Author(s): Purhonen, Jenna; Nirhamo, Aleksi; Jäntti, Mari; Halme, Panu

Title: Forest fuel extraction does not affect macrolichens on deadwood substrates, but only if coarse woody debris is not collected

Year: 2024

Version: Published version

European Journal of Forest Research
https://doi.org/10.1007/s10342-024-01692-y

RESEARCH

Forest fuel extraction does not affect macrolichens on deadwood substrates, but only if coarse woody debris is not collected

Jenna Purhonen[1,2,3] · Aleksi Nirhamo[4] · Mari Jäntti[5] · Panu Halme[1,3]

Received: 13 December 2023 / Revised: 20 February 2024 / Accepted: 10 April 2024

Abstract

The increasing use of forest fuels poses risks to biodiversity. Lichens that grow on deadwood may be affected as fuel extraction removes their substrates. We surveyed deadwood and macrolichens on deadwood in two types of clearcuts: sites in which forest fuels, stumps and slash, had been extracted, and standard clearcut sites, i.e. control sites with no fuel extraction. Extraction sites had 52% lower deadwood volume (44.3 m^3/ha vs. 21.4 m^3/ha) and 36% less deadwood surface area. However, the negative impact of fuel extraction on macrolichen species richness was low: 21.4 and 16.9 species on average were found in control and extraction sites, respectively. We found a clear positive relationship between macrolichen species richness and the surface area of logs, which are usually not targeted by forest fuel extraction. Species composition varied more among extraction sites than control sites and differed between all the studied deadwood types. Species of *Cladonia* were associated with stumps, while species in the family Parmeliaceae were associated with logs. Slash was of negligible importance to macrolichens. Stumps may hold value, particularly if large-sized deadwood is otherwise not available. Thus, we conclude that the extraction of slash poses no threat to macrolichen diversity, whereas extensive extraction of stumps can cause losses in lichen diversity. The loss of coarse woody debris during forest fuel extraction has negative effects on lichen diversity and should be avoided.

Keywords Bioenergy harvest · Community ecology · Ecological sustainability · Forest management · Logging residual

Introduction

Many forest-dwelling species are dependent on deadwood, and their diversity has been reduced significantly because of the massive reduction of deadwood volume caused by forest management (Siitonen 2001). The majority of studies have focused on large-sized deadwood, i.e. coarse woody debris (CWD), but some studies have shown that small-sized deadwood, i.e. fine woody debris (FWD), and stumps are also host to many species, with the species compositions on them often being different from those on CWD (Kruys and Jonsson 1999; Jonsell et al. 2007; Brin et al. 2013; Juutilainen et al. 2014; Kubart et al. 2016). Thus, further reduction of deadwood in the form of forest fuel extraction is likely to continue the reduction of the diversity of deadwood organisms.

The demand for renewable energy to mitigate climate change has been growing in the recent years. This has led to the increased extraction of forest fuels to replace fossil fuels, which, in turn, can lead to other environmental issues such as the loss of biodiversity (de Jong et al. 2017; Ranius et al. 2018). The extraction of forest fuels refers to the harvesting of logging residues such as stumps, tree tops, branches and roots (Bouget et al. 2012). This effectively means that a notable portion, 40–80% according to estimates (Rudolphi and Gustafsson 2005; Eräjää et al. 2010), of deadwood is removed from clearcut areas. Only

Communicated by Claus Bässler.

✉ Jenna Purhonen
jenna.purhonen@jyu.fi

1 Department of Biological and Environmental Science, University of Jyväskylä, Jyväskylä, Finland

2 Biodiversity Unit, University of Turku, Turku, Finland

3 School of Resource Wisdom, University of Jyväskylä, Jyväskylä, Finland

4 School of Forest Sciences, University of Eastern Finland, Joensuu, Finland

5 Centre for Economic Development, Transport and the Environment of North Savo, Kuopio, Finland

Published online: 27 April 2024

a few studies have considered the effect of forest fuel harvesting on organisms utilizing deadwood. Most of the studies have found neutral or contrasting effects (Ranius et al. 2018). In studies that found negative effects, especially stumps have been an important resource compared to slash for fungi and beetles (Toivanen et al. 2012; Hiron et al. 2017).

Deadwood has been estimated to be utilized by 43% of the epiphytic lichen flora, so that 10% of epiphytic lichens are obligate deadwood users (Spribille et al. 2008). Different lichen assemblages are found on different deadwood types (Caruso et al. 2008; Nascimbene et al. 2008). Previous studies have shown that stumps may host notable numbers of lichen species, while FWD usually is less important to lichens (Caruso et al. 2008; Svensson et al. 2013, Hämäläinen et al. 2015, Svensson et al. 2016; but see Hiron et al. 2017). Many of the lichen species on these substrates are common generalists, but stumps may also host some deadwood-dependent species (Svensson et al. 2013, Hämäläinen et al. 2015, Svensson et al. 2016). Many studies have investigated the lichen assemblages found on substrate types that are used as forest fuels, but none have studied the actual effects of forest fuel extraction on lichens that use fuel materials as their substrate.

In this study, we compared the amounts of different types of deadwood and the macrolichen assemblages on deadwood between clearcuts in which forest fuels had been extracted and regular clearcuts (forest fuels not extracted). We assessed the impact of forest fuel extraction on macrolichen species richness and composition, and we compared the importance of different deadwood types found on clearcuts for macrolichens. Thus, we were able to provide new insights into the biodiversity impacts of forest fuel extraction.

Materials and methods

This study was conducted in 12 study sites provided by forestry company UPM in the southern boreal zone in central Finland (Ahti et al. 1968). The sites were *Picea abies* -dominated managed forests that had been clearcut 7–9 years ago. Forest fuels had been extracted from seven sites, so that stumps and slash had been harvested from five sites, while only slash had been harvested from two sites. Five sites were regular clearcuts where slash and stumps had not been harvested. In each study site, we set up three study plots of 10 m x 5 m. The plots were positioned 10, 20 and 30 m from the central point of the site towards randomized compass directions.

The field work was conducted in the summer 2015. We surveyed all deadwood units with > 20 cm length and > 2 cm width that had their basal end within the plot. Stumps were surveyed if more than half of them was within the plot. Deadwood that was underground or covered by a thick layer of humus was ignored. We categorized the deadwood units into logs, stumps and slash. Logs with diameter < 5 cm were categorized as slash. Only a few units of standing deadwood were found from the plots in the whole study, so we decided to ignore standing deadwood. Some of the extraction sites contained several stumps that had been pulled from the ground but not collected. We assumed that this was a deviation from the common procedure of forest fuel extraction. Thus, we ignored the uprooted stumps to depict a situation where these stumps had also been collected. We used the formula for a cylinder to calculate the surface area and volume of stumps, and the formula for a truncated cone for all other deadwood units.

We recorded all macrolichen occurrences on the wood and bark of the surveyed deadwood units within the plots. We considered the presence of a lichen species on any deadwood unit as a single occurrence of the species. Most observations of *Peltigera*, *Usnea* and *Bryoria* were juvenile thalli that could not be identified at the species level, and thus they were recorded at the genus level.

We used a generalized linear model (GLM) with a Poisson distribution to analyze the association of macrolichen species richness with the surface area of logs, stumps and slash. A quadratic term for log surface area was added, since the response of macrolichen richness to log surface area was nonlinear, and the inclusion of the quadratic term increased the R^2 of the model. We attained virtually identical results when volumes of the different deadwood types were used as explanatory variables, but focused on surface area as it is a more accurate measure of habitat availability for lichens. We used ordination analyses to examine macrolichen community composition in the study sites. We used non-metric multidimensional scaling (NMDS) to analyze the dissimilarities of site-level communities. For the site-level analysis, the abundance of the species was based on the number of occurrences of a species in a site. We performed another NMDS to examine communities at the level of deadwood units. Deadwood units with two or less lichens were excluded. Moreover, species with less than five total occurrences were excluded from the NMDS analyses. In addition, we calculated the phi coefficient of association (r_{Φ}) between species and sites (De Cáceres and Legendre 2009), which in this case were individual deadwood units. This way, we analysed the associations between species and different deadwood types. The statistical analyses were

Table 1 (**a**) The surface area (m²/ha) of total deadwood and different deadwood types, (**b**) the volume (m³/ha) of total deadwood and different deadwood types, and (**c**) the species richness of all macrolichens, Cladonia and Parmeliaceae on the study plots in control sites and extraction sites. All values are averages. The extraction sites include both sites where stumps and slash were extracted and the sites where only slash were extracted, except for stumps, where the sites where only slash was extracted were included in control sites

	Control sites	Extraction sites	%-difference
a) Deadwood surface area (m²/ha)			
Total	1527	839	45%
Logs	606	393	35%
Stumps	349	174	50%
Slash	573	212	63%
b) Deadwood volume (m³/ha)			
Total	44.28	21.39	52%
Logs	22.20	11.12	50%
Stumps	15.53	5.69	63%
Slash	6.56	2.57	61%
c) Lichen species richness			
Macrolichens	21.4	16.9	21%
Cladonia	11.0	10.3	6%
Parmeliaceae	10.2	6.1	40%

performed with R software version 4.2.2 (R Core Team 2023), and the ordination analyses were performed using the 'vegan' package (Oksanen et al. 2022), and the analysis of species-sites-associations with the 'indicspecies' package (De Cáceres and Legendre 2009).

Results

We recorded a total of 1257 deadwood units, of which 721 (57%) hosted at least one macrolichen species. The extraction sites had on average 36% lower total deadwood surface area (ANOVA: $F(1,10)=4.50$, $p=0.060$), and 52% lower total deadwood volume (ANOVA: $F(1,10)=7.70$, $p=0.020$) compared to the control sites (Table 1). Total deadwood volume and surface area were highly correlated (Pearson's correlation coefficient $r=0.94$; Fig. 1a). We made a total of 2024 macrolichen observations consisting of 35 species, which all belonged either to the genus *Cladonia* or the family Parmeliaceae apart from 7 observations of *Peltigera*. Macrolichen species richness per study site ranged from 6 to 26, and from 0 to 16 per deadwood unit. Average macrolichen species richness was 21.4 in control sites and 16.9 in extraction sites (ANOVA: $F(1,10)=2.03$, $p=0.184$) (Table 1).

Site-level species richness was explained by deadwood surface area. When deadwood surface area was split between deadwood types, site-level species richness was shown to be controlled by the surface area of logs (CWD) specifically, while the surface area of slash and stumps had no effect (Table 2; Fig. 2).

The site-level NMDS indicated that sites where forest fuels have been extracted may host differentiated macrolichen communities. The communities on control sites were more similar with each other, while communities on the forest fuel extraction sites (slash and stump and slash) varied more from each other (Fig. 3). At the level

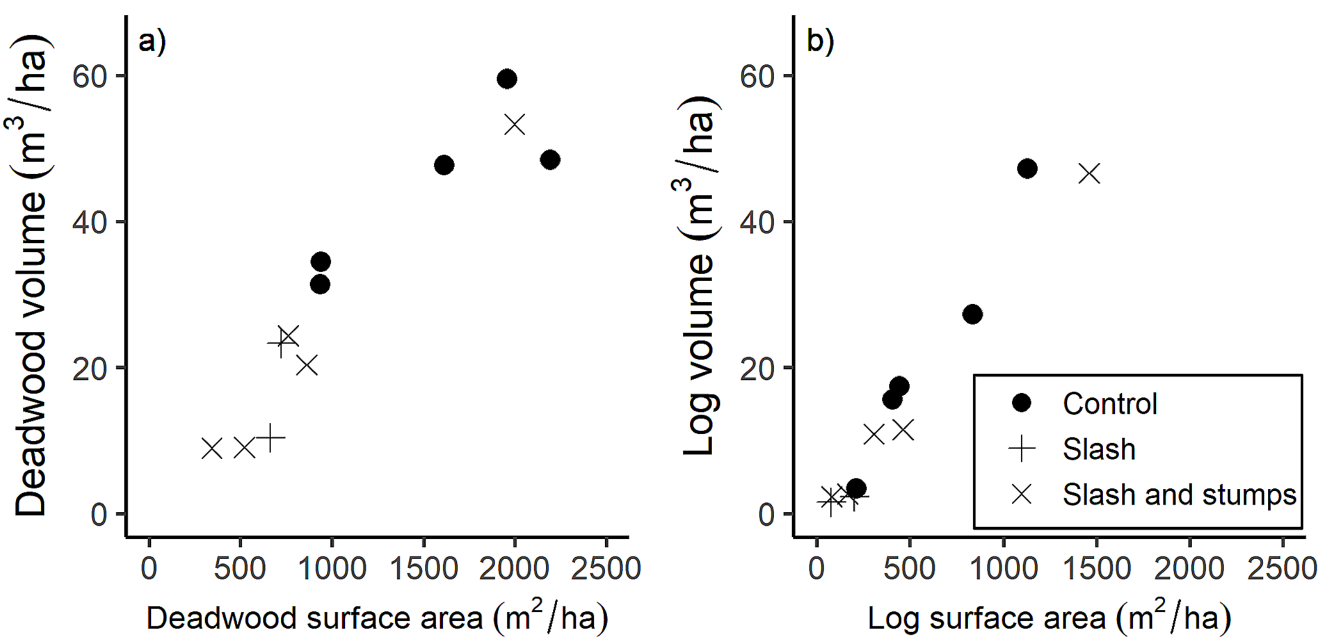

Fig. 1 The relationship between deadwood surface area and volume for (**a**) all deadwood, and (**b**) logs. R software, version 4.2.2 (R Core Team 2023)

Table 2 GLM results for macrolichen species richness and its association with the surface area (reported exceptionally for dm²/ha to avoid large number of decimals in the table) of different deadwood types. For the model, $R^2 = 0.72$

	Estimate	SE	z value	*p*-value
Intercept	2.301	0.226	10.187	< 0.001
Log surface area	0.163	0.064	2.549	0.011
Log surface area²	-0.007	0.004	-1.726	0.084
Stump surface area	0.029	0.046	0.621	0.535
Slash surface area	0.008	0.017	0.455	0.650

of deadwood units, stumps, logs and slash had differences in macrolichen community composition (Fig. 4). In the analysis of associations between species and deadwood types, there was a distinct split between *Cladonia* being associated with stumps and Parmeliaceae with logs (Table 3). No species were found to be associated with slash.

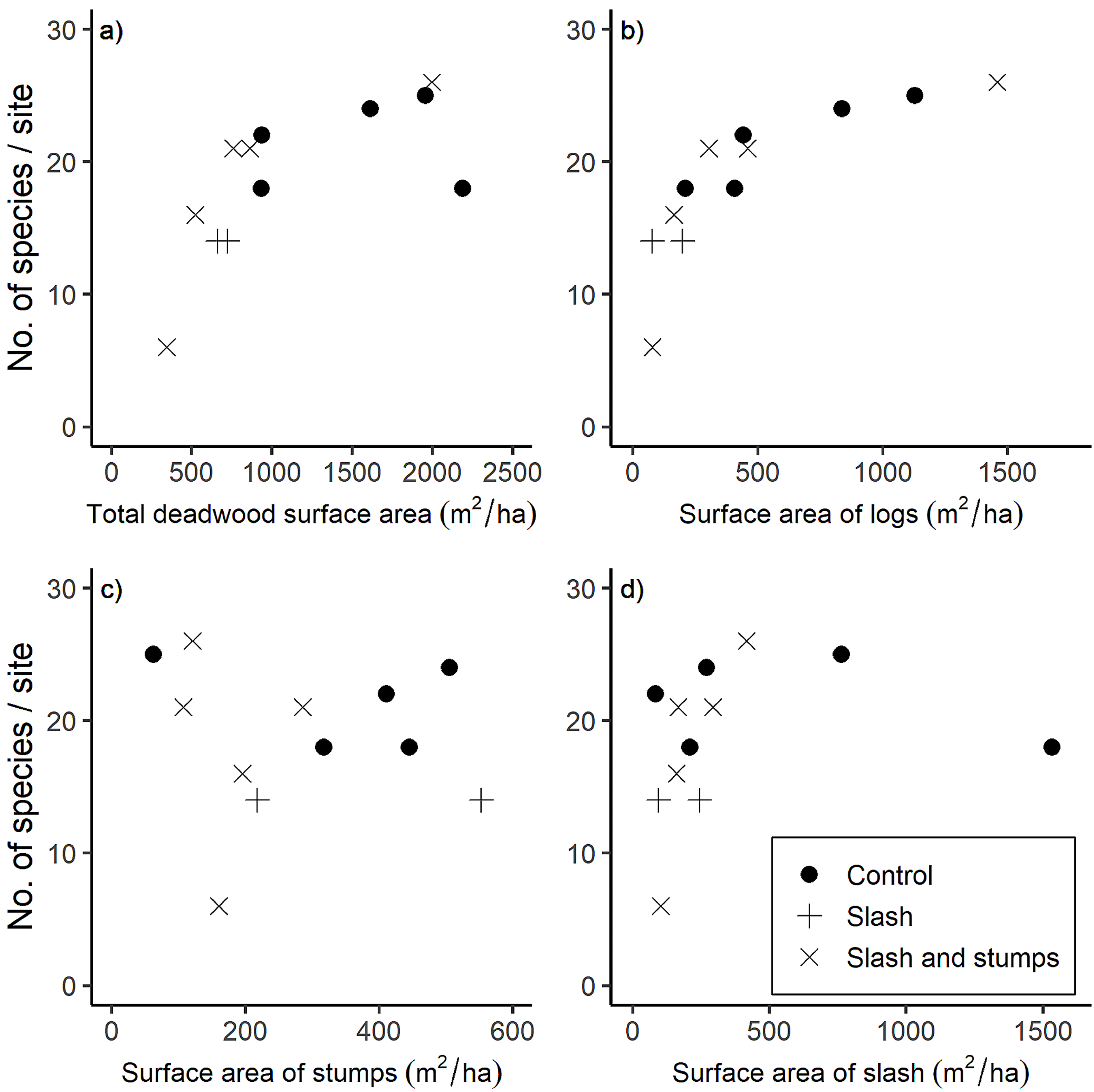

Fig. 2 The response of site-level macrolichen species richness to (**a**) total deadwood surface area, and the surface area of (**b**) logs, (**c**) stumps and (**d**) slash. R software, version 4.2.2 (R Core Team 2023)

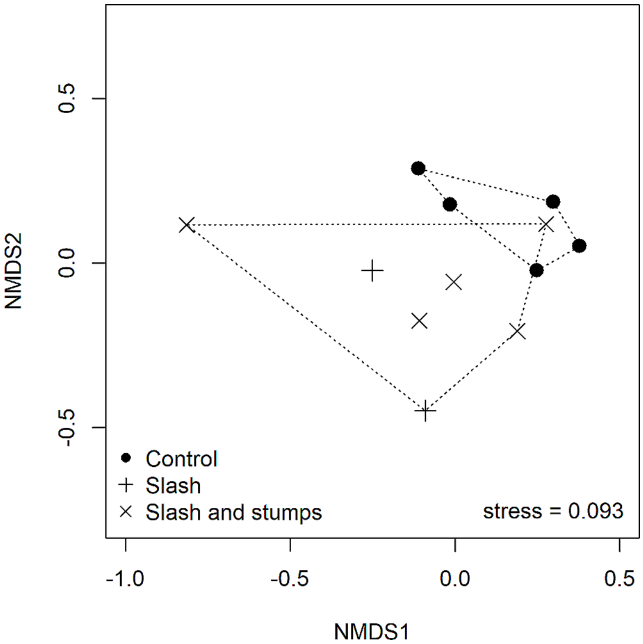

Fig. 3 Site-level non-metric multidimensional scaling of the macrolichen communities occurring in differently managed study sites. The dashed lines outline the areas within which all symbols of control and extraction sites are located for illustrative purposes. The stress for scaling is reported in the bottom of the figure. R software, version 4.2.2 (R Core Team 2023)

Discussion

We found that macrolichen species richness on deadwood in clearcut sites is closely associated with available deadwood surface area. Since the extraction of forest fuels reduces the amount of deadwood (Eräjää et al. 2010), it may be expected to affect lichen diversity negatively. However, we found the negative impact on species richness to be low. This was because macrolichen species richness was associated specifically with the surface area of logs (CWD), which are primarily not affected by forest fuel extraction (but see Rudophi & Gustafsson 2005). Notably, macrolichen richness increased steeply until log surface area was approximately 500 m²/ha, which corresponded to a volume of about 15 m³/ha, after which the richness increase was weaker. However, we surveyed rather small plots (0.015 ha per site), and it is highly uncertain whether the relationship between deadwood quantity and lichen richness would scale up similarly if larger areas and numbers of logs were surveyed. Regardless, our results clearly indicate that the richness of lichens on deadwood is connected to deadwood quantity. This has been noted widely for deadwood-associated biota, but the topic has been studied scarcely in regard to lichens (Parajuli and Markwith 2023).

In contrast, the amounts of stumps and slash, the types of deadwood that are removed in forest fuel extraction, were less important for macrolichen diversity. As may be expected, the surface area of stumps and slash was distinctively lower in the extraction sites. While the surface area of stumps was not associated with macrolichen species richness, the macrolichen community composition was unique on stumps compared to slash or logs. Stumps were the preferred substrate for many species, although these species did occur also on logs. Since logs and snags are infrequent in the managed landscape while stumps are abundant, stumps may act as a substitute substrate for species that naturally occur on logs or snags. Consequently, stumps have a high relative importance as substrates for deadwood-associated lichens in managed forests (Svensson et al. 2016). Therefore, particularly in the absence of logs and snags, the extraction of stumps is likely to cause losses in lichen diversity. Moreover, a relatively short time (7–9 years) had passed since the clearcuts in our study sites. Lichen diversity on stumps and therefore also the diversity impacts of stump extraction may be expected to increase over time, since lichen richness is known to be higher on older stumps (Caruso and Rudolphi 2009; Svensson et al. 2013). A similar effect is unlikely on slash because of its quicker decomposition due to its small size.

Extraction sites had 52% less deadwood volume and 36% less deadwood surface area compared to control sites. Previous studies have reported rather similar reductions of deadwood volume by forest fuel extraction (Rudolphi and Gustafsson 2005; Eräjää et al. 2010). However, Eräjää et al. (2010) reported a higher reduction of stump volume and a lower reduction of slash volume, which may reflect a lack of a standard approach to forest fuel extraction. We found much lower amounts of slash and stumps in the extraction sites, as expected, but also log volume was 50% lower than in non-harvested sites. Even though collecting logs is not a part of forest fuel extraction in principle, it is possible that logs are also collected during forest fuel extraction (Rabinowitsch-Jokinen and Vanha-Majamaa 2010). In addition, logs or snags may be destroyed by trampling by harvesting machinery (Hautala et al. 2004; Rabinowitsch-Jokinen and Vanha-Majamaa 2010). Our study highlights the importance of CWD, and since the amount of CWD is very low in managed forests (Siitonen 2001), any CWD should be left intact during forest fuel extraction and other forestry operations.

Nine out of the twelve study sites contained more than half (≥ 17) of the species observed in the study. This indicates that the species pool of macrolichens occurring on deadwood in these sites consisted mainly of common

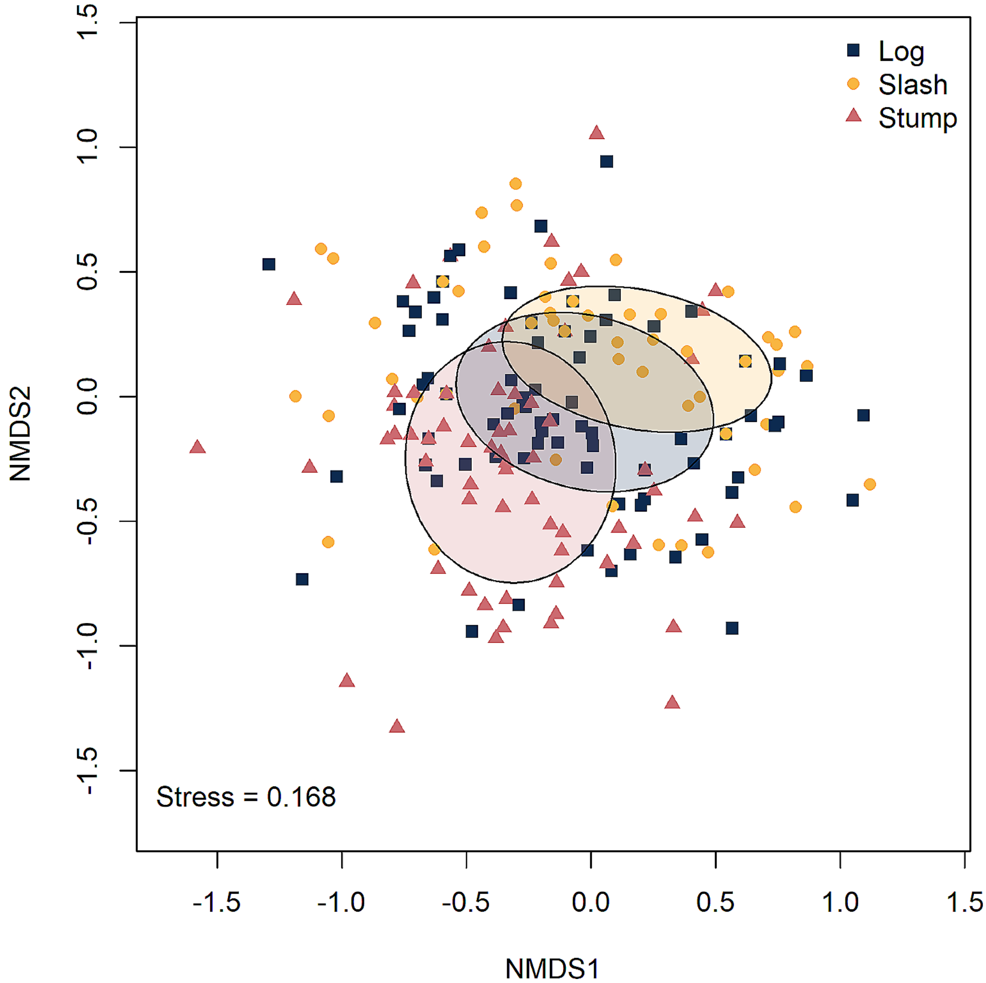

Fig. 4 Deadwood-level non-metric multidimensional scaling of the macrolichen communities on different deadwood types. The ellipses describe the standard deviation of the points from the centroid of the given deadwood type. The colors of the ellipses correspond to the colors of the symbols. R software, version 4.2.2 (R Core Team 2023)

species. Most of the macrolichen species observed in this study can be characterized as generalists that occur mainly on the ground or on humus (e.g. reindeer lichens *Cladonia rangiferina*, *C. arbuscula*) or on the bark of living trees (members of Parmeliaceae) and utilize deadwood as a facultative substrate. However, for some of the observed *Cladonia* species, deadwood may be the primary substrate even though none of them are strictly dependent on it. Therefore, the studied substrates do not have special importance for macrolichen diversity on a large scale.

Our study did not include microlichens. Approximately three out of four epiphytic lichens found in Fennoscandia are microlichens, and nearly all deadwood-dependent lichens are microlichens (Spribille et al. 2008). Thus, a significant section of the lichen diversity on deadwood substrates was omitted. Deadwood-dependent microlichens have been shown to occur frequently on stumps, but scarcely on dead branches (Svensson et al. 2016). We found similar patterns in the relative importance of these substrates for macrolichens. Furthermore, occurrence patterns of full lichen assemblages (with microlichens included) on these deadwood substrates observed in other studies (Caruso et al. 2008, Hämäläinen et al. 2015), are similar to the patterns we observed for macrolichens here. Thus, the occurrence patterns of microlichens likely were similar to those of macrolichens in our study sites. However, concerning lichens on deadwood, microlichens have been shown to be more sensitive to forest management than macrolichens (Kantelinen et al. 2022), and this could also be the case regarding forest fuel extraction.

In conclusion, we expect the extraction of slash to possess no threat to the diversity of macrolichens, since the species that we found on slash are common and they grow on a wide range of substrates. Stumps, on the other hand, are utilized by a wider range of species, including species that are deadwood specialists (Caruso and Rudolphi 2009; Svensson et al. 2016). Therefore, extensive extraction of stumps can lead to a loss of lichen diversity, especially if there is no CWD available otherwise. These claims are also supported by other studies on lichens on these types of deadwood substrates (Caruso et al. 2008, Hämäläinen et al. 2015, Svensson et al. 2016; Snäll et al.

Table 3 Species with a statistically significant association with a certain deadwood type. "rφ" expresses the strength of the association with a range from 0 to 1

Species	r_{φ}	p
Logs		
Platismatia glauca	0.189	< 0.001
Hypogymnia tubulosa	0.153	0.002
Parmelia sulcata	0.144	0.002
Parmeliopsis hyperopta	0.134	0.008
Pseudevernia furfuracea	0.134	0.007
Usnea spp.	0.128	0.010
Parmeliopsis ambigua	0.128	0.009
Bryoria spp.	0.119	0.024
Vulpicida pinastri	0.099	0.045
Stumps		
Cladonia coniocraea	0.502	< 0.001
Cladonia cenotea	0.373	< 0.001
Cladonia grayi	0.339	< 0.001
Cladonia fimbriata	0.272	< 0.001
Cladonia digitata	0.264	< 0.001
Peltigera spp.	0.223	< 0.001
Cladonia bacilliformis	0.217	< 0.001
Cladonia rangiferina	0.215	< 0.002
Cladonia arbuscula	0.188	< 0.001
Cladonia carneola	0.170	< 0.001
Cladonia gracilis	0.145	0.002
Cladonia chlorophaea	0.144	0.003
Cladonia merochlorophaea	0.135	0.006
Cladonia botrytes	0.130	0.009
Slash		
N/A		

2017). Continuing effort should be put into increasing the amount of CWD in the managed forest landscape.

Acknowledgements We thank UPM for providing the study sites. We also thank Sandra Savinen and Meeri Väätäinen for assisting in the data collection. We are grateful to Annina Kantelinen for guiding the lichen identification and Martin Chilman for commenting the work. This study was funded by Alfred Kordelin Foundation, Kuopion Luonnon Ystäväin Yhdistys, Suomen Biologian Seura Vanamo, and Societas pro Fauna et Flora Fennica.

Author contributions All authors contributed to the study conception and design. Material preparation and data collection was performed by J.P. and M.J. Preliminary analysis was performed by M.J. and J.P., while A.N. performed the final analysis and prepared the figures. The first draft of the manuscript was written by M.J., J.P. and P.H. The second draft was written by A.N. and J.P. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding provided by University of Jyväskylä (JYU). Alfred Kordelin Foundation to Jenna Purhonen; Kuopion Luonnon Ystäväin Yhdistys, and Suomen Biologian Seura Vanamo, and Societas pro Fauna et Flora Fennica to Mari Jäntti.
Open Access funding provided by University of Jyväskylä (JYU).

Data availability The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflicts of interest/Competing interests All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication All authors agreed with the content, and all gave explicit consent to submit, and obtained consent from the responsible authorities at the institute where the work was carried out, before the work was submitted.

References

Ahti T, Hämet-Ahti L, Jalas J (1968) Vegetation zones and their sections in northwestern Europe. Ann Bot Fenn 5:169–211. https://www.jstor.org/stable/23724233

Bouget C, Lassauce A, Jonsell M (2012) Effects of fuelwood harvesting on biodiversity – a review focused on the situation in Europe. Can J Res 42:1421–1432. https://doi.org/10.1139/x2012-078

Brin A, Bouget C, Valladares L, Brustel H (2013) Are stumps important for the conservation of saproxylic beetles in managed forests? – insights from a comparison of assemblages on logs and stumps in oak-dominated forests and pine plantations. Insect Conserv Divers 6:255–264. https://doi.org/10.1111/j.1752-4598.2012.00209.x

Caruso A, Rudolphi J (2009) Influence of substrate age and quality on species diversity of lichens and bryophytes on stumps. Bryologist 112:520–531. https://doi.org/10.1639/0007-2745-112.3.520

Caruso A, Rudolphi J, Thor G (2008) Lichen species diversity and substrate amounts in young planted boreal forests: a comparison between slash and stumps of Picea abies. Biol Conserv 141:47–55. https://doi.org/10.1016/j.biocon.2007.08.021

R Core Team (2023) R: A Language and Environment for Statistical Computing. https://www.r-project.org/. Accessed 21 November 2023

De Cáceres M, Legendre P (2009) Associations between species and groups of sites: indices and statistical inference. Ecology 90:3566–3574. https://doi.org/10.1890/08-1823.1

de Jong J, Akselsson C, Egnell G, Löfgren S, Olsson BA (2017) Realizing the energy potential of forest biomass in Sweden – how much is environmentally sustainable? Ecol Manage 383:3–16. https://doi.org/10.1016/j.foreco.2016.06.028

Eräjää S, Halme P, Kotiaho JS, Markkanen A, Toivanen T (2010) The volume and composition of dead wood on traditional and forest fuel harvested clear-cuts. Silva Fenn 44:203–211. https://doi.org/10.14214/sf.150

Hämäläinen A, Kouki J, Lõhmus P (2015) Potential biodiversity impacts of forest biofuel harvest: lichen assemblages on stumps and slash of scots pine. Can J Res 45:1239–1247. https://doi.org/10.1139/cjfr-2014-0532

Hautala H, Jalonen J, Laaka-Lindberg S, Vanha-Majamaa I (2004) Impacts of retention felling on coarse woody debris (CWD) in mature boreal spruce forests in Finland. Biodiv Conserv 13:1541–1554. https://doi.org/10.1023/B:BIOC.0000021327.43783.a9

Hiron M, Jonsell M, Kubartova A, Thor G, Schroeder M, Dahlberg A, Johansson V, Ranius T (2017) Consequences of bioenergy wood extraction for landscape-level availability of habitat for dead-wood dependent organisms. J Environ Manage 198:33–42. https://doi.org/10.1016/j.jenvman.2017.04.039

Jonsell M, Hansson J, Wedmo L (2007) Diversity of saproxylic beetle species in logging residues in Sweden – comparisons between tree species and diameters. Biol Conserv 138:89–99. https://doi.org/10.1016/j.biocon.2007.04.003

Juutilainen K, Mönkkönen M, Kotiranta H, Halme P (2014) The effects of forest management on wood-inhabiting fungi occupying dead wood of different diameter fractions. Ecol Manage 313:283–291. https://doi.org/10.1016/j.foreco.2013.11.019

Kantelinen A, Purhonen J, Halme P, Myllys L (2022) Growth form matters – crustose lichens on dead wood are sensitive to forest management. Ecol Manage 524:120529. https://doi.org/10.1016/j.foreco.2022.120529

Kruys N, Jonsson BG (1999) Fine woody debris is important for species richness on logs in managed boreal spruce forests of northern Sweden. Can J Res 29:1295–1299. https://doi.org/10.1139/x99-106

Kubart A, Vasaitis R, Stenlid J, Dahlberg A (2016) Fungal communities in Norway spruce stumps along a latitudinal gradient in Sweden. Ecol Manage 371:50–58. https://doi.org/10.1016/j.foreco.2015.12.017

Nascimbene J, Marini L, Motta R, Nimis PL (2008) Lichen diversity of coarse woody habitats in a *Pinus-Larix* stand in the Italian Alps. Lichenologist 40:153–163. https://doi.org/10.1017/S0024282908007585

Oksanen J, Simpson G, Blanchet F, Kindt R, Legendre P, Minchin P, O'Hara R, Solymos P, Stevens M, Szoecs E, Wagner H, Barbour M, Bedward M, Bolker B, Borcard D, Carvalho G, Chirico M, De Caceres M, Durand S, Evangelista H, FitzJohn R, Friendly M, Furneaux B, Hannigan G, Hill M, Lahti L, McGlinn D, Ouellette M, Ribeiro Cunha E, Smith T, Stier A, Ter Braak C, Weedon J (2022) vegan: Community Ecology Package. R package version 2.6-4. https://CRAN.R-project.org/package=vegan. Accessed 21 November 2023

Parajuli R, Markwith SH (2023) Quantity is foremost but quality matters: a global meta-analysis of correlations of dead wood volume and biodiversity in forest ecosystems. Biol Conserv 283:110100. https://doi.org/10.1016/j.biocon.2023.110100

Rabinowitsch-Jokinen R, Vanha-Majamaa I (2010) Immediate effects of logging, mounding and removal of logging residues and stumps in managed boreal Norway spruce stands. Silva Fenn 44:51–62. https://doi.org/10.14214/sf.162

Ranius T, Hämäläinen A, Egnell G, Olsson B, Eklöf K, Stendahl J, Rudolphi J, Sténs A, Felton A (2018) The effects of logging residue extraction for energy on ecosystem services and biodiversity: a synthesis. J Env Manage 209:409–425. https://doi.org/10.1016/j.jenvman.2017.12.048

Rudolphi J, Gustafsson L (2005) Effects of forest-fuel harvesting on the amount of deadwood on clear-cuts. Scand J Res 20:235–242. https://doi.org/10.1080/02827580510036201

Siitonen J (2001) Forest management, coarse woody debris and saproxylic organisms: Fennoscandian boreal forests as an example. Ecol Bull 49:11–41. https://www.jstor.org/stable/20113262

Snäll T, Johansson V, Jönsson M, Ortiz C, Hammar T, Caruso A, Svensson M, Stendahl J (2017) Transient trade-off between climate benefit and biodiversity loss of harvesting stumps for bioenergy. Glob Change Biol Bioenergy 9:1751–1763. https://doi.org/10.1111/gcbb.12467

Spribille T, Thor G, Bunnell FL, Goward T, Björk CR (2008) Lichens on dead wood: species-substrate relationships in the epiphytic lichen floras of the Pacific Northwest and Fennoscandia. Ecography 31:741–750. https://doi.org/10.1111/j.1600-0587.2008.05503.x

Svensson M, Dahlberg A, Ranius T, Thor G (2013) Occurrence patterns of lichens on stumps in young forests. PLoS ONE 8:e62825. https://doi.org/10.1371/journal.pone.0062825

Svensson M, Johansson V, Dahlberg A, Frisch A, Thor G, Ranius T (2016) The relative importance of stand and dead wood types for wood-dependent lichens in managed boreal forests. Fung Ecol 20:166–174. https://doi.org/10.1016/j.funeco.2015.12.010

Toivanen T, Markkanen A, Kotiaho JS, Halme P (2012) The effect of forest fuel harvesting on the fungal diversity of clear-cuts. Biomass Bioenergy 39:84e93. https://doi.org/10.1016/j.biombioe.2011.11.016