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RESEARCH ARTICLE

Debarking harvesters simultaneously combat the European spruce bark beetle (*Ips typographus*) and conserve non-target beetle diversity

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Abstract

1. In the face of climate change, the European Spruce Bark Beetle (*Ips typographus*) breeding predominantly in Norway spruce (*Picea abies*) led to exceptional amounts of damaged timber in European forests. Up to now, if pest control is applied, damaged or weakened *P. abies* trees are either extracted by salvage logging or, when quantities are low, made unsuitable for breeding by manual debarking techniques. Both pest control interventions are costly, are often limited by the short timeframe of effectiveness and come with negative impacts on the non-target biodiversity.
2. As alternatives for timely removal, a debarking head for harvesters for large scale disturbances and a bark gouging device for motor-manual treatment have been developed in recent years to make breeding material unsuitable for bark beetles and reduce existing larvae.
3. Based on data from an experimental design with infested Norway spruce logs, we show that the harvester debarking head and the motor-manual bark gouging regulate *I. typographus* populations efficiently, whereas a conventional harvester did not reduce the emerging bark beetles. Species assemblages of non-target beetles living in the infested Norway spruce logs were altered from the natural species assemblages in control logs by processing logs with the debarking head or the bark gouging device but not by the conventional harvester. None of the bark treatments reduced non-target beetle species richness in this experiment.
4. *Practical implication*. We endorse the debarking head and bark gouging as alternatives to salvage logging and manual debarking. This uncouples pest control from

in-time dependencies on the availability of transport capacities. The debarking head and bark gouging open up the opportunity to retain dead wood biomass in the forest, supporting ecological benefits and conservation goals. Particularly for protected areas these two new management options better balance requirements of pest control and biodiversity conservation.

KEYWORDS
bark beetle regulation, biodiversity, dead wood retention, disturbance, forest management, pest control, saproxylic beetles

1 | INTRODUCTION

Norway Spruce (*Picea abies* (L.) H. Karst.) is still the most economically important and abundant tree species in Europe (Schelhaas et al., 2018). *Picea abies* plantations for timber production are widely distributed in Europe, extending outside of their natural range (Hagge, Leibl, et al., 2019). Facilitated by preceding windstorms (Seidl & Rammer, 2017) and droughts (Marini et al., 2017), the European bark beetle [*Ips typographus* (Linnaeus, 1758)] is the major pest insect in Europe's forests, causing more than 50% of the annual *P. abies* timber harvest for some countries in recent years (Hlásny et al., 2019; Patacca et al., 2022). Windstorms are currently the most important disturbance agent in European forests (Seidl et al., 2017), with a projected climate change induced increase (Seidl et al., 2014). The abundance of damaged timber, serving as breeding substrate, in combination with favourable weather conditions for reproduction, promotes rapid population build-ups of *I. typographus*, enabling it to overcome natural defence mechanisms even of healthy spruce trees (Biedermann et al., 2019; Netherer et al., 2019). Consequently, the disturbance regime of bark beetle outbreaks is amplified by the interaction with climatic extremes (Seidl & Rammer, 2017).

Insect outbreaks and the resulting canopy dieback are inherent elements of *P. abies* forest dynamics (Franklin et al., 2002) and play a key role for natural regeneration and biodiversity (Müller et al., 2008). Many species profit from the increased light availability, interior edges and the resource pulse of deadwood after disturbance (Bässler & Müller, 2010; Beudert et al., 2015; Busse et al., 2022; Hilmers et al., 2018; Lehnert et al., 2013). The remaining dead biomass can increase ecosystem resilience by maintaining nutrient, water and carbon cycles (Leverkus et al., 2020). Windstorms and bark beetle outbreaks contribute to the transition of conventionally managed spruce forests to more heterogeneous, near-natural forests (Thorn et al., 2017).

Particularly in recent years, *I. typographus* outbreaks have caused large financial losses (Hlásny et al., 2021). The most common measure to halt eruptions of *I. typographus* after windstorms or infestation of weakened trees, is the timely removal of suitable breeding material away from potential host trees within the first 5 weeks of infestation (Hoch et al., 2020; Schroeder & Lindelow, 2002; Wermelinger, 2004). This prevention measure of pest control seems only successful when 80%–95% of (infected) trees and logs are detected and removed before beetles emerge (Dobor et al., 2020; Fahse & Heurich, 2011). However, when trees are affected at a landscape scale, capacities for wood transport often become limited and the retention of logs in the forest can minimize harvest costs and offset low timber prices (Toth et al., 2020). To counteract temporal bottlenecks in work capacity and to buffer price fluctuations, a temporary storage of infested timber in forests is an often-applied strategy. Nevertheless, it has to be secured that no *I. typographus* emerge from this intermediate storage of timber. The application of pesticides, plastic foil for wrapping or wet storage are effective measures, yet are accompanied with high additional costs and likely negative concomitant effects on the environment (Hlásny et al., 2019).

Integrated pest control methods that enable natural dynamics by retention of tree biomass after disturbances are especially needed for about 40% of Europe's protected areas within in the natural range of *P. abies* (Hagge, Leibl, et al., 2019). Particularly in national parks the pest management must fulfil the requirements of biodiversity conservation, environmental education and recreation (IUCN primary objective of a national park; www.iucn.org, Schiermeier, 2017). Owners of forests for timber production bordering protected areas identified these areas as a risk for their management goals and as the source of uncontrolled *I. typographus* outbreaks (Müller & Imhof, 2019). This conflict led to designated buffer zones with pest control interventions around strictly protected areas, where a 'benign neglect strategy' is often applied for bark beetle outbreaks to allow for natural dynamics (Hlásny et al., 2021; Müller et al., 2010). To mitigate interactions and safeguard nearby timber production, salvage logging after wind disturbance or bark beetle infestations is a common management response in these buffer zones and sometimes also in the entire areas of protected areas (Lindenmayer et al., 2017; Müller et al., 2019; Schiermeier, 2017).

However, removing biomass is in strict contrast to the concept of conservation areas with natural ecosystem dynamics and without or minimal human interventions. Salvage logging is accompanied by a reduction in saproxylic biodiversity (Georgiev et al., 2020; Müller et al., 2010; Thorn et al., 2020) and can decrease ecosystem resilience (Leverkus et al., 2021). Hence, on-site bark beetle control measures, which maintain the tree biomass in the forest stand and regulate insect pests populations, are increasingly promoted to combine multiple purposes of forest use (Hagge, Leibl, et al., 2019). Recently, new technical solutions have been developed for the treatment of bark beetle breeding material at different scales and conditions.

For successful pest regulation, the bark, as breeding habitat of *I. typographus*, is either removed completely or manipulated in a way that renders the logs unsuitable for reproduction (preventative). In case the logs are already colonized by *I. typographus*, bark treatments need to insure that no individuals are able emerge from the logs (therapeutic). The optimal time for mechanical treatment of infested logs is during the larval stage (first 5 weeks), since fully developed beetles can complete their life cycle also in the detached bark (Delb et al., 2021). In case teneral beetles are already present, guidelines recommend to burn, chip, cover or remove bark residues from the forest (Kautz et al., 2021; Wermelinger, 2004). In forestry, various techniques of bark manipulation to combat *I. typographus* are practiced. In forests with protective functions, terrain inaccessible by machinery, wetlands and conservation areas, logs are traditionally debarked manually with a debarking spud (flat knife attached on wooden stick; Zarges et al., 2023). For mechanized debarking an attachment for conventional chainsaws with rotating knives has been developed. This device has undergone further development, resulting in a motor-manual bark gouging device that removes approximately 30% of the bark and phloem in regular stripes. This pest control method is more cost-effective than complete debarking and reduces *I. typographus* populations on logged wood greatly (Hagge, Leibl, et al., 2019; Thorn et al., 2016; Zarges et al., 2023). The rotating knives are milling of the bark in small pieces, which likely also decimates fully developed beetles. Bark gouging is conservation-friendly, as the remaining bark preserves essential habitat functions for other (saproxylic) species (Hagge, Leibl, et al., 2019; Thorn et al., 2016).

Yet, regulating populations of eruptive pests with techniques based on (motor-) manual labour is neither cost effective nor fast enough, when large amounts of breeding substrate need to be processed. In salvage logging operations, conventional harvesters are commonly used to process (infested) *P. abies* logs. The pressure from the feed rollers and delimbing knives results in partial perforation, bruising and removal of the bark. In theory, this already reduces the potential for bark beetle reproduction by destroying existing beetles and larvae and an increasing desiccation of the phloem. However, preliminary studies suggest that damage to the bark and larvae from salvage logging by conventional harvesters is insufficient to protect remaining trees from eruptive population densities of *I. typographus* (Delb et al., 2021). A fully mechanized solution to remove the bark from large quantities of (infested) logs is the modification of the conventional harvester aggregate for debarking (hereafter referred as debarking head) (Heppelmann, Labelle, Wittkopf, & Seeling, 2019). The feed rollers are replaced with debarking rollers that force the log to rotate. By passing over three times, the delimbing knives remove the bark on the entire surface. Best results of debarking can be expected during the summer months when sap flow is high (Heppelmann, Labelle, Wittkopf, & Seeling, 2019). Up to now, the impact of debarking heads on saproxylic organisms has not been studied, while empirical studies examining the pest control effectiveness are limited to preliminary results (Delb et al., 2021).

In this study, we examine the effects of the harvester debarking head on the reproduction of bark beetles and biodiversity of non-target beetle species. In a field experiment, we surveyed logs treated with the harvester debarking head, the conventional harvester head and the motor-manual bark gouging device, and an untreated control group, for *I. typographus* infestation and the biodiversity of emerging beetles. We hypothesize that the extensive bark removal produced by the debarking head not only decreases the number of emerging *I. typographus* more than all other techniques but also reduces the number of non-target beetle species and alters their assemblages.

2 | MATERIALS AND METHODS

2.1 | Study area and bark treatments

The study was conducted in the buffer zone of the Bavarian Forest National Park, where active bark beetle interventions are implemented (49°5′13″ N, 13°14′0″ E). Forest stands in this area are dominated by *P. abies* and have experienced extensive *I. typographus* outbreaks in the past (Müller et al., 2010). Sixteen *P. abies* trees of similar size, age and with signs of early colonization (white larval stage without teneral beetles) by *I. typographus* were felled in June 2020. All trees met the criteria for removal of the regulations for the buffer zone management and were randomly assigned in groups of four trees to each of the treatments, to account for potential differences in colonization densities between trees. The control trees were felled without any further bark manipulation (Figure 1). After felling, delimbing and cutting into sections, the second group was treated with the bark gouging device attached on a conventional chainsaw ('Streifenmesser Nationalpark Bayerischer Wald', EDER Maschinenbau GmbH, Wolfenbüttel, Lower Saxony, Germany). The four modified knifes are mounted parallel in pairs and have a V-shape to gouge the bark every 16 mm with a width of 14 mm (Figure S1). Another group of four trees was felled and processed with a harvester fitted with a conventional aggregate, representing the effect to logs from salvage logging and extraction operations. The last group was debarked using a John Deere 1270 G 8-wheel harvester in combination with an H 480 C debarking head, refitted with four debarking rolls and a Eucalyptus measuring wheel (Figure S2). The bark was completely removed by passing over the logs multiple times (Figure 1).

2.2 | Sampling

From each log, three segments, measuring 70 cm, were cut out at random locations to account for differences of colonization densities within the logs. Then, the 48 segments (12 per treatment) were placed in rearing barrels to collect abundances of all emerging

FIGURE 1 Experimental design with the machinery for the treatments and pictures of the condition of the bark on the logs after processing. From each of the four logs per treatment three 70 cm segments were cut out at random locations ($n = 12$) and placed in rearing barrels to assess the abundances of emerging *Ips typographus* for pest control efficiency and number of non-target beetle species as a measure of biodiversity.

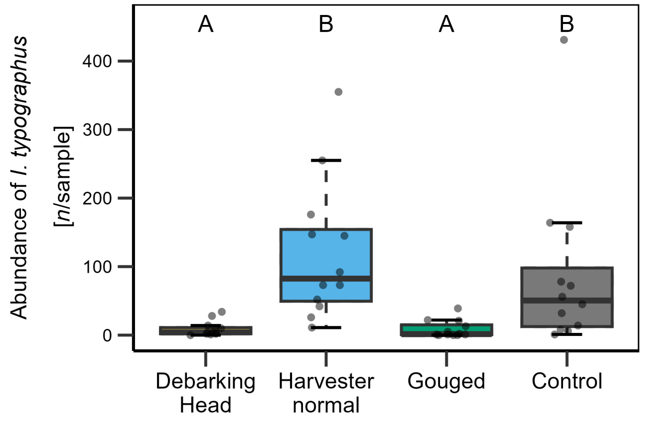

FIGURE 2 Abundance of *Ips typographus* sampled from the four different bark treatments. Points ($n = 12$) specify the 70 cm segments from *Picea abies* logs. Different letters above indicate significant difference between treatments based on the Quasi-Poisson GLMs.

arthropods from June until October 2020. All beetle species were separated from other arthropods and identified to species level by taxonomic expert Andreas Weigel. The abundance of emerging *I. typographus* was used to assess the pest control efficiency of the bark treatments. The species richness (number of species) and assemblage of non-target beetle species represent the impact of the different treatments on beetle biodiversity with the exclusion of the focal pest species *I. typographus*.

2.3 | Data analysis

All statistical analyses were performed in R 4.2.2 (R Core Team, 2022). To adjust for overdispersion in the count data, we used quasi-Poisson linear models (function *glm*) to test for the effects of the four different bark manipulation treatments on the abundance of *I. typographus* and the number of non-target beetle species. We used multiple comparison tests using the function *glht* in R-package *multcomp* (Hothorn et al., 2023). Tukey contrasts were specified in the *glht* objects using the *mcp* function. To control for multiple testing in the comparison between treatments we utilized the function *cftest* from the package *multcomp* (Hothorn et al., 2023) with single-step adjusted *p*-values. Furthermore, the beetle assemblages were visualized and tested for differences between the treatments by means of non-metric multidimensional scaling (NMDS) using the function *metaMDS* from the R-package *vegan* (Oksanen et al., 2022). Species with only one or two observations (28 out of 62 non-target species) were removed due to their little contribution to the differences in assemblages in comparison to the more common species. Pairwise analysis of variance based on the Bray–Curtis dissimilarity community matrix were applied by the function *adonis* provided in *vegan* (Oksanen et al., 2022). *p*-values were adjusted for multiple testing with *Bonferroni* correction. Additionally, the individual percentage of contribution to the Bray–Curtis dissimilarity for each species was calculated to identify the key species in each community assemblage per treatment using the function *simper* in R-package *vegan* (Oksanen et al., 2022).

3 | RESULTS

In total, we obtained 13,488 Coleoptera specimens of 63 species (Table S1). The four most abundant beetle species accounted for 91% of the individuals. *Dalotia coriaria* (Kraatz, 1856), a generalist predatory rove beetle, was the most abundant species accounting for 32% ($n = 4362$) of all sampled beetles, followed by three bark beetle species, *Pityogenes chalcographus* (Linnaeus, 1760) with 21% ($n = 2770$), *Ips typographus* with 20% ($n = 2729$) and *Crypturgus cinereus* (Herbst, 1794) with 18% ($n = 2440$).

3.1 | Pest control of bark beetles

Both the harvester debarking head and the bark gouging reduced the emerging population of *I. typographus* significantly (Figure 2;

Table S2). When compared to the control logs (50.5 beetles), only 7.9% (median of 4 beetles) emerged from the logs processed with the debarking head and 3% (1.5 beetles) emerged from logs with gouged bark. Processing the infested logs with a conventional harvester aggregate had no significant effect on the population of *I. typographus* compared to untreated control logs.

3.2 | Species richness and assemblage composition of non-target beetles

None of the four treatments had a significant effect on the number of non-target beetle species (see Figure 3; Table S2).

Assemblage composition (NMDS 2D stress = 0.09) of logs treated with the regular harvester did not differ from control logs ($p = 0.13$). However, for all other combinations assemblage composition of non-target beetles between treatments were different from each other ($p < 0.05$, see Figure 4; Table 1). Dissimilarities in assemblages of beetle species between debarking head and control were mostly characterized by *Crypturgus cinereus* (5%), *Placusa depressa* (5%) and *Dalotia coriaria* (4%).While between debarking head and harvester normal *Crypturgus cinereus* (6%), *Crypturgus pusillus* (5%) and *Placusa depressa* (4%) were prevailing, between debarking head and bark gouging *Crypturgus pusillus* (7%), *Crypturgus cinereus* (5%) and *Placusa tachyporoides* (4%) contributed predominantly to differences in assemblages. Dissimilarities in beetle species assemblages between bark gouging and harvester normal were characterized by *Placusa depressa* (5%), *Pityogenes chalcographus* (4%), *Placusa tachyporoides* (3%). *Placusa depressa* (7%), *Dalotia coriaria* (4%), *Crypturgus pusillus* (4%) contributed most to the differences between bark gouging and control. For differences between control and harvester normal *Pityogenes chalcographus* (4%), *Dalotia coriaria* (4%) and *Crypturgus pusillus* (3%) (Table S3).

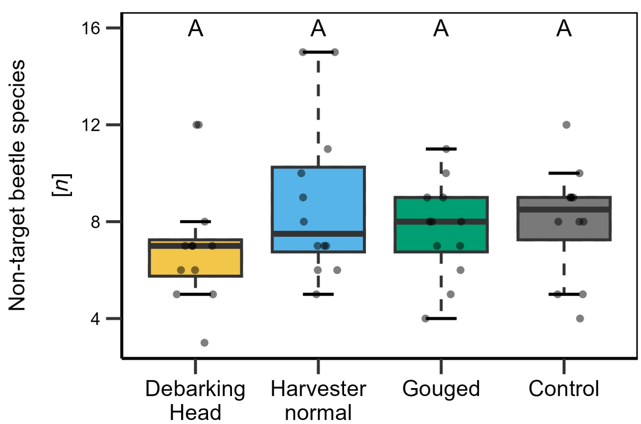

FIGURE 3 Species richness (number of species) of emerged non-target beetles per sample. Points ($n = 12$) indicate the 70 cm segments from *Picea abies* logs with four different bark treatments. Letters above indicate significant difference between treatments based on the quasi-Poisson linear models.

4 | DISCUSSION

With a current increase in disturbance of European Norway spruce forests there is an urgent need for new management prospects, particular for a conservation-friendly regulation of pests in protected areas. Our results suggest that harvesters equipped with debarking heads could be a promising option for early therapeutic treatment of *I. typographus* populations before fully developed beetles are present. This approach allows for temporary storage of bark beetle breeding material within the forest or for permanent deadwood enrichment to support biodiversity conservation.

Handling bark beetle infested *P. abies* logs with a conventional harvester aggregate had no significant effect on the reduction of *I. typographus*. For the treatment of breeding material at small scales or in terrain inaccessible for machinery, we endorse bark gouging as the economic and conservation friendly pest control method. None of the tested treatments had a significant effect on the species richness of non-target beetles. Assemblages of beetle species differed significantly between all treatments, except for the comparison between control and harvester normal logs, demonstrating the importance of bark for the colonization processes of wood inhabiting beetles.

4.1 | Using debarking heads for efficient pest control after large scale disturbances

After storm damage and bark beetle infestation, timely intervention is the highest priority for successful pest regulation (Kautz et al., 2021; Wermelinger, 2004), while forest workers face numerous safety risks (Sanginés de Cárcer et al., 2021). Consequently, motor-manual work is discouraged since fully mechanized methods provide a safety advantage with the enclosed cabin. With the debarking head attached to the harvester, only one machine operator is needed to process large amounts of breeding material. Our finding that with a conventional harvester aggregate, bark beetle populations in infested *P. abies* trees cannot be reduced sufficiently is in contrast to previous studies, showing that normal handling already had pest control effect in the larval stage (Delb et al., 2021). Delb et al. (2021) indicated that higher population reduction can be obtained when the logs were processed a second time through the conventional aggregate (similar to the debarking head, just without the modified feed rollers). In the same study, the debarking head was very effective in reducing pest populations at the larval stage. However, in case teneral beetles are already present, the removed bark pieces can be large enough for the beetles to finish their lifecycle and emerge from the residues, stressing the importance of intervention during the larval stage (Delb et al., 2021; Kautz et al., 2021).

Thus, removing the bark before or within a maximum of 5 weeks after colonization allows for timber storage near potential host trees, without risking a mass outbreak. Decoupling transport and sale of timber from large scale disturbances reduces dependencies on the availability of machinery as well as low market prices for raw

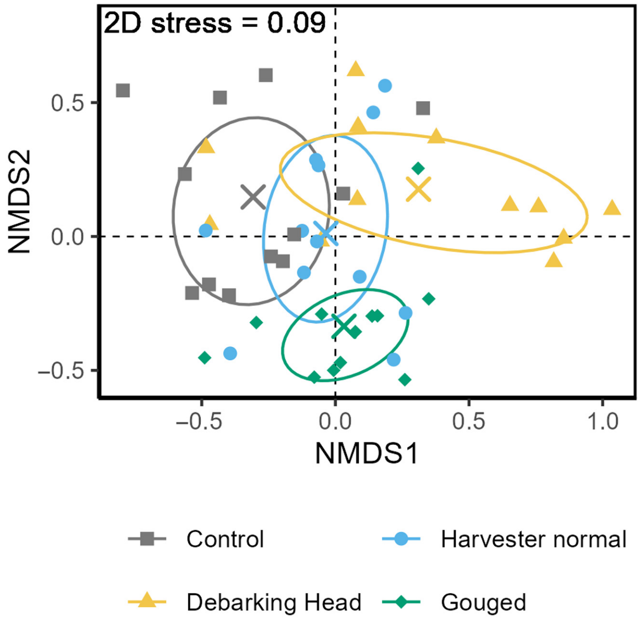

FIGURE 4 Non-metric multidimensional scaling based on presence-absence data Bray–Curtis dissimilarity matrix of non-target beetle species with more than two observations (34 species) in spruce logs treated with harvester debarking head (yellow squares), harvester normal (blue triangles), bark gouging (green crosses) and control (grey circles). For each treatment, centroids are marked with 'X' and ellipses show the spread of 50% in the data.

TABLE 1 Results from pairwise analysis of variance (*adonis*) of beetle species assemblages between bark treatments.

Comparison	*F* value	R^2	Adj. *p*-value
All treatments	4.13	0.22	**0.007**
Control—Harvester normal	2.63	0.11	0.105
Control—Debarking head	4.71	0.18	**0.014**
Control—Gouging	5.86	0.21	**0.007**
Debarking head—Harvester normal	3.34	0.13	**0.021**
Debarking head—Gouging	4.3	0.16	**0.014**
Harvester normal—Gouging	4.22	0.16	**0.007**

Note: The analysis is based on Bray–Curtis dissimilarity matrix with presence and absence of non-target beetle species with more than two observations (34 species) emerging from 70 cm *Picea abies* log segments. *p*-values were adjusted with *Bonferroni* correction for multiple testing. Bold values are significant at the 0.05 level.

timber. The cost of modifying conventional harvester aggregates for debarking can be achieved with less than €10,000, while the running costs per machine hour increase on average by 10% (Heppelmann, Labelle, Wittkopf, & Seeling, 2019). Processing time per log increases, due to the need to pull the logs multiple times through the aggregate. The amount a conventional harvester usually processes is halved when logs are completely debarked with the debarking head (Heppelmann, Labelle, Wittkopf, & Seeling, 2019; Mergl et al., 2021). A reduction in transport costs can be expected, as debarked logs are lighter and dry out faster (Heppelmann, Labelle, & Wittkopf, 2019). Even though the intense processing may increase damage to the wood by the delimbing knives, the usable quantity and value are not decreasing considerably (Labelle et al., 2019). While with the debarking head approximately 11 m^3 per hour (Heppelmann, Labelle, Wittkopf, & Seeling, 2019) are debranched, debarked and cut to length, with the bark gouging device only about 3 m^3 per hour after previous debranching (Hagge, Leibl, et al., 2019; Thorn et al., 2016; Zarges et al., 2023) can be made unsuitable for bark beetle breeding. Thus, when compared to motor-manual bark gouging harvesters with debarking heads are feasible for timely interventions for bark beetle management also on larger scales.

In-stand debarking retains important nutrients in the forest that benefit nutrient cycling and stand productivity (Vos et al., 2023; Yan et al., 2017). When used for biomass as thermal energy, debarked logs have less ash and fine dust emissions than logs with bark (Werkelin et al., 2005). Conversely, many sawmills rely on the bark as a fuel to generate energy in their power plants. In case the debarked logs remain (for intermediate storage) in the forest stand, the bacterial richness of decomposer communities decreases, which in turn benefits wood decaying fungi species potentially devaluing the timber (Hagge, Bässler, et al., 2019).

4.2 | Debarking head as possible solution to promote biodiversity

Deadwood from bark beetle infestations plays a significant role as a resource for various species and is essential for maintaining forest biodiversity and supporting nature conservation efforts (Müller et al., 2010; Viljur et al., 2022). Due to the fact that debarking heads can effectively reduce breeding habitat and emerging bark beetles, it is the sustainable alternative to salvage logging for phytosanitation at large scales. Profound interventions (like clearing of large areas) for the control of forest pests can lower the recreational value of protected areas due to its poor perception by national park visitors (Berto, 2005). Additionally, salvage logging shifts natural regeneration to a dominance of pioneer species, since the top soil is disturbed and the coarse woody debris (CWD) as regeneration niche of *P. abies* is removed (Fischer et al., 2002). Our results demonstrate that the number of emerging non-target beetle species was not reduced by debarking or gouging over the first year. However, in previous multiyear research, completely debarked logs contained fewer saproxylic species, which can affect higher trophic levels like woodpeckers (Hagge, Leibl, et al., 2019; Thorn et al., 2016). The fact that we found no reduction in beetle species, is likely connected to the absence of beetles with a longer development. Yet, the assemblages of beetle species between treatments is characterized by different species than in untreated logs. For crooked, very large or small diameter logs debarking percentages by the debarking head can be expected to be lower (Heppelmann, Labelle, Wittkopf, & Seeling, 2019) which likely leads to a higher habitat heterogeneity affecting the species assemblages. For conservation goals it is beneficial to sustain unlogged areas with dead wood biomass to uphold specified species diversity in disturbed forests (Thorn et al., 2020). However, when it comes to supporting saproxylic biodiversity, it's crucial to provide a variety of CWD differing in size, exposition, and quality, rather than focusing solely on quantity (Müller et al., 2015; Seibold et al., 2015; Thorn et al., 2020). Therefore, if extra focus is put on the habitat heterogeneity of retained CWD, ensuring a mix between standing and lying as well as shade and sun exposed locations, some of the wood can also be sold to offset operational costs.

4.3 | Bark treatments for pest control shape assemblage of beetle species

Even though the species richness (number of species) was not reduced, the beetle species assemblages in the logs with (partly) removed bark differed from the logs with no or low (Harvester normal) impact on the bark layer. This shift needs to be disentangled in more detailed follow up research, to verify the additional benefit for biodiversity from debarked wood and which habitat characteristics influence the assembly processes. Bark is an important structural and nutritious component of dead wood. Especially during the initial colonization, numerous species specialize in utilizing phloem and bark as resources, habitats or shelters. (Parisi et al., 2018; Ulyshen, 2018).

The shifts we found in abundances of certain species between treated and control logs may be attributed to changes in habitat availability, nutrition supply and competitive interactions with other species. So for example the generalized predatory rove beetle *Dolotia coriaria* showed higher total abundance in treated logs likely benefiting from reduced competition. *Monotoma longicollis* and *Cartodere nodifer* as two abundant facultative saproxylic species (Graf et al., 2022) showed higher total abundances in treated logs, which might be attributed to their connection to decaying plant matter or moulds for their nutrient uptake. Moulds growing on the wood surface and decomposing bark remnants might be more abundant and accessible in logs with manipulated bark. *Nudobius lentus* and *Placusa depressa* are predatory on bark beetles and use the galleries as their habitat (Möller, 2009) and both indicated highest total abundance in the control logs without bark treatment and high bark beetle abundance. *Cartodere constricta* is another saproxylic species feeding on fungi under the bark (Möller, 2009) with higher total abundance in the control logs (see Table S1).

Species assemblages in the later stages of decaying CWD are characterized by the preceding processes and assemblages. Thus, the primary structural integrity of dead wood after treatment for bark beetle reduction is creating the legacy of saproxylic colonization. Intact bark also serves as barrier for wood decaying fungi and maintains constant conditions (i.e. humidity) for the succession of saproxylic beetle species (Hagge, Bässler, et al., 2019). With the multivariate analysis of the species data, we provide evidence that the assemblage of beetle species in the early colonization process is characterized by the intensity of bark removal. Biodiversity oriented management of disturbances and CWD will increase the resilience of forests in the face of the ongoing global environmental crises (Müller et al., 2023). Hence, the debarking head can be recommended to process large quantities of (infested) breeding material, without threatening the goals of biodiversity conservation.

5 | CONCLUSIONS

We present a conservation-friendly method to safeguard timber production forests from bark beetle outbreaks after disturbances like windstorms. Wood treated during the larval stage or before infestation with the harvester debarking head or the bark gouging device can remain for intermediate storage or CWD retention within the forest stands. Harvesters equipped with debarking heads are a compromise between nature conservation and more economic 'forest protection' goals. Due to the capacity of treating large amounts of wood, they are particularly well-suited for managing disturbances at large scales and can prevent dependencies on transport or fluctuating market prices for commercial forestry. In protected areas, the use of debarking heads for pest control should be considered as an alternative to salvage logging, to maintain ecosystem integrity. For the treatment of logs at small scales, bark gouging is the most conservation friendly bark beetle control method. In both cases, the wood can be retained within the stand to maintain natural processes in the re-growing forests. Despite an impact on species assemblage, the species richness of non-target beetles remains unaffected with the (partial) removal of bark. These alternative pest control methods are suitable for promoting biodiversity without the more detrimental effects to ecosystem functioning associated with salvage logging.

AUTHOR CONTRIBUTIONS

Jonas Hagge and Jörg Müller designed and conceived the research. Sebastian Zarges conducted the literature research, statistical analysis and wrote the first draft of the manuscript. Jonas Hagge collected the insect samples. Jan Wohlert processed the insect samples. All authors critically contributed by reviewing and editing the manuscript. Jonas Hagge supervised and administrated the project. All authors contributed and approved to the final version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

Jonas Hagge is an Associate Editor for *Ecological Solutions and Evidence* but was not involved in the peer-review and decision-making process. The authors do not have any conflicts of interest regarding the article.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Data supporting the findings of this research article are available at the DRYAD public repository: https://doi.org/10.5061/dryad.4f4qrfjmr (Zarges et al., 2024).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1: Debarking device with the rotating cylinder at two positions equipped with the four modified knifes for bark gouging.

Figure S2: (a) Harvester John Deere 1270 G fitted with a (b) harvesting aggregate H 480 C modified for debarking (debarking head) and the resulting debarked logs. (c) Standing snags can also be debarked for phytosanitation with the debarking head to regulate *Ips typographus* populations and retain a variety in dead wood to support biodiversity.

Table S1: List of beetle species sorted according to FHL-Code with number of emerged individuals from the experimental logs for harvester debarking head, harvester normal, gauged and control.

Table S2: Results of multiple comparisons of the differences in abundance of emerged *Ips typographus*, and number of non-target beetle species between treatments, based on results of the quasi-Poisson models.

Table S3: Results of the simper analysis for the contribution of the top three species to the differences in beetle species assemblages between the four treatments.

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