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## Habitat associations drive species vulnerability to climate change in boreal forests

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**ESM 1**  
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# Habitat associations drive species vulnerability to climate change in boreal forests

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**Abstract** Species climate change vulnerability, their predisposition to be adversely affected, has been assessed for a limited portion of biodiversity. Our knowledge of climate change impacts is often based only on exposure, the magnitude of climatic variation in the area occupied by the species, even if species sensitivity, the species ability to tolerate climatic variations determined by traits, plays a key role in determining vulnerability. We analyse the role of species' habitat associations, a proxy for sensitivity, in explaining vulnerability for two

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poorly-known but species-rich taxa in boreal forest, saproxylic beetles and fungi, using three IPCC emissions scenarios. Towards the end of the 21st century we projected an improvement in habitat quality associated with an increase of deadwood, an important resource for species, as a consequence of increased tree growth under high emissions scenarios. However, climate change will potentially reduce habitat suitability for ~9–43 % of the threatened deadwood-associated species. This loss is likely caused by future increase in timber extraction and decomposition rates causing higher deadwood turnover, which have a strong negative effect on boreal forest biodiversity. Our results are species- and scenario-specific. Diversified forest management and restoration ensuring deadwood resources in the landscape would allow the persistence of species whose capacity of delivering important supporting ecosystem services can be undermined by climate change.

## 1 Introduction

Assessing species climate change vulnerability requires an estimate of their exposure, sensitivity and adaptive capacity (Dawson et al. 2011). Foden et al. (2013) carried out an evaluation of well-studied taxonomic groups such as birds (~9800 species, 35 % found susceptible to climate change), amphibians (~6200 species, 52 % susceptible) and important ecosystem engineers such as corals (~800 species, 70 % susceptible). Our knowledge of the impacts of climate change on other poorly known but functionally important taxa, such as insects, remains limited (Bush et al. 2014; Mair et al. 2014; Arribas et al. 2012; Bellard et al. 2012; Wilson and Maclean 2011). For this neglected majority of species, vulnerability has often been based only on their exposure to climate change. However it is well-established that sensitivity and adaptive capacity also play a role in determining species vulnerability (Garcia et al. 2014; Foden et al. 2013; Triviño et al. 2013; Arribas et al. 2012; Summers et al. 2012; Dawson et al. 2011). The knowledge of species characteristics affecting their sensitivity to climate change is very limited for most species, and practically null concerning their adaptive capacity (Bush et al. 2014; Arribas et al. 2012). Furthermore, species vulnerability critically depends on land use change (Barbet-Massin et al. 2012; Ponce-Reyes et al. 2012; Brook et al. 2008). Accounting for this important component of global change when predicting vulnerability improves predictions about future species persistence (Fordham et al. 2013; Triviño et al. 2013; Ponce-Reyes et al. 2012).

Here we analysed the role of species' habitat associations in affecting climate change vulnerability for 129 Finnish threatened saproxylic (deadwood associated) beetles and fungi (Tikkanen et al. 2006), two species-rich taxonomic groups in boreal forests. Both groups depend on deadwood, the main habitat and food resource for 25 % of the species living in this biome, and are functionally important in key processes like nutrient and carbon cycling and soil formation (Harmon et al. 1986). For this assessment we used the SIMA forest simulator to forecast the effects of climatic conditions on ecological processes (Kellomäki et al. 2008). The simulator can translate forest changes driven by climatic scenarios and management regimes into changes in habitat characteristics for saproxylic species (details in Supplementary Methods 1–3, limitations in Supplementary Methods 6). In our simulations, the vulnerability of species was measured as a combination of species sensitivity to changes in habitat characteristics and exposure of forest stands to climate change.

We simulated forest ecosystem dynamics for 2816 sample plots (forest stands) of the National Forest Inventory in Finland, evenly spanning across all vegetation subzones of the

boreal forest (Supplementary Methods 2). We selected a time horizon of 90 years (2010–2099), and evaluated the changes in habitat quality for deadwood species. We assumed no changes in land use and forest management during the time horizon, with 91 % of the forest area currently under intensive timber production (Yrjölä 2002) and 9 % set-aside. Even if management practices remain the same, shorter forest rotations will take place following faster tree growth caused by climate change (Kellomäki et al. 2008). To account for stochasticity in SIMA models (Supplementary Methods 3), we reran the simulations ten times and calculated the average values of the characteristics of the forest sample plots under three different IPCC emissions scenarios (B1, A1B, A2) downscaled for Finland (Jylhä 2009) (Supplementary Methods 1).

We evaluated the effects of climate change on species habitat availability by comparing these results with the outputs from simulations with current climatic conditions. Estimates of habitat availability for saproxylic species were based on the best available knowledge on their resources (tree species and diameter, deadwood decay stage) and micro-climatic niche axes (Kouki and Tikkanen 2007) (Supplementary Methods 4 and 6). For each species we calculated a climatic vulnerability value and identified *winner* (species experiencing improved habitat quality in the future), *loser* (reduced habitat quality) and *stable* species. We estimated the climate change vulnerability of the landscape by summing for each stand the species-specific vulnerability values. Finally, we used Generalized Linear Models (GLMs) for each IPCC scenario to assess the effects of sensitivity (species habitat association) vs. exposure (projected rate of climate change) on species climatic vulnerability.

## 2 Methods

Details concerning the climate data, the National Forest Inventory data modeling and simulation procedures applied in this manuscript are reported in Supplementary Methods 1–3. In the following sections we only report information about *threatened saproxylic species data*, the procedures to calculate *climate vulnerability (CV)*, and the *GLMs* relating vulnerability with habitat associations and climate.

**Threatened saproxylic species data** We extracted records of threatened species from the Hertta database, a subset of the Environmental Information System of SYKE, the Finnish Environment Institute, based on the data updated to 2013 for 64 coleopteran and 65 fungal species (Tikkanen et al. 2006) (Supplementary Table 2). Threatened saproxylic species are considered good indicators of the quality of forests, being able to survive only with reasonably high amounts of deadwood in the stand ( $\geq 20\text{m}^3/\text{ha}$ ); therefore favourable conditions for species survival in the stands can guarantee the persistence for many other saproxylic species inhabiting boreal forests.

**Climate Vulnerability (CV)** For each stand of the National Forest Inventory (NFI) we calculated Stand Conservation Capacity (*SCC*) as a weighted sum of species-specific habitat suitabilities (*HSIs*), the weights being the *HSIs* themselves (Supplementary Methods 4, 5 and 6). *CV* of forest stands is defined by subtracting the *SCC* calculated under three IPCC emissions scenarios ( $s = B1, A1B, A2$ ), regionally downscaled for Finland (Jylhä 2009), from the *SCCs* calculated under baseline climatic conditions ( $s = BC$ ). *SCCs* were averaged across

the last three simulated decades of the 21st century (2070–2099), when the effects of climate change on forest dynamics are predicted to be the highest (Jylhä 2009):

$$CV_s = \Delta SCC = SCC_{BC} - SCC_{s=B1,A1B,A2}$$

Original  $SCC$  values vary between 0 and 1. To put more emphasis on changes in values in the middle of the gradient ( $SCC$  values around 0.5 having more biological importance), we transformed  $CV$  values as follows:

$$scaled\ CV_s = CV_s [SCC_{BC} \times (1 - SCC_{BC})].$$

This transformation accounts for the fact that a small change in habitat suitability induced by climate change is expected to have less biological importance when the initial level of  $SCC$  under stationary climate is either very low or very high, and the highest importance is for intermediate  $SCC$  values. A negative sum of scaled  $CV$  values across the whole NFI corresponds to an increase in  $SCC$  induced by climate change (improved landscape quality); a positive sum of scaled  $CV$  values corresponds to a decrease in  $SCC$  under climate change (landscape degradation). In the text, figures, tables and supplementary materials, when not specified, the notation ‘ $CV$ ’ always must be considered as an abbreviation for ‘scaled  $CV$ ’ values.  $CV$  depends both on the modifications of stand quality induced by climate change (exposure) and on how species respond to these changes on the basis of their habitat association (sensitivity) (Dawson et al. 2011).

We also calculated the species-specific scaled  $CV$  values, i.e., the sum of differences across stands in  $HSI$  for each species, between the current and future climate. In the assessment we categorized species into winners if their average scaled  $CV$  across all stands belonged to the lowest quartile of the range of  $CV$  values, and losers when  $CV$  was in the highest quartile; all other species were considered stable typically having both negative and positive  $CV$  values (Supplementary Table 2). To summarize the species-specific information we calculated the average values of climate vulnerability for each species’ habitat associations in terms of resources and micro-climatic associations (Supplementary Table 1).

*Generalized Linear Models (GLMs)*: the association between climate vulnerability (response variable) and the joint and separate effects of sensitivity (i.e., species habitat association in terms of resources and micro-climatic associations as a categorical predictor) and exposure (i.e., climate change rate as a continuous predictor) were evaluated using GLMs for each IPCC emissions scenario (Supplementary Table 3). Climate change rate was measured as the difference between future and baseline emissions scenarios for the best combination (in terms of the lowest AIC values and limited multicollinearity) of five climatic variables (temperature sum, dry days, evaporation, evapotranspiration, precipitation) simulated for the end of the 21st century (averaged across the period 2070–2099). For the response variable we assumed a gamma distribution of errors (random part of the model) and a log link function (systematic part) between the dependent variable and the predictors. The means of GLM regression parameters for  $CV$  were calculated with the Wald test using robust standard errors. The importance of habitat association and climate change in explaining  $CV$  in the full model was evaluated by summing up for each of these two  $CV$  components the averaging sequential sums of squares over all orderings of regressors proposed by Lindeman et al. (1980) (lmg values) calculated for each variable related with these two components for the corresponding linear models. The sum of lmg values for all the climate change-related variables ( $\Delta T_{sum}$ ,  $\Delta Dry$  days, etc) defined the effect of climate, and the corresponding sum of habitat association

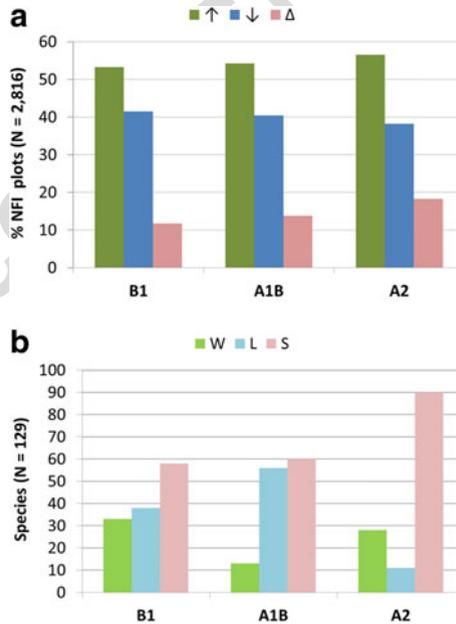
variables (tree, decay stage, etc) measured the effect of habitat factors. The relative effect of the two predictors in the full model was then summarized as a percent share of the total sum of lmg values.

All statistical analyses were performed using SPSS 20.0 (IBM Corp. 2011). Lmg values to evaluate the importance of the predictors in the GLMs were calculated via the R package “relaimpo” (<https://cran.r-project.org/web/packages/relaimpo/relaimpo.pdf>, Grömping 2006).

### 3 Results

#### 3.1 Response of forest landscape and species to climate change

Across all studied species we projected negative vulnerability values, i.e., improvement in habitat quality, for 53 % to 57 % of stands, depending on the IPCC scenario, and positive vulnerability, i.e., habitat degradation, for 38 % to 42 % of the stands (Fig. 1a). Even if there was an overall improvement in habitat quality losers were represented in the landscape depending on the emission scenario and in the case of the B1 and A1B scenario outperformed winners (Fig. 1b). Between 9 % and 43 % of the 129 deadwood-associated species can be considered losers and 10–26 % winners, while 45–70 % are stable in the face of climate

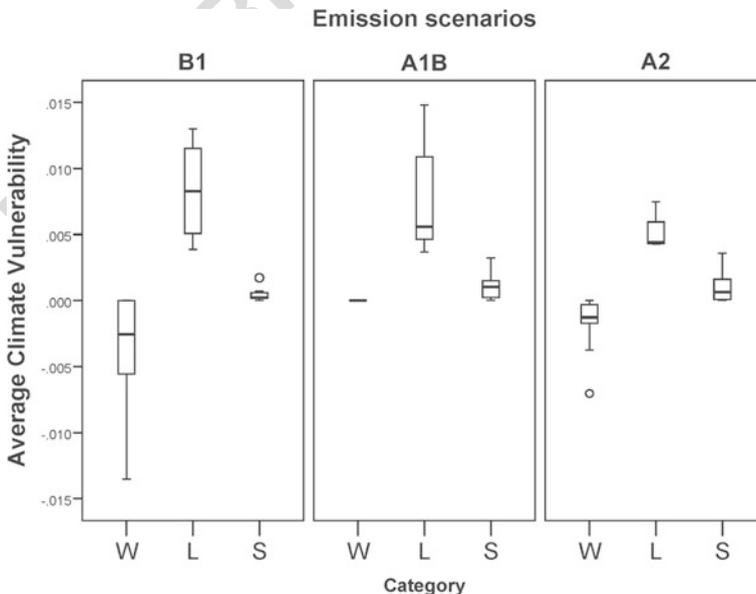


**Fig. 1** Response of forest landscape (a) and species (b) to climate change. (a) Percentages of the National Forest Inventory (NFI) sample plots, which are predicted to have either an improvement (↑) or a reduction (↓) in habitat quality towards the end of the 21st century under different climate change scenario. The difference between improvement and reduction (Δ) qualifies the overall trend for the landscape. (b) Number of threatened species predicted to be either winners (W), i.e., experience an improvement in their habitat quality, losers (L), i.e., experience a reduction in habitat quality, or stable (S), i.e., experience constant habitat quality under climate change. For (a), (b) changes in habitat quality refer to climate vulnerability values for the three IPCC emissions scenarios (Jylhä 2009) (B1, A1B, A2) respect to the baseline scenario for Finland

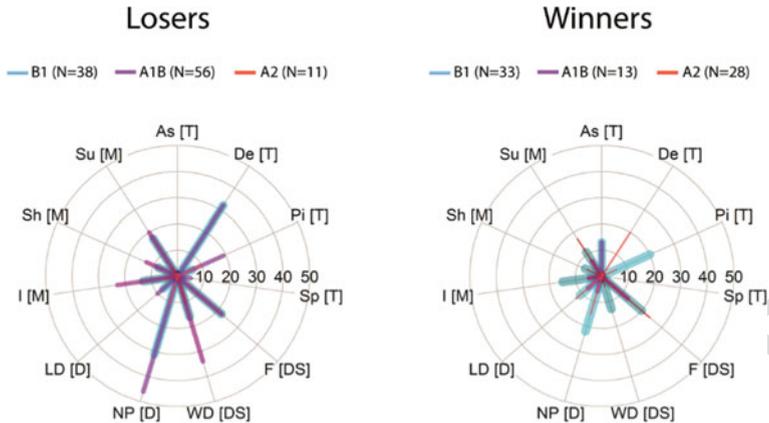
change (Fig. 1b). The proportions of winners was the highest under a low emission scenario (B1) while the losers were more represented under intermediate emissions (A1B) and the proportion of stable species increased with emissions (from B1 to A2) (Fig. 1b). For winners the average vulnerability was lower under low emissions (B1) than for higher emissions scenarios (A1B, A2). For losers even if the highest average vulnerability was observed under low (B1) emissions, the highest extreme values were observed under intermediate emissions (A1B) (Fig. 2).

### 3.2 Response of forest species to climate change with regards to their habitat associations

Winners and losers differed in terms of their habitat associations (Fig. 3, Supplementary Tables 1 and 2). The losers under low (B1) and intermediate (A1B) emissions were predominantly associated with deciduous trees (birch i.e., *Betula pendula* and *B. pubescens*) (respectively 84 % and 57 % of the species) while under high (A2) emissions losers were more often (91 %) associated with Scots pine. The winners were associated with Scots pine under low (B1) emissions (61 %), with aspen (100 %) under intermediate (A1B) and with other deciduous trees (71 %) under high (A2) emissions. With concern to decay stage associations, losers were more frequently associated with fresh deadwood (58 % under B1 scenario) or with well-decayed deadwood (61 % under A1B and 100 % under A2 scenario) than winners. Association with large diameter deadwood was not a crucial factor differentiating winners from losers. Under intermediate (A1B) and high (A2) emissions a large proportion of winners (respectively 54 and 61 %) were associated with sunny microclimate.



**Fig. 2** Variability in the response of forest species to climate change. Boxplots of average levels of climate vulnerability for each response category to climate change (W = Winners, L = Losers; S = Stable) of the threatened species for IPCC scenarios of increasing emissions (Jylhä 2009)



**Fig. 3** Response of forest species to climate change with regards to their habitat associations. For each IPCC emissions scenario (Jylhä 2009) (B1, A1B, A2) numbers of threatened species, separated for their habitat associations, which experienced either a reduction (losers) or an improvement (winners) in their habitat quality. Explanations and abbreviations reported in the following footnotes. *Species habitat association*: evaluated in terms of tree species [T], decay stage of deadwood [DS], tree diameter [D], and microclimate [M]. The attribution of threatened species to each habitat association is based on the notes reported in Tikkanen et al. (2006). *Species response*: average climate vulnerability (CV) among the NFI sample plots. Species responses can be: winner (the species experiences an improvement in its habitat quality), loser (the species experiences a reduction in its habitat quality), or stable (species keeps constant habitat quality). Classification of response categories: W = Winners = (average CV value <25th percentile of CV range), L = Losers = (average CV value >75th percentile), S = Stable = (25th percentile < average CV value <75th percentile). Legend: As = Aspen. De = Deciduous; Pi = Pine; Sp = Spruce; F = Fresh deadwood. WD = Well-decayed deadwood. LD = association for large diameter deadwood (>30 cm). NP = No association for a certain diameter classes. Su = preferring sunny sites. Sh = Demanding shade. I = Indifferent to microclimate

### 3.3 The contribution of sensitivity and exposure to climate vulnerability

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Species sensitivity, represented as habitat association, was a much stronger predictor of vulnerability across the landscape than climatic exposure, represented by the rate of projected climate change. In the full regression model where CV was explained both by habitat association (sensitivity) and climate change (exposure), predictors related with habitat association represented between 91 and 96 % of the explanatory power of the model (in terms of share of sum of lmg values) and only 4–9 % was explained by climatic exposure (Supplementary Table 3).

## 4 Discussion

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In the present study we analyse the role of species' habitat associations in explaining climate change vulnerability for two poorly-known but species-rich taxa in boreal forest, saproxylic beetles and fungi, using three IPCC emissions scenarios. We found towards the end of the 21st century an improvement in their habitat quality associated with an increase of deadwood, an important resource for these species, as a consequence of increased tree growth but also a reduction of habitat suitability likely caused by future increase in timber extraction and decomposition rates.

In accordance with previous studies addressing species' climate change vulnerability (Garcia et al. 2014; Triviño et al. 2013; Foden et al. 2013; Summers et al. 2012), we projected

more losers than winners for both the low (B1) and intermediate (A1B) emission scenarios while under high emission (A2) the winners increased dramatically respect to losers. Under low-intermediate emissions, about 30–40 % of the threatened deadwood-associated species were projected to face reduced habitat quality by the end of the 21st century, while habitat quality improved for a smaller fraction of species. However, across all species we projected an improvement in habitat quality for >50 % forest stands, most likely caused by increased deadwood (Mazziotta et al. 2014) as a result of increased in-tree growth and mortality with climate change (Mazziotta et al. 2014; Kellomäki et al. 2008).

The higher number of losers than winners for two emission scenarios, notwithstanding the overall increase in habitat quality, highlights the importance of accounting for species-habitat associations when evaluating vulnerability. This mismatch may be explained by the fact that, even though global warming is expected to increase deadwood availability through increased tree growth and mortality, the increased rate in deadwood turnover may ultimately limit species persistence in the landscape. Nevertheless, the strong decrease in stand habitat quality that we projected for about 40 % of stands reveals that climate change effects on habitat quality vary with the current characteristics of localities. With increasing emissions, the higher difference in the landscape's response to climate change among plots reflects the higher proportion of stable species. Especially under high emission (A2), the stronger increase in tree growth and mortality may outpace the increased rate in deadwood turnover overall increasing deadwood habitats. However this increased habitat availability is still partly determined by the local landscape suitability.

Suitable habitat conditions will increase in the future for winners species. However, even if habitat becomes available, many of these species may be unable to colonize this new space because of limited dispersal ability (Menéndez et al. 2006; Devictor et al. 2008). This is specially the case for poor dispersers like saproxylic species. Moreover, climate change is predicted to create novel communities from the new associations of species able to track their habitat and climatic niche (Williams and Jackson 2007). Species that are able to reach these new suitable species space might not be able to survive in these novel communities because they are not competitive enough, ultimately resulting in extinction events difficult to predict (Urban et al. 2012). Many species may continue to persist at local scale as an effect of extinction debt even after many decades of unfavorable environmental changes, ultimately maintaining high local levels of species richness, but their populations might become extinct in the long run (Hyvärinen et al. 2006; Berglund and Jonsson 2005).

We forecasted a positive trend in species associated with Scots pine and deciduous trees as a consequence of the predicted enhancement in annual growth of these tree species with increasing emissions (Mazziotta et al. 2014; Kellomäki et al. 2008). We also projected a decline of species preferring well-decayed deadwood. This stems from the fact that with climate change the retention time of the deadwood stock will be reduced by increased decomposition rates (Tuomi et al. 2011) making their habitats more temporary. Climate change also results in more frequent final harvest and subsequent harrowing (Kellomäki et al. 2008), further shortening deadwood retention times (Rabinowitsch-Jokinen et al. 2010). On the other hand, fresh deadwood will become more available, favoring species associated with this resource.

Earlier research has suggested that the relative importance that climatic exposure and ecological sensitivity have in determining vulnerability depends on the spatial scale. Exposure has more importance than sensitivity at the landscape or regional scale, while the opposite tends to be true at the local scale (Bradshaw et al. 2014; Garcia et al. 2014; Arribas

et al. 2012; Summers et al. 2012). In our regional-scale analysis, we projected that sensitivity, i.e., habitat associations, accounted for a much larger proportion of the variance in vulnerability than exposure. Evidently, whether exposure or sensitivity is driving vulnerability varies not only with spatial scale, but also among taxa and perhaps within their ecological niches. Earlier work has shown that the abundance, diversity and community composition of wood-decaying fungi are more dependent on the amount and diversity of resources than on macroclimate (Bässler et al. 2010). In other words, coarse (>10 cm) woody debris may create local microclimatic conditions that effectively isolate saproxylic species from the direct effects of macroclimate, and consequently climate change, at the landscape level (Bradford et al. 2014). This mismatch between micro- and macroclimatic conditions may explain why we projected strong effect of habitat associations (sensitivity) and very weak effect of macroclimate (exposure) on the vulnerability of saproxylic species.

## 5 Conclusions and implications

Many poorly known threatened species that are vitally important for supporting ecosystem services may be negatively influenced by climate change (Wilson and Maclean 2011; Mooney et al. 2009). This calls for action by policymakers and forest managers in establishing management and restoration measures to make the most of the positive effects of climate change for species, while alleviating the negative effects at the landscape level (see e.g. the decision framework for species conservation management in Shoo et al. (2013) and its critics in Ahteensuu et al. (2015)). Factors making some species losers vary among emissions scenarios to some extent. This uncertainty calls for management decisions providing large enough variability in forest structures, e.g. in terms of tree species composition, forest rotation lengths and amount of retained forest biomass. As habitat association is so important for explaining species climate vulnerability, management and restoration actions should aim at increasing habitat diversity and maximizing resources for deadwood species (Mazziotta et al. 2014; Halme et al. 2013; Mönkkönen 1999) to support their persistence in production landscapes in the face of climate change. These actions can be achieved, relatively low opportunity costs for society if carefully planned (Mönkkönen et al. 2014). The preservation of biodiversity under climate change may be in conflict with other societal interests. For example, European level policy incentives for more renewable climate-friendly energy (Stupak et al. 2007) has already resulted in increasing forest fuel harvesting, which in turn will reduce resource availability of deadwood-associated species and further cause species endangerment (Eräjää et al. 2010). More comprehensive forest management planning is needed for reconciling ecosystem services and the protection of biodiversity simultaneously (Mönkkönen et al. 2014). Enhanced biomass accumulation due to climate change may help to compensate the costs (i.e., declined land area for biomass production) of habitat improvement for saproxylic species.

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**Compliance with ethical standards**

**Conflict of interest** The authors declare no conflict of interest.

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