were established within German state forests in Lower Saxony and in Bavaria. These tests were repeated in both summer and winter seasons to evaluate the influence of associated tree sap flows on debarking quality. Three different harvesting heads were modified to assess the altered mechanical characteristics and setups. To assess debarking ability originating from head modifications, a photo-optical measurement system developed within the scope of the project was used. The results demonstrate that especially for summertime operations, simple modifications to currently used harvesting heads are able to provide an average debarking efficiency up to 90% depending on the modifications. Another key finding is that a negatively affected sap flow, experienced during wintertime operations, resulted in 46% lower debarking efficiency, while spruce bark beetle infestations only resulted in a wider spread of the variation. Additionally, the vertical position of the log within the tree proved to have an influence on debarking efficiency, resulting in 15% lower average debarking for butt logs and 9% for top logs as compared to middle logs. Since a debarking process requires the stem to be fed through the harvesting head on multiple occasions to remove bark, average harvesting productivity might be reduced by approx. 10% compared to productivity measured with conventional harvesting heads. Considering the results and the extent of the modifications, the system proved to be a potential addition to existing harvesting methods facing changing challenges in future forestry.

Keywords Debarking · Single-grip harvester · Forest operations · Norway spruce · Scots pine · Bark beetle · Sustainability · Nutrients · European forestry

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Introduction

In times of climate change and uprising biotic (insects, fungi, pathogens) and abiotic (fire, drought, storms, snow, nutrient/soil exploitation) threats to the European forests (Holuša et al. 2017; Irauschek et al. 2017; Seidl et al. 2017) and the intensified utilization of forest resources (Weis and Göttlein 2012), modern forestry needs to be flexible and proactive in finding new solutions. A promising approach to address several of the above-listed challenges might be the return to a once broadly established practice—in-stand debarking.

Debarking of logs remains an essential work task within the value chain of timber processing industries. All sectors of the wood industry share the same commonality as the wood needs to be debarked before it can be processed into further products (Baroth 2005; Gerasimov and Karjalainen 2006). This particular stem-debarking process went through a major development from manual debarking within the stands to fully mechanized debarking facilities located directly at wood processing industries. Furthermore, distribution channels for the remaining bark were established to create additional value instead of raising costs for waste disposal (Kupferschmid 2001). Despite the technical achievements of debarking logs at the processing facilities, debarking harvested wood directly in the forest stand offers multiple benefits as well, if the bark remains within the forest ecosystem.

The main benefits of in-stand debarking are:

- In context with an intensified utilization of forest biomass, nutrients located in the bark are remaining within the ecosystem and become available to the residual forest stand (Hopmans et al. 1993; Weis and Göttlein 2012; Nieminen et al. 2016; Yan et al. 2017)
- Log mass and volume are reduced through the removal of the bark, and the subsequent exposure of the wood surface entails a higher drying rate as compared to barked logs (Heppelmann et al. 2019a). These changes in mass and volume result in a lower wood humidity and therefore again less mass that needs to be transported. Depending on the species, a threefold increase in drying rate was measured when comparing 0% debarked and 100% debarked wood (Defo and Brunette 2005; Röser et al. 2011)
- In-stand debarking can play a major role when considering forest health and spruce bark beetle (*Ips typographus*) prevention. This is especially the case for windthrow operations, as the layer between the bark and wooden body is the breeding habitat, which can be removed or destroyed by debarking the logs (Schroeder and Lindelow 2002; Thorn et al. 2016; Irauschek et al. 2017). The urgency for new spruce bark beetle preventative treatments is highlighted by the fact that within the Bavarian state forests, over 710,000 m^3 had to be harvested in 2017 as a result of spruce bark beetle infestations. This affected volume accounted for 15% of the total annual harvest (BaySF 2018)
- Burning debarked wood produces less ash remains and fine dust emissions compared to barked wood, reducing problems within the thermal utilization of wood. (Werkelin et al. 2005)

Occurring negative effects of in-stand debarking can be summarized as:

- Increased complexity of material handling due to the rather slippery wood surface of stems immediately after harvesting and debarking
- Removal of the protective bark layer, thus exposing the surface of stems to contaminants such as soil or fungi
- The utilization of bark as a source of secondary products (e.g., chemical products (Kofujita et al. 1999), gardening products, fuel for drying chambers, fuel for heating and power plants (Päivinen et al. 2012) is limited.

To reintroduce debarking as part of the harvesting process, a method of combining debarking with modern and highly mechanized operations was sought. Similarities with the harvesting systems in Eucalyptus plantations all over the world (Brazil, South Africa, Australia, New Zealand, etc.) showed a potential solution. In Eucalyptus plantations, most of the harvesting is performed with single-grip debarking harvesting heads that are mounted on excavator-based or wheeled-based harvesters. As the harvested wood is destined to be distributed into the pulp and paper industry, the bark needs to be completely removed. Since the bark of Eucalyptus trees sticks tightly onto the wooden body as the felled trunks begin to dry out, debarking during the processing phase is the preferred method.

Since over 60% of the German wood harvest is performed with fully mechanized systems and the most common harvesting system focuses on single-grip harvesters and forwarders, the question was raised if harvester-based debarking might also be practicable for central European forests based on the model of Eucalyptus plantations (BaySF 2018). Therefore, a research project was initiated to investigate the potential and general feasibility of this system. To maintain operational flexibility and lower costs, the project focused on modifying conventional harvesting heads (with modification costs limited to 10,000 €) to provide them with debarking ability instead of utilizing purpose-built Eucalyptus harvesting heads (costs up to 90,000 €). Within this approach, it was essential to establish a benchmark of the achievable debarking results with the most reasonable effort.

Within the scope of the project, the following research questions were under review:

(1) Determine which type of technical modifications and operational procedures are required to adapt conventional harvesting heads and provide them with debarking ability.
(2) Perform field tests to evaluate and quantify the debarking percentage achieved with different modification setups being operated on spruce and pine trees during both summer and winter seasons.
(3) Obtain a general overview of harvesting productivity between conventional and modified harvesting heads.

Materials and methods

Machinery, harvesting heads and modifications

The focus of the project was directed at modifying conventional harvesting heads on harvesters currently used by German forest entrepreneurs. Prior to modifications and field tests, a market study was performed to identify suitable harvesting heads. Apart from the technical compatibility of assuring a match between the harvesting head and the harvester and the use of the appropriate on-board computer operating software (Timbermatic, MaxiXplorer, Opti4G, Dasa, etc.), three of the largest manufacturers of cut-to-length wood harvesting technology on the German market were selected (Table 1). The combination of harvesting head and harvester will be referred to as Setup 1 (S1), Setup 2 (S2) and Setup 3 (S3).

The three harvesting heads tested were technically modified in order to achieve a debarking effect within the harvesting process. Modifications were performed with the support of machine manufacturers and were limited to the use of existing parts. In this regard, attempts were made to minimize the complexity of modifications in order to limit the conversion costs and were therefore mostly focused on the replacement of feed rollers.

The replacement of conventional feed rollers (Fig. 1a) with debarking rollers (Eucalyptus rollers) forces the felled tree to rotate along its longitudinal axis within the harvesting head during the processing phase, thus allowing the delimbing knives and the feed rollers themselves to remove bark on the entire stem surface. In addition, the blade-like edges on the feed rollers ensure a cutting of the bark layer into sections and a slight lift from the wooden body, thus enabling the delimbing knives to slip below the bark layer. Most common debarking rollers can be divided into two traction-type sub-categories: single-edge and diamond-shape. The S1 and S2 harvesting heads were modified with single-edge rollers (Fig. 1b), while S3 used the hybrid diamond-shape system (Fig. 1c). Hereby, a normal series of full-length splines are alternating with a series of splines with edges, which can increase traction in the forward and backward thrust, but lowers the rotational frequency of the logs (Fig. 1c).

To prevent damage of the measuring wheel through the occurring lateral force and to improve the measurement accuracy, measuring wheels were also replaced on the S1 and S3 prototypes with wider and less aggressive wheels. The S3 prototype was further modified with the addition of improved top and upper delimbing knives. All modifications are illustrated in Fig. 2. Besides these technical modifications, harvesting head software settings referring to feed pressure, knife pressure, feed speed, pressure curves, pitch angle of the delimbing knives and length measurement calibration had to be addressed. Those settings depended on tree species and dimensions as well as

Table 1 Harvesters and harvesting heads studied

	Setup 1	Setup 2	Setup 3
Harvester	John Deere 1270E	TimberPro 620E	Ponsse ScorpionKing
Harvesting head	John Deere H480C	Log Max 7000C	Ponsse H7

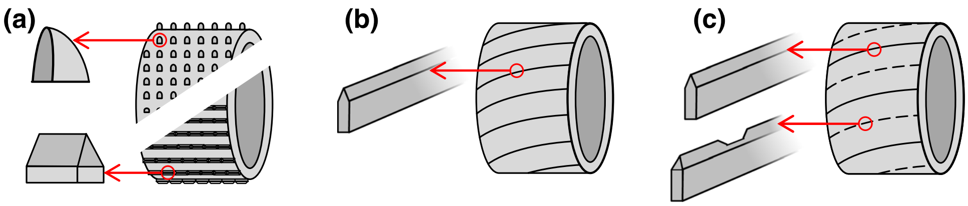

Fig. 1 Different traction types of feed rollers with **a** conventional spike rollers without debarking effects or abilities, **b** single-edge debarking roller, used within the S1 and S2 tests, **c** diamond-edge debarking rollers, used within the S3 tests

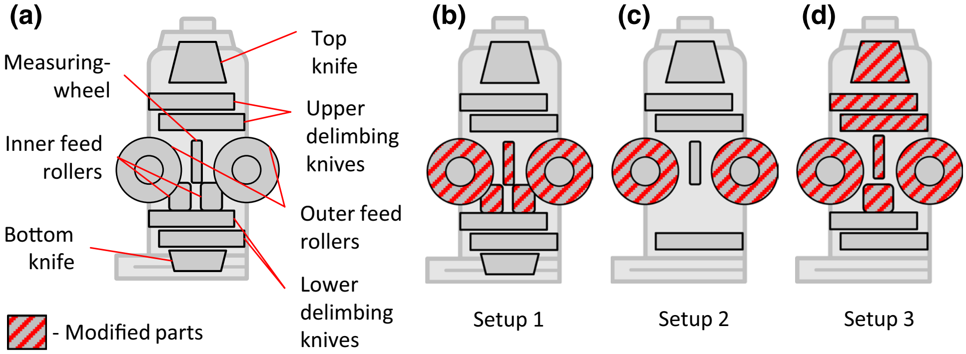

Fig. 2 Modifications performed on the three different harvesting head prototypes with **a** general overview of modifiable parts of conventional harvesting heads, **b** tested S1 modifications (inner and outer feed rollers, measuring wheel), **c** tested S2 modifications (feed rollers), **d** tested S3 modifications (inner and outer feed rollers, measuring wheel, upper delimbing knives, top knife)

machine type and were therefore adjusted individually for each machine and at every harvest site.

Following hardware and software modifications, the actual process of wood harvesting needed to be altered with an additional step: after the tree was felled, it was fed in its complete length forward and back (steps 1 and 2) through the harvesting head. At the same time, the trunk was spinning on its own longitudinal axis and the bark and branches were being removed during the first pass and only bark during the second pass. Crosscutting the delimbed stem into assortments (step 3) occurred at the end of the harvesting process during a third pass. Within the field trials, operators were instructed to consistently apply the above-mentioned process (steps 1–3), in order to obtain comparable results for all harvesting operations within the seven field trials.

Study design and stand characteristics

Seven field tests were established in Lower Saxony and Bavaria within Germany (Fig. 3). Tests were repeated in both summer and winter seasons to evaluate the influence of associated tree sap flows on debarking quality. In total, 1720 debarked Norway spruce and Scots pine logs (976

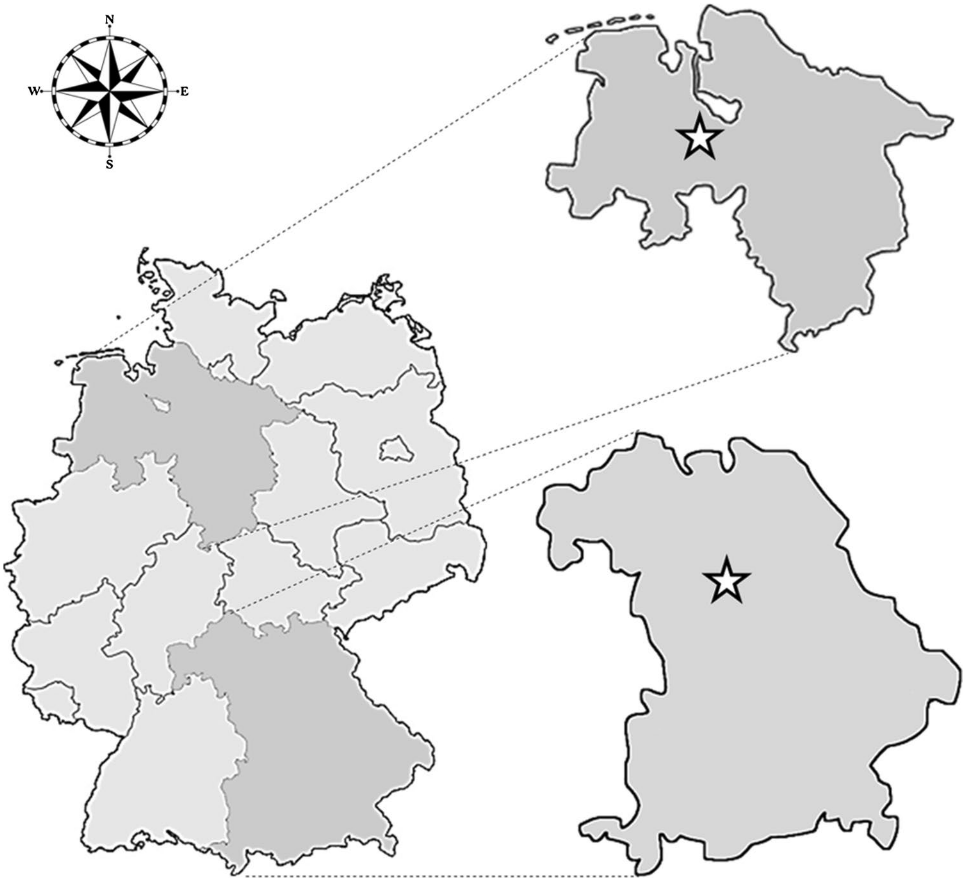

Fig. 3 Test sites located within Germany: Harpstedt 52°57′32.3″N, 8°38′46.7″E, northern Germany (Lower Saxony); Kipfenberg 48°52′43.1″N, 11°17′08.7″E, southern Germany (Bavaria)

logs in summer operations and 744 in winter operations) originating from about 400 trees were investigated. Summer and winter seasons were defined according to the German Meteorological Service (DWD)—winter: from December 01 to February 28/29; summer: from June 01 to August 31.

The test sites provided different stand characteristics and conditions (Table 2). For the first test runs, optimal tests sites and conditions (species, stem diameter and tree form) for the investigated harvesting heads were chosen to determine whether modifications performed on commonly used harvesting heads could provide debarking ability. Due to its strong apical dominance and associated straight growth structure in combination with its high importance for the German forestry sector (annual softwood harvest accounts for 76% of the total harvested wood in Germany in 2017 (Statistisches Bundesamt 2018), the focus was set on the Norway spruce (*Picea abies* L. H. Karst) and Scots Pine (*Pinus sylvestris* L.).

Due to the harvesting guideline of the Bavarian State Forests in summer 2017 (only harvesting of bark beetle-infested wood), the S2 and S3 summer field tests had to be performed in spruce bark beetle-infested stands. Therefore, pine was not present within those particular field trials.

The S3 winter is listed as a winter test, but due to delays of machine and stand availability, the test run was carried out at the end of April and the sap flow was partly established. Therefore, S3 winter needed to be considered as an intermediate/spring test and was thereby excluded from further investigations relating debarking percentages to season.

Field sampling and equipment

After the trees were harvested and processed with the respective head configurations, each single log was registered and tagged with a number plate that was inserted into the wood at the end surface of the log. Individual logs could therefore be linked to a specific tree and position (e.g., butt log, mid log, top log). Overall, an average of 245 logs per field test (originating from 55 trees) were assessed. After processing and tagging, logs were forwarded to a nearby forest road or landing area with a forwarder where they were unloaded and randomly

Table 2 Basic stand characteristics presented by operation

Operation	Location	Tree species composition	DBH	Age
Setup 1 summer I	Lower Saxony	Mixed coniferous stand—mainly Scots pine mixed with Norway spruce and silver birch (*Betula pendula* Roth)	15–20 cm	35
Setup 1 winter	Lower Saxony	Mixed coniferous stand—mainly Scots pine mixed with Norway spruce	15–25 cm	50
Setup 1 summer II	Lower Saxony	Pure coniferous stand of Scots pine	25–30 cm	70
Setup 2 winter	Bavaria	Mixed coniferous stand—mainly Norway spruce mixed with Scots pine and larch (*Larix decidua* Mill.)	30–35 cm	65 (50–105)
Setup 3 winter[a]	Bavaria	Mixed coniferous stand—mainly Norway spruce mixed with Scots pine and larch	30–35 cm	65 (50–105)
Setup 2 summer[b]	Bavaria	Pure coniferous stand of Norway spruce	25–40 cm	30–100
Setup 3 summer[b]	Bavaria	Pure coniferous stand of Norway spruce	25–40 cm	30–100

[a]Intermediary test performed in April, [b]Norway spruce bark beetle treatments

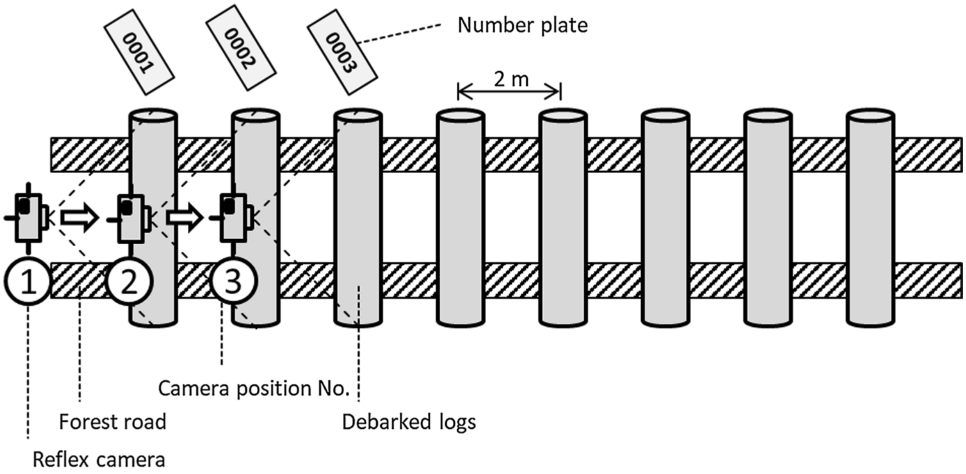

Fig. 4 Schematic showing the positioning of logs placed on a forest road ready for picture acquisition

Table 3 Infestation index with associated average surface moisture content (wet basis)

Index value	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Value 7	Value 8
Average surface moisture content	100%	99–90%	89–80%	79–70%	69–60%	59–50%	49–40%	39–30%

placed in a parallel fashion perpendicular to the forest road with an approximate spacing of 2 m between logs (Fig. 4). At the forest road, the diameter at both ends (mm accuracy) and the length of each log (cm accuracy) were recorded with a caliper and measuring tape. Logs varied between 2.4 and 5.4 m in length, and diameters ranged from 8.0 to 54.7 cm. Following these measurements, a single picture per log (broadside) was taken with a reflex camera mounted on a tripod set at a height of 1.50 m above ground (Heppelmann et al. 2019b). The camera was moved after every picture and relocated to the next log.

Bark beetles and associated pathogens often have a direct influence on the sap flow of the infested tree (Kirisits and Offenthaler 2002; Wullschleger et al. 2004). To evaluate the intensity of spruce bark beetle infestations in the S2 and S3 summer field tests, the sap flow was examined by measuring the moisture content of the log surface directly after the debarking process with a contact moisture meter, using the invasive-electrical resistance method to determine the proportional water content (wet basis). Therefore, the surface moisture content was measured on three logs per tree originating from different heights (butt log, mid log, top log). Those three measurements were taken to calculate an infestation index ranging from 1 to 8, where an unaffected sap flow equaled 1 (control group with 100% moisture content) and a completely interrupted sap flow (almost dead tree) equaled 8 with an average surface moisture content of 39–30% (fiber saturation point) (Table 3).

To obtain a general overview of the technical performance, harvester data from the on-board computer (OBC) were gathered and analyzed. Due to time and logistics constraints and because of the secondary importance of productivity in this particular article, harvesting productivity for the debarking configuration was performed by an associated project partner and focused on the S1 summer test where most trees harvested were Scots pine (avg. dbh of 15–20 cm, age of 35). As a benchmark, harvesting productivity of the same machine, operator and harvesting head under conventional settings was obtained from a stand of very similar dimensions and species composition. In addition to OBC reports, two video cameras were mounted inside the harvester cabin and on the boom and were both aimed at the harvesting head to acquire video footage of the entire operation of the S1 summer test. The footage could be viewed in the office whenever questions arose concerning specific trees. The required time for debarking was calculated by subtracting the average processing time with debarking minus the average processing time without debarking (Eq. 1):

$$T_{\text{deb}} = T_{\text{Operation+Debarking}} - T_{\text{Operation}} \tag{1}$$

Debarking percentage

Once in the office, debarking percentage was evaluated with a computer software solution that was developed within the scope of the project (Stemsurf). With the digital pictures of logs as input, the software used polygons to define debarked areas and calculated the total debarking percentage for the log using the additional measured physical values (diameter and length) (Heppelmann et al. 2019b). The polygons were delineated manually and defined either as wood, bark, inner bark, covered, or not measurable. The inner bark was multiplied by a factor of 0.5 as it indicated partial debarking. Due to distortion, pixels located toward both extremities and the upper and lower sides of the stem were also subjected to a factor as the pixel described more surface than a pixel located in the middle of the log. Therefore, the curvature and distortion were also taken into account by considering this effect within the Stemsurf algorithm (Heppelmann et al. 2019b). The debarking percentage was calculated as (Eq. 2):

$$\text{Percent debarking} = 100\% - \left(X\%_{\text{Bark}} + \left(Y\%_{\text{Inner-bark}} \times 0.5\right)\right) \tag{2}$$

Statistical analyses

IBM SPSS Statistics version 24 (SPSS) was used to perform the statistical tests and evaluations. Kolmogorov–Smirnov (KS) tests were performed to verify the data for normal distribution, besides the optical evaluation via Q–Q plots and histograms. KS tests showed that for most of the datasets, a normal distribution was not present. Particularly for the summer tests, this is due to the limitation at a 100% debarking percentage. Therefore, Levene's test was carried out to test the homogeneity of variances and to check for the possibility of using *T* test to investigate the significant differences. As those tests appeared to be negative as well, it was decided that for all evaluations, parametric tests (ANOVA with Tamhane and Dunnet T3 post hoc) were performed. Both the Tamhane and Dunnet T3 post hoc tests were chosen as they are particularly tailored for datasets without the homogeneity of variances. The decision to perform parametric tests was based on the information from latest publications that parametric tests can deliver robust results even when the assumption of normal distribution is violated (Norman 2010) as long as the database is large enough to calculate with the asymptotic significance. According to Norman (2010), a sample size of 5 up to 10 per group is sufficient to calculate robust results even for non-normal and asymmetric distributions. The present sample sizes for statistical calculations exceeded this requirement often to a high extent, depending on the calculation. The sample size is therefore presented throughout the investigated results. However, to crosscheck the results on significant differences between the investigated data groups, additional nonparametric Kruskal–Wallis tests followed by a pairwise comparison were performed to ensure that the parametric test results were robust and plausible.

Results

Effect of machine type and season on debarking efficiency

An overview of the full dataset, subdivided sequentially according to the field tests, showed many significant differences between single field tests (Fig. 5). The most prevalent difference in debarking percentage appeared between the summer and winter tests resulting in a statistically lower average debarking efficiency (46%) in wintertime as compared to summer operations. In this overall result, S3 winter test was not included in the winter data because it was considered an intermediary trial.

Based on a one-way ANOVA followed by Tamhane and Dunnet T3 post hoc tests, significant differences between the single machine setups during the summer season were detected. When considering summer operations, the highest debarking percentage (90%) was achieved within the S1 summer II test, whereas the lowest debarking percentage (73%) and the highest amount of variation were experienced during the S2 summer tests. Both further summer tests, S1 summer I and S3 summer, performed similarly with an average debarking percentage of 84%.

Significant differences were also present within the winter tests. Average debarking percentage varied between 35% for S2 winter and 54% for S1 winter, thus equaling a 56% increase in debarking efficiency in favor for S1 winter. With an average debarking percentage of 83%, the intermediary test S3 winter performed on par with the S1 summer II and S3 summer tests.

Effect of species and season on debarking efficiency

To determine whether tree species influenced debarking efficiency, debarking results within the S1 tests were investigated separately (Fig. 6). The S1 field tests were chosen, as sufficient trees of both species were harvested under comparable conditions during summer and winter seasons. A one-way ANOVA showed no statistical difference between the debarking efficiency of spruce and pine for summer operations. With 87%, the achieved average debarking percentage was similar for both species. Conversely, a significant difference was detected between the average debarking percentages of pine and spruce during winter operations. Average debarking percentage varied between 43% for spruce and

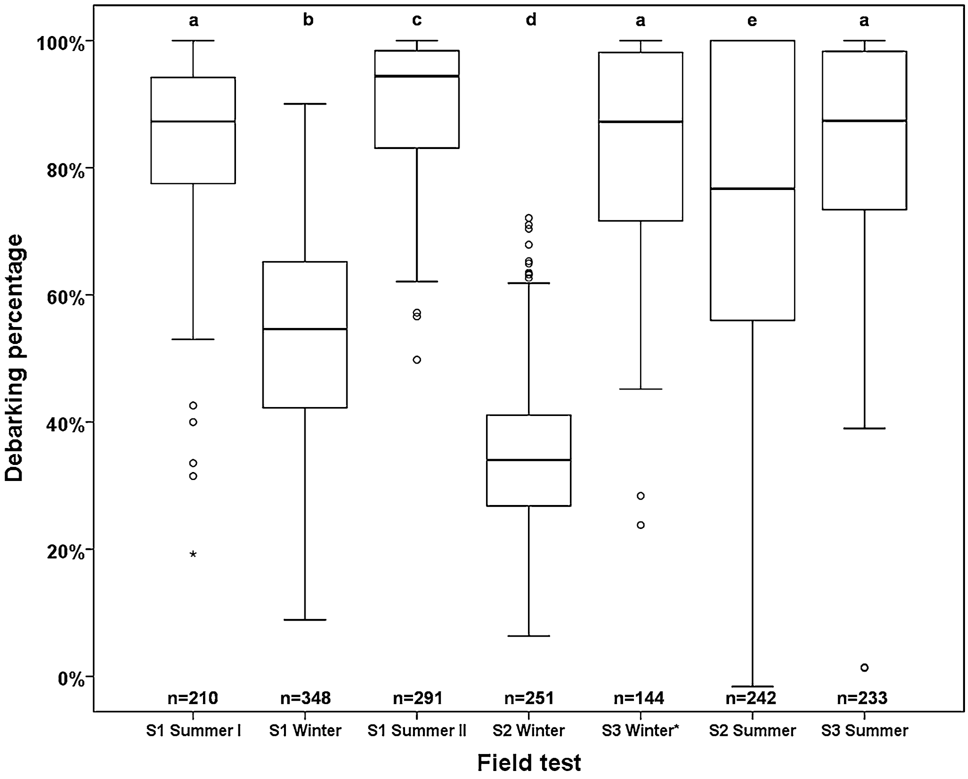

Fig. 5 Overview of all measured debarking percentages within the different field tests (pine and spruce species combined). S1—Setup 1; S2—Setup 2; S3—Setup 3. S3 Winter* represents the Setup 3 intermediate/spring test (April)

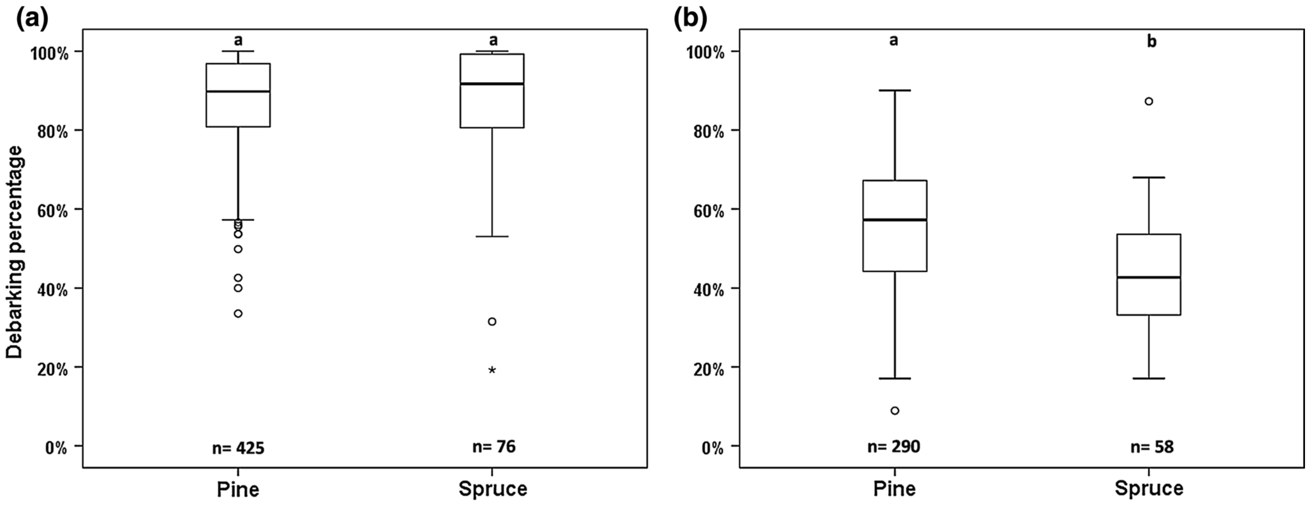

Fig. 6 Measured debarking percentages for spruce and pine subdivided in **a** summer and **b** winter test for the S1 debarking database

55% for pine, thus equaling a 24% higher average debarking efficiency favoring pine in winter operations.

Effect of log diameter, species and season on debarking efficiency

To examine whether log diameter had an influence on debarking efficiency, diameter categories were established in 5 cm increments and the associated debarking percentages clustered. A one-way ANOVA showed significant differences between the mean debarking percentages for pine in summer (Fig. 7a). The average debarking percentages illustrate an inverse parabola with the maximum debarking efficiency of 91% occurring at diameter 20–25 cm and significantly lower debarking results of 79% observed at 10–15 cm. The average debarking percentage tended to be lower when large stem diameters were encountered, particularly during summer operations (Fig. 7a, b).

Debarking spruce during summer operations resulted in the highest debarking percentage (82%) occurring for 30–35 cm log diameter, but also lower debarking percentages for both small and large diameters with 70% for 10–15 cm and 78% for 40–45 cm (Fig. 7b). The differences within the debarking percentages were not statistically significant.

For winter operations, pine showed a comparable trend with lower average debarking percentages to both extremities of the diameter range and the maximum for medium diameters (Fig. 7c). At both extremes, lower average debarking percentages were measured at 39% for 5–10 cm and 56% for 20–25 cm compared to the maximum of 57% for log diameters of 15–20 cm. However, according to a one-way ANOVA, only the difference between the smallest diameters compared to the rest of the dataset can be considered as significant.

Within winter spruce operation, log diameter had no significant influence on the debarking efficiency (Fig. 7d). The average debarking percentages ranged between 38 and 32%. Nevertheless, it was noticeable that for summer operations and pine winter operations, the debarking percentages tended to decrease for smaller and larger diameters resulting in a considerably lower average debarking percentage for those diameter classes compared to the measured maximum.

Effect of log positioning in tree, species and season on debarking efficiency

Visual observations during the field tests hinted that for butt logs and top logs the debarking efficiency tended to be lower. To investigate this assumption, logs were clustered according to their vertical position in the tree (Fig. 8) where B refers to a butt log, M_x to a middle log and t to a top log. A one-way ANOVA followed by post hoc tests revealed significant differences between the average debarking percentages of butt logs (62%) compared to the middle logs (73%) of the same trees, thus resulting in a 15% lower average debarking percentage for butt logs (Fig. 8a–d). This effect was stronger in summer than in winter operations and more prevalent for pine than for spruce. Similar to the butt logs, the top logs also showed lower average debarking efficiency (66%) when compared to middle logs, resulting in a 9% lower average debarking percentage.

Influence of spruce bark beetle infestation on debarking efficiency

Statistical calculations showed no clear trend toward lower debarking percentages for spruce with rising sap flow for

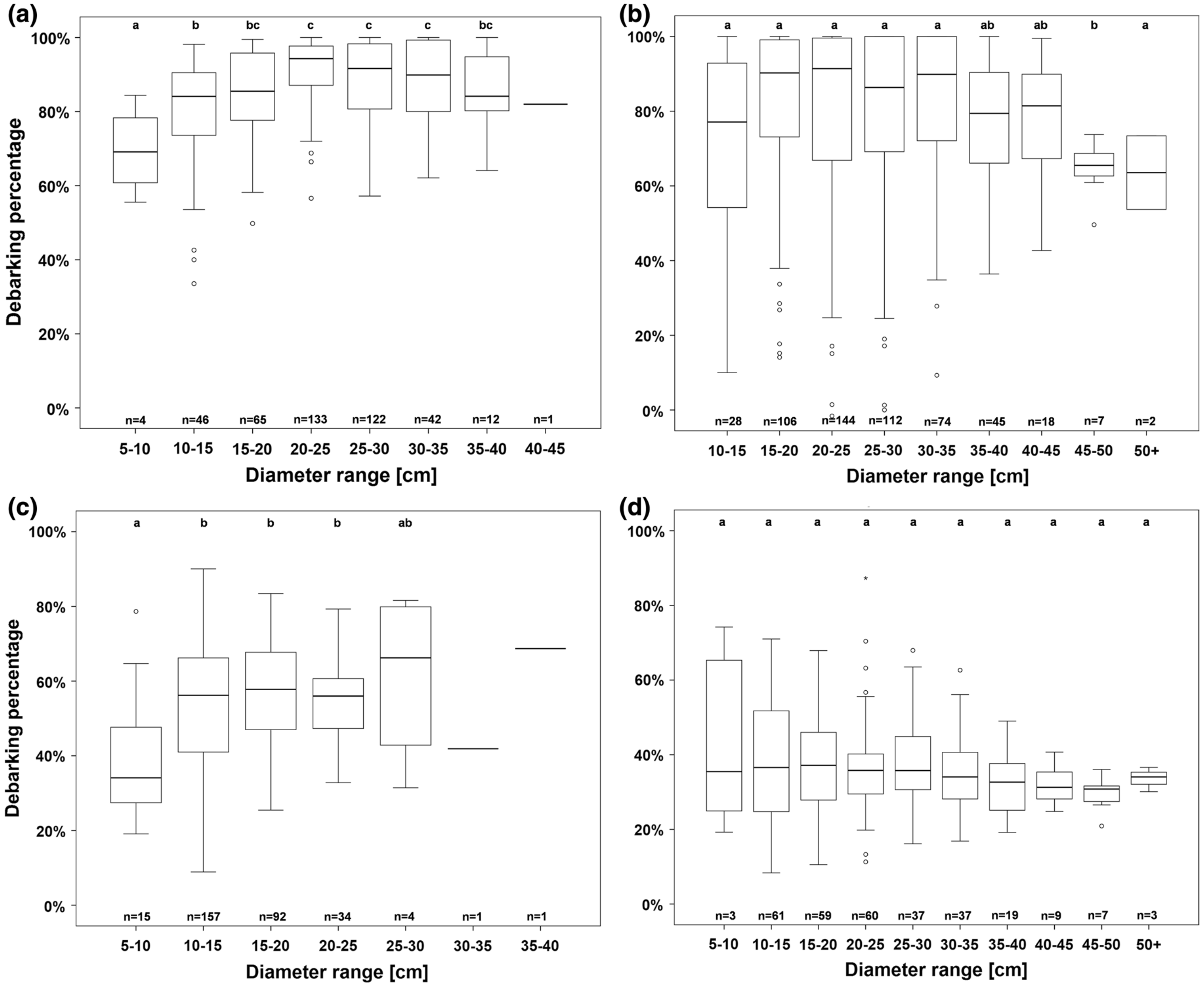

Fig. 7 Overview of the measured debarking percentages by 5-cm log diameter categories and species/season according to: **a** pine summer, **b** spruce summer, **c** pine winter and **d** spruce winter tests

both investigated setups (S2 and S3) linked to bark beetle infestations (Fig. 9). Debarking results improved as infection level increased, reaching the maximum debarking efficiency at category 6 showing a higher average debarking percentage compared to the control group (category 1). The trend seemed similar for both tested setups, with one exception: the variance of measured debarking percentages was similar for both control groups. However, the spread of variance was higher for the S2 prototype resulting in a lower overall debarking percentage (Fig. 9a). The lowest average debarking percentage was detected for trees of category 8 as also the variance of debarking percentages increased for both tested setups.

Harvesting productivity

To estimate harvesting productivity loss and the associated additional costs, OBC data were collected for (1) harvester and conventional harvesting head; (2) harvester with modified harvesting head applying debarking as part of the hardware and harvesting process. Average harvesting productivity was calculated for pine trees in summertime over a quantity of 227 m^3 with the conventional head and with 461 m^3 for the debarking configuration. Comparing the main work cycle elements, processing time was higher for harvesting operations with debarking, while a higher share of other activities (manipulation, operational delays, non-operational

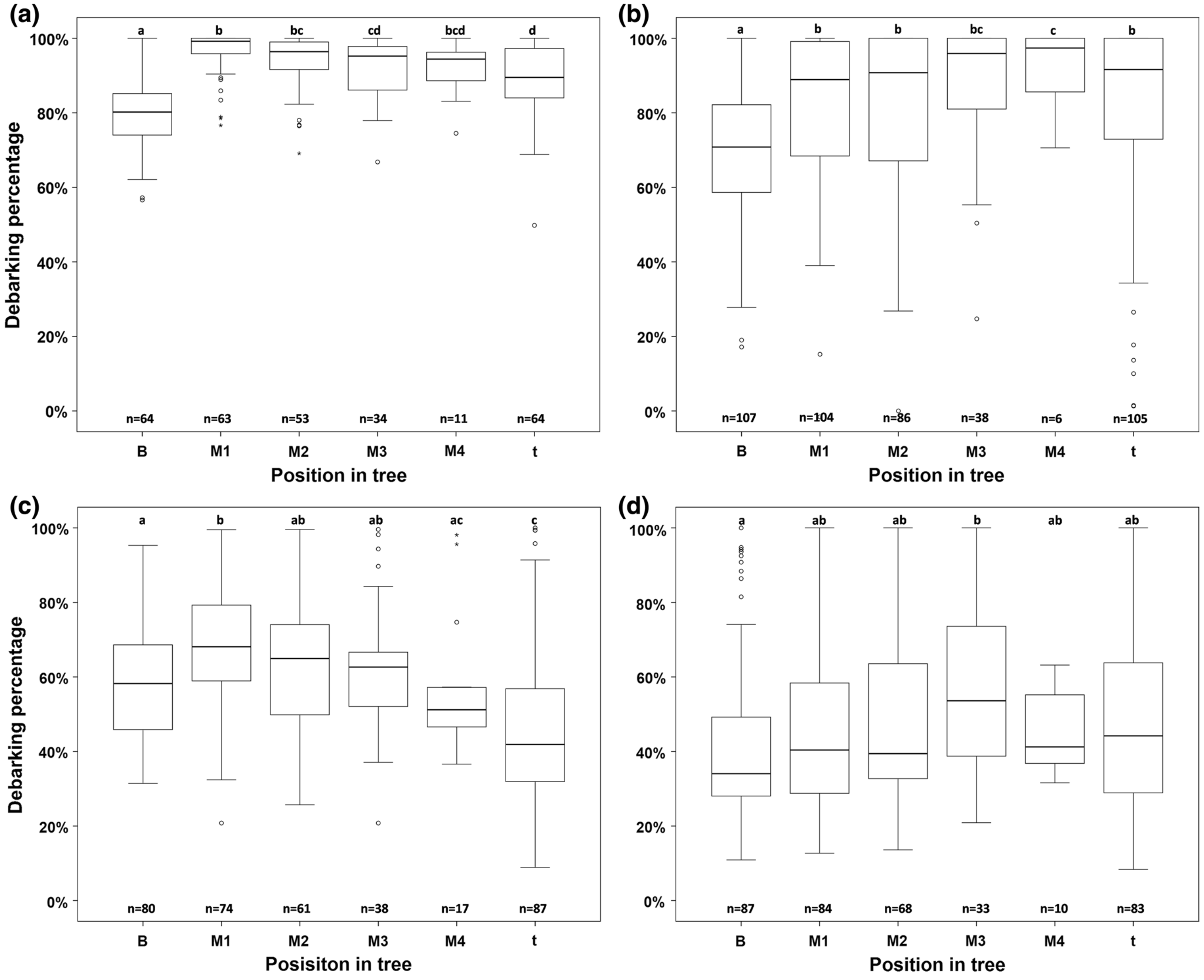

Fig. 8 Overview of the measured debarking percentages by vertical position of the log within the tree (B—butt log; M1–M4—mid-positioned logs, t—top log) and species/season according to: **a** pine summer, **b** spruce summer, **c** pine winter and **d** spruce winter tests

delays) was recorded during conventional harvesting operations (Fig. 10).

Considering the absolute values, average processing time (delimbing, cutting stem into assortments) was increased by 48% compared to conventional (single pass-over) operations (Table 4). Under the tested conditions, harvesting productivity was on average 10% lower with the debarking configuration compared to conventional operations performed in similar sized stems (Abschlussbericht 2018).

Discussion

Study design and modifications

The study design was chosen to determine whether conventional harvesting heads could be modified to allow debarking within the harvesting process. In general, the modifications performed well, especially during summer operations. With three passes of the stem within the harvesting head, debarking percentages over 90% were regularly achieved. In a second step, the demands and debarking expectations of the wood processing industry on the debarked roundwood needs to be clarified. If those requirements for the different treatments (e.g., spruce bark beetle), operations (summer, intermediate or winter time) or assortments are known, further tests might be necessary to optimize certain modifications in order to meet the given demands. A strategic approach could be developments specifically tailored for European tree characteristics (larger diameter often exhibiting complex crown structure), as most of the tested modification parts were originally designed to debark Eucalyptus trees. By installing additional top and/or bottom delimbing knives,

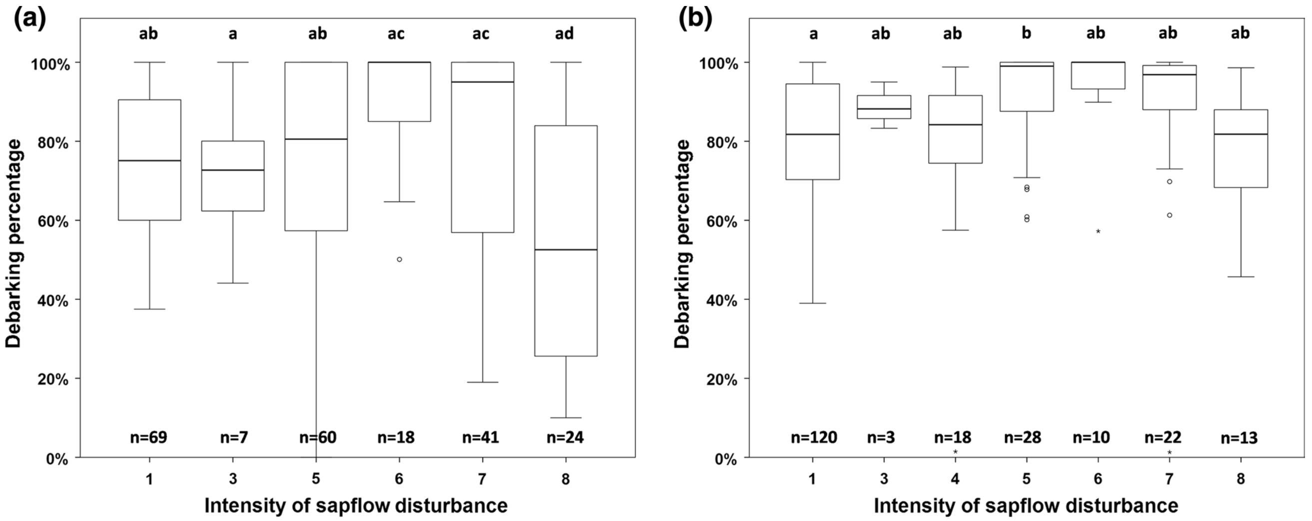

Fig. 9 Overview of the measured debarking percentages of spruce categorized by intensity of sap flow disturbance (1—no disturbance, 8—very high disturbance) for: **a** Setup 2 summer test and **b** S3 summer test carried out in bark beetle-infested stands

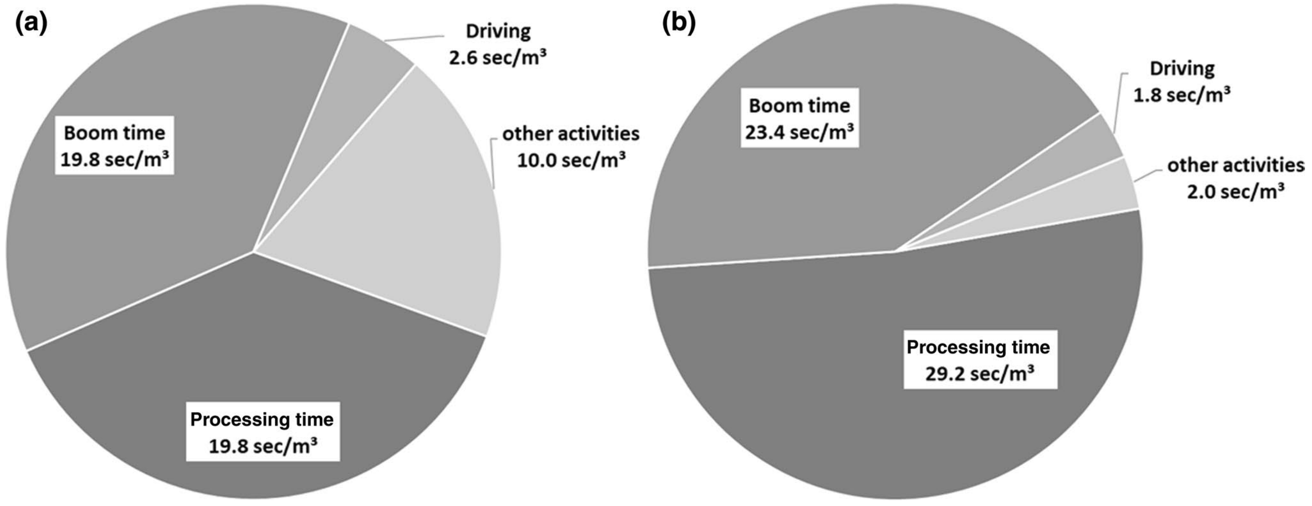

Fig. 10 Total share of the main working elements for harvesting operations **a** conventional without debarking, **b** with debarking

Table 4 Productivity data of on-board harvesting computer of conventional and debarking operations

	Average log volume (m^3 u.b.[1])	Average processing time/stem (s)	Average boom and driving time/stem (s)	Productivity (m^3/h)
Conventional	0.18	20.0	22.7	12.3
Debarking	0.18	29.5	26.6	11.1

[1] Under bark

increased debarking efficiency could potentially be obtained. Besides the delimbing knives, the presence of a top saw on the harvesting head could improve overall processing performance by limiting the frequency of regripping of the trunk. Such top saws are already available but were not standard on any of the tested harvesting heads within the scope of the project.

Beyond hardware modifications, it would also be possible to increase the number of passes to achieve a higher debarking percentage. However, as reported by van der Merwe et al. (2015), more severe damages on the log surface and loss of biomass can occur. When the number of passes is limited to three (as in our study), Labelle et al. (2019) reported that the frequency and severity of penetrations into the wood caused by the feed rollers were actually deeper under standard configuration (8.7 mm) than with the debarking configuration (6.7 mm).

The fact that two of the summer tests had to be performed within spruce bark beetle stands added important information about the performance of the setups within this field of application, but basic information on the performance of S2 and S3 modifications under undisturbed summer conditions is lacking.

Field sampling and equipment

To assess the debarking result and debarking percentage, two possible approaches were under consideration: (1) measuring within the sawmill and (2) measuring within the forest stand. In modern sawmills, measurement devices are usually installed that are not only capable of measuring the physical characteristics of a log but also measure the debarking percentage. The difficulty with the first approach is that it required transportation of all logs from the felling site to a processing facility, a working step that could have triggered complications in retracing individual logs in addition to further increasing the debarking percentage because of wood handling during transport. Instead, it was decided to design a measurement system that easily delivers a sufficient amount of data and could be performed with a manageable effort directly in the forest. The measurement system was based on a photo-optical evaluation system that used one picture of every stem and estimated the rest of the stem surface. Tests showed that the average debarking percentage is very precise over a larger sample size ($n > 20$) (Heppelmann et al. 2019b). However, the downside was that the individual values have only limited significance, since in the photo-optical analysis only a maximum of 50% of the total surface was displayed and actually measured. A second approach using a T-LiDAR was also pilot-tested for a subset of logs within the project. This measurement system showed promise to provide a higher area of log surface to be measured and also obtain detailed information on the taper and curviness of the logs. Further studies should consider T-LiDAR as the main instrument to collect log information.

Effect of machine type, season and beetle infestation on debarking efficiency

The most remarkable difference in the debarking efficiency was detected between the winter and summer field tests. We believe this was linked to the sap flow of the tree, which worked as a natural separation layer between the bark and the wooden body (Kupferschmid 2001). When sap flow was fully established, it facilitated stripping of the bark in up to 16-meter-long strips at once. Within the winter season and therefore without this separating layer, the average debarking percentage decreased to 35–54%, while only very short segments of bark were stripped from the wooden body. With these findings, it was expected that operations within spruce bark beetle infected stands would show similar results as the infection also impairs sap flow. However, the effect was not as strong as expected, but especially for the S2 prototype, an unusual large variation of measured debarking percentages was detected. On the other hand, the S3 prototype did not present this effect at all, delivering results comparable to the S1 summer trials. We anticipate this result is related to two main reasons. First, the tested S2 harvesting head was mounted on a harvester with limited setting options (only manual, no computer-based adjustment possible) and the delimbing knives were quit worn. This could have increased the effect of the beetle-related sap flow disturbance as brand new manufactured S3 prototype performed similar to the S1 prototypes. This hypothesis is strengthened with the latest experiences of entrepreneurs using modern S2 heads with fresh pairs of delimbing knives for debarking, reporting similar results as for the S3 harvesting head outside the project. Second, the S3 harvesting head performed a considerable share of the debarking process with the purposefully designed delimbing knives. In the S3 setup, the feed rollers actually played a minor role in the debarking process, and the rotation of the tree on its longitudinal axis served mostly as a cleaning mechanism to remove bark stripes wedged between the stem and the measuring wheel. Compared to the worn conventional delimbing knives and the fact that S2 uses mainly the feed rollers to debark the trees, this also might explain the much higher variation of measured debarking percentages in Fig. 9. Overall, this leads to the assumption that debarking percentages, especially in operations with impeded sap flow (beetle-infested stand, droughts, intermediate season, wintertime, etc.), could be further improved by modifications and optimizations of the delimbing knives.

Effect of log diameter and its vertical position on debarking efficiency

The diameter of the processed logs was also expected to influence debarking efficiency. This effect could partly be proven for pine, but not for spruce (see Fig. 7). For pine, the average debarking percentage was decreasing as the processed diameters were decreasing. However, the sample sizes that are carrying this assumption must be considered as they were getting rather limited at both ends of the investigated range, describing a trend rather than a robust calculation. This effect could have originated from a different circumstance investigated in Fig. 8. Within the field tests, it was observed that for the butt logs, a segment of un-debarked area remained for every tree. This occurred because neither the feed rollers nor the delimbing knives can process this part of the log since they are located further away from the cutting plane. Potential software solutions for this problem already exist within the harvester operating systems, originally developed for Eucalyptus operations, but were not utilized for the field tests within the studies. Those settings might help to mitigate this effect in the future.

Another observed impact factor was the rather complex crown architecture (forks, crooks, severe curviness), especially for Scots pine stands in Lower Saxony. The poorly shaped upper parts of the trees, combined with their high branchiness and smaller stem diameters, resulted in a lack of forward thrust and grip of the harvesting head, which negatively impacted the debarking efficiency. Taken together, lower debarking percentages for both larger and smaller stem diameters could be influenced by the diameter itself or originate from the combination of diameter and vertical position within a tree (butt log and top/crown logs).

Nutrients

According to Weis and Göttlein (2012), 14% of the nitrogen, 17% of the phosphorus and 31% of the calcium found in Norway spruce trees are located in the bark under average conditions in Bavaria (Germany). This represents a considerable share of the total bound nutrient content that is stored in a rather small volume compared to the wooden body. With 36% of the calcium located in the solid wood, the share is almost equal to bark. Therefore, the debarking system has the potential to keep those nutrients within the forest ecosystem. At this stage, the debarking efficiency is 46% higher for summer than for winter operations. Considering the nutrient supply, the debarking percentage should therefore be improved for winter operations, as for example an average of 35–56% of the bark and its associated nutrients were left in the forest for the S1 and S2 winter trials. This could also help to treat the deposition of organic acids originating from softwood litter directly within the stand without the need of costly fertilizer or lime application (Reif et al. 2014). A broad distribution of the bark is expected to turn out beneficial as the contained nutrients are not accumulated on a rather small area. In the study, the operator was instructed to work as usual, also with debarking, to achieve a better comparability between the two modifications. Therefore, the bark was mostly accumulated in small piles in a close range beside the machine operating trail and in rather few cases also with the brush material on the operating trail. As supported by Borchert et al. (2015), nutrient concentration within machine operating trails can be redistributed beyond the trail and therefore be accessible to residual trees.

Harvesting productivity

The productivity calculations provided in this study should only be used as general orientation since the amount of information gathered is only able to provide a coarse overview. Furthermore, productivity data were collected in a rather poor quality stand of Scots pine without any previous silvicultural treatment. Factors such as increased wear, additional fuel consumption and entrepreneurial profits were not considered as the database was not sufficient to provide robust information, yet. Furthermore, actual productivity impacts for the different stages of modification are not known as those modification kits are not readily available on the market. The prices for conversions will also vary if further optimization and developments will be carried out for European markets. These factors will clarify as large amounts of wood will be harvested and processed with this system over a longer period. At the present stage, only a conservative estimation of a 10% lower productivity when using modified debarking heads as compared to conventional heads can be given as orientation (not considering the above-mentioned factors). The conservative estimation is supported by a study by Magagnotti et al. (2011) that assessed the costs of stump-site debarking in Eucalyptus plantations and reported potential monetary savings of 11–17% when avoiding stump-site debarking. When calculating the additional costs based on the collected data and further considering a higher fuel consumption during the debarking process, the 10% productivity reduction results in a comparable cost range to the one presented in the study by Magagnotti et al. (2011). However, it is necessary to reiterate that these assumptions are not based on a representative amount of data. Further impacting factors on harvesting productivity could be: stand characteristics, tree species, tree architecture, terrain and slope, operator experience, stand density and regrowth, size of harvest blocks, and fast and flexible availability of modified machines.

Conclusions

The debarking of common European tree species (Norway spruce and Scots pine) through modifications of conventionally used harvesting heads proved to be possible, financially feasible and promising for future operations. Within the summer season, the prototypes of John Deere H480C (S1), Log Max 7000C (S2) and Ponsse H7 (S3) achieved average debarking percentages of 73%, up to 90%, respectively, when keeping the number of passes through the harvesting head constant at three.

Throughout the seven field tests, the season and associated tree sap flow proved to be the main influencing factors on the debarking efficiency. This led to a 46% lower average debarking percentage for winter operations as compared to summer operations. Therefore, the tested systems are currently recommended for summer operations if spruce bark beetle stands need to be treated or the general export of nutrients lowered within the harvesting operations. For comparable performances in winter operations, further modifications would be required, or the working procedure would need to be customized.

Harvesting productivity for the S1 summer test was on average 10% lower with the debarking modifications as compared to harvesting with the conventional head operating in similar sized trees. This decreased productivity was mostly attributed to the increased number of pass-overs of the stem in the head required to achieve the debarking effect.

Overall, the tested debarking systems proved to be a very promising solution for upcoming modern forestry challenges within European forest ecosystems. Additional research focusing on a more comprehensive analysis of harvesting productivity and associated harvesting costs should be performed to gain a more holistic understanding of the proposed systems.

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