Impacts of dead wood manipulation on the biodiversity of temperate and boreal forests. A systematic review

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Abstract

1. Dead wood (DW) provides critical habitat for thousands of species in forests, but its amount, quality and diversity have been heavily reduced by forestry. Therefore, interventions aiming to increase DW might be necessary to support its associated biodiversity, even in protected forests, which may be former production forests. Our aim was to synthesize the current state of knowledge drawn from replicated experimental studies into solid quantitative evidence of the effects of DW manipulation on forest biodiversity, with a focus on protected forests.

2. We conducted a full systematic review of effects of DW manipulation on forest biodiversity in boreal and temperate regions. We included three intervention types: creation of DW from live trees at the site, addition of DW from outside the site and prescribed burning. Outcomes included abundance and species richness of saproxylic insects, ground insects, wood-inhabiting fungi, lichens, reptiles and cavity-nesting birds. In total, we included 91 studies, 37 of which were used in meta-analyses.

3. Although meta-analysis outcomes were heterogeneous, they showed that increasing the amount of DW (“DW enrichment”) has positive effects on the abundance and richness of saproxylic insects and fungi. The positive effect on saproxylic pest insect abundance tended to be less than that on saproxylic insects in general. No significant effects were found for ground insects or cavity-nesting birds.

4. Although reviewed studies were mainly short term, our results support that management that increases DW amounts has the potential to increase the abundance of DW-dependent species and, in most cases, also their species richness. Studies of burning showed positive effects on the abundance of saproxylic insects similar to those of other interventions, even though burning on average resulted in a smaller enrichment of DW amounts.

5. Policy implications. The findings of the review suggest that manipulating dead wood (DW) can be an effective part of conservation management to support biodiversity in protected areas. The findings also indicate that the diversity of DW
types is important, a mix of DW qualities should be favoured. Burning seems to be an effective method to increase biodiversity but to benefit cavity-nesting birds, snag losses need to be minimized.

**KEYWORDS**
coarse woody debris, dead wood, diversity, forest conservation, forest restoration, habitat management, prescribed burning, saproxylic species

1 | INTRODUCTION

A large body of research in recent decades has demonstrated the ecological value of dead wood (DW) in forests (e.g. Harmon et al., 1986; Stokland, Siitonen, & Jonsson, 2012; Ulyshen, 2018). DW, including snags, downed fine and coarse woody debris and DW attached to living trees, provides critical habitat for thousands of wood-dependent (saproxylic) species in forests (e.g. Siitonen, 2001). It is integral to a variety of ecosystem functions such as forest regeneration and recovery after disturbance (e.g. Macek et al., 2017) and carbon, nutrient and hydrological cycles (Gurnell, Gregory, & Petts, 1995; Pan et al., 2011; Watkinson et al., 2006). Intensification of forest management has heavily reduced the amount and diversity of DW and dying trees throughout the world (Gauthier, Bernier, Kuuluvainen, Shvidenko, & Schepaschenko, 2015), resulting in losses of saproxylic species (e.g. Grove, 2002a; Seibold et al., 2015). Thus, the ongoing decline of DW threatens global forest biodiversity.

Large amounts of DW occur in young forests after natural disturbances as well as in older forests due to natural forest dynamics (Harmon et al., 1986; Junninen, Similä, Kouki, & Kotiranta, 2006). In production forests, harvesting and thinning interfere with natural DW dynamics, that is, the initial pulse of DW enrichment caused by a natural stand-replacing disturbance and the subsequent slow accumulation of DW due to self-thinning, minor disturbances and natural mortality as trees age (Ulyshen, 2018). Thus, timber harvesting influences the amount and composition of DW for many decades (Jönsson, Fraver, & Jonsson, 2009; Svoboda, Fraver, Janda, Bace, & Zenahlkova, 2010). Even forest reserves can have low levels of coarse DW if they were managed for timber production before being protected; for example, in Swedish forest reserves the average DW volume is only 24 m$^3$/ha (Anon, 2006), well below the expected natural values of 80–120 m$^3$/ha (Ranius, Kruys, & Jonsson, 2004; Siitonen, 2001).

The current scarcity and slow accumulation of DW in many forest ecosystems suggests that interventions aiming at rapidly increasing the amount of DW might be needed to support biodiversity (Halme et al., 2013; Similä & Junninen, 2012; Speight, 1989). Such interventions, which are gradually becoming more common, may include felling, girdling, creation of high stumps with harvesters or explosives, leaving of logging residues, tree crowns, logs and snags during harvest operations, and restoration burning that increases tree mortality (Bernes et al., 2015).

The collective knowledge on biodiversity connected to DW has grown significantly in recent decades (Jönsson, Kruys, & Ranius, 2005; Junninen & Komonen, 2011; Müller & Büttler, 2010; Stokland et al., 2012; Ulyshen, 2018). Unfortunately, the evidence base for guiding restorative DW manipulation is lagging behind management interests. A recent review of experimental studies of DW biodiversity (Seibold et al., 2015) focused on knowledge gaps with the aim of guiding further experimental work, but did not provide a full systematic review of outcomes. Furthermore, Seibold et al. (2015) focused only on species richness and did not separate between different intervention types. Another recent study (Mason & Zapponi, 2015) reviewed literature on forest management to conserve saproxylic species but included no quantitative synthesis of the evidence.

A dialogue with conservation managers and decision-makers identified a need to synthesize the current knowledge drawn from replicated experimental studies into solid quantitative evidence of the effects of DW manipulation on forest biodiversity. Hence, we conducted a systematic review (CEE, 2013) on this topic built on a peer-reviewed protocol (Bernes et al., 2016). Three kinds of intervention that can change DW amounts and properties were covered: creation of DW (e.g. through felling or girdling of trees), addition of DW transported from elsewhere and prescribed burning. We identified and synthesized studies of how the abundance, species richness and species composition of several taxonomic groups in temperate and boreal forests were affected by such interventions (as compared with non-intervention or alternative kinds or levels of intervention).

The ultimate aim of our review was to examine whether manipulation of DW can be effective for conserving or restoring biodiversity in protected forests. Nevertheless, we included studies not only from protected forests but also from forests under commercial management, as some forestry practices may be useful for restoration purposes as well.

2 | MATERIALS AND METHODS

An in-depth description of the methods applied is given in Appendix S1. Methods follow the review protocol (Bernes et al., 2016) apart from a few instances that are specified below.
2.1 Identification and screening of studies

Most of the published evidence examined in this systematic review was included in a systematic map of how biodiversity is affected by active forest management interventions that may be relevant for use in protected forests (Bernes et al., 2015). About one-third of the studies covered by the map reported on effects of prescribed burning or creation/addition of DW and were therefore potentially relevant to this review (Appendix S2).

We excluded studies of effects on trees, ground vegetation and soil biota, since effects of DW changes on these groups are likely to be either insignificant or difficult to distinguish from other consequences of the interventions studied (e.g. effects of burning on light and shading, microclimate or soil conditions). Among studies of prescribed burning, moreover, we included only those that described effects on saproxylic species (primarily wood-inhabiting insects, fungi and lichens, and cavity-nesting birds). Finally, in accordance with the review protocol, we excluded studies of prescribed burning that provided no measurements of changes in DW amounts, since burning may not only create new DW but also consume existing DW.

In order to identify recently published literature, we performed a search update in September to October 2016, using a subset of the search terms (Appendix S3) applied for the systematic map (Bernes et al., 2015). To be included in the review, articles identified during the search update had to pass a set of relevance criteria (Appendix S1). Articles rejected on the basis of full-text assessment are listed in Appendix S4 together with the reasons for exclusion. This appendix also lists studies of DW manipulation that were included in the systematic map but excluded from this review since they did not fulfill all inclusion criteria for the review.

Studies that passed the relevance criteria were subject to critical appraisal. Based on assessments of their clarity and susceptibility to bias, they were categorized as having high, medium or low/unclear validity (with regard to the topic of our review). Studies judged to have low or unclear validity were excluded from the review (see Appendix S5). The criteria used for this appraisal (including some deviations from the protocol) are listed in Appendix S1.

All studies included in the review are described in a narrative table where data on study design, validity, setting and findings have been summarized (Table S1).

2.2 Extraction and synthesis of data

Data extraction and statistical details are fully described in Appendix S1. Outcomes suitable for meta-analysis were extracted together with potential effect modifiers from tables and graphs in the included articles, or were requested from study authors (Table S2). Although many studies reported on outcomes over multiple post-treatment years, we only used data from the final year of sampling for our main set of analyses. The interval between intervention and final sampling ranged from 0.4 to 22 years. We focused on extracting data on the abundance and richness of saproxylic insects, beetles (saproxylic or not), ground insects, wood-inhabiting fungi (excluding lichens) and cavity-nesting birds, as only these groups were described in a large enough number of studies to be analysed. Data were only extracted from studies where DW amounts had been manipulated throughout entire stands (implying stand-scale biodiversity effects). In addition to these "stand-scale studies," the review also includes "tree-scale studies" that examined effects of addition/creation/burning of individual snags or logs (by sampling on the snags/logs themselves or in their immediate vicinity), but these studies were too heterogeneous for quantitative synthesis.

Standardized mean difference effect sizes, and associated 95% confidence intervals, were derived for extracted outcomes using Hedges’ g statistic (Borenstein, Hedges, Higgins, & Rothstein, 2009). Positive effect sizes indicate that the response parameter (abundance or richness) was higher where DW amounts had been manipulated than where no such manipulation had taken place. Summary effect sizes were calculated using meta-analytical approaches (Borenstein et al., 2009; Koricheva, Gurevitch, & Mengersen, 2013). Since multiple levels of manipulation were sometimes reported from the same site, the site ID was included in the meta-analysis as a random factor. We analysed effects on the major taxon groups listed above, but we also made separate analyses of species identified by study authors as “rare" and of saproxylic insects categorized by us as "pest species" (Appendix S6).

Influences of effect modifiers were examined by means of subgroup analyses and meta-regressions (Thompson & Higgins, 2002), focused on the abundance and richness of saproxylic insects (Appendix S1). A number of additional analyses (e.g. analyses of data from the first year of sampling, leave-out analyses, funnel plots and fail-safe numbers) were made to investigate whether our findings might be affected by bias caused by suboptimal study designs or by specific selections of studies and outcomes (Appendix S7).

3 RESULTS

3.1 Identification and characterization of available evidence

Of the 812 studies in our systematic map (Bernes et al., 2015), 276 were listed as describing effects of prescribed burning or creation or addition of DW, thus being potentially relevant to our review. However, only 84 of these studies fulfilled all of the inclusion criteria (Appendix S2). Another 16 relevant studies were identified during our updated literature search (Appendices S3 and S4). Critical appraisal of the 100 studies that passed the relevance criteria led to the exclusion of nine studies due to low or unclear validity, mainly related to pseudo-replication or severely confounding factors (Appendix S5).

Consequently, 91 studies were included in this review. A list of data sources used in our study is provided in the Data sources section. Of the included studies, six were categorized as having medium validity, whereas the rest were considered to have high validity. Most of the studies had a Control/Impact design, but a Before/After/Control design had been applied in 27 of them. The vast majority of articles (87) were written in English, and only three were published earlier than 2001 (see Table S1 for information on all individual studies).
Most of the studies were conducted in northern Europe, including Finland (28), Sweden (20), Germany (7) and one each in Estonia, Norway and the United Kingdom. The other studies were conducted in United States (24), Canada (6) or Australia (3). Thus, there was good coverage of parts of the temperate and boreal zones but a notable lack of studies from Asia and boreal North America (Figure 1a). This was reflected by a reasonably good coverage of the range of precipitation levels and temperatures in temperate and boreal regions, but very few studies were made in wetter or colder regions (Figure 1b; note, however, that the latter include large non-forested tundra regions that were not relevant to our review).

The majority of included studies focused on conifer-dominated or mixed (conifer + broadleaf) forests; only seven were made in broadleaf forests. Stand ages were documented in 66 studies. Of these, 10 had examined stands aged 60 years or less, while 50 reported on stands older than 60 years or described as “mature” or “old-growth.” Another six studies had examined both young and old stands.

Altogether, there were 59 “stand-scale studies” and 32 “tree-scale studies.” Effects of prescribed burning were described in 48 studies, while effects of creation and addition of DW were described in 37 and 21 studies respectively. These numbers include 19 cases in which 2–3 intervention categories had been combined. Most of the studies covered a relatively short period of time: the time from intervention to final sampling was ≤2 years in 49 studies; 3–9 years in 35 studies and 10 or more years in 7 studies.

The outcomes most frequently reported were effects of interventions on beetles (48 studies), birds (23), fungi (15) and arthropods other than beetles (14) (Table 1). Data on abundance and species richness within one or several groups were reported in 74 and 44 studies respectively. Ten studies focused on effects on single species, either of cavity-nesting birds (five studies) or of beetles (five studies). Effects on the composition of species assemblages were reported by 24 studies.

### 3.2 Quantitative analyses of stand-scale effects on abundance and richness

We extracted quantitative data from 37 stand-scale studies, recording a total of 241 comparisons across time and/or space of the abundance or richness of insects, wood-inhabiting fungi or cavity-nesting birds exposed (vs. not exposed) to manipulation of DW. Some of the abundance comparisons referred to single species, whereas others referred to entire assemblages. The evidence base was heterogeneous, in several cases consisting of a limited number of comparisons per species group and measure of biodiversity. Nevertheless, it allowed us to perform a number of meta-analyses, particularly of saproxylic insects, which was the most frequently studied group (with 47 and 30 comparisons of abundance and richness respectively).
TABLE 1  Number of included studies by intervention and species group

<table>
<thead>
<tr>
<th>Species group studied</th>
<th>Intervention</th>
<th>Burning</th>
<th>Addition of DW</th>
<th>Creation of DW</th>
<th>Both burning and creation/ addition of DW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beetles</td>
<td></td>
<td>11</td>
<td>8</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>Arthropods other than beetles</td>
<td></td>
<td>2</td>
<td>3</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Birds</td>
<td></td>
<td>16</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Reptiles</td>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wood-inhabiting fungi</td>
<td></td>
<td>2</td>
<td>3</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>Lichens</td>
<td></td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Some studies appear more than once in the table, since they investigated more than one species group.

Using data from the final year of sampling for each study, we found that DW manipulation significantly increased the abundance and richness of saproxylic insects and wood-inhabiting fungi in general, and also the abundance of “unspecified” beetles (saproxylic or not; Figure 2), whereas it had no significant effect on the abundance and richness of ground insects. For saproxylic insect species categorized by study authors as rare, we found positive responses of abundance and richness, whereas rare wood-inhabiting fungi showed no significant response. A positive response of the abundance was also seen in the subcategory of pest insects (Figure 2), but the mean effect size tended to be smaller than for saproxylic insects in general. We found no clear differences between the effects of different methods of DW manipulation on saproxylic insects (Figure 2), despite increases in DW volumes being on average more than twice as large in the studies of addition or creation of DW as in the burning studies (Table 2). We detected no significant overall effect on the abundance of cavity-nesting birds (Figure 2). This result was based on seven burning studies. Four of the studies showed increased DW amounts post burning, whereas the three other ones showed decreased amounts, but average effects on bird abundance differed very little between these two subgroups (Appendix S7).

To check the robustness of our findings, we repeated our meta-analyses using data from the first post-treatment year of sampling instead of the final year (Appendix S7). The average time since intervention did not differ much between the two sets of analyses, since most studies reported effects over only one or a few years (Table 1 in Appendix S7). Hence, the pattern of abundance and richness responses remained largely unchanged. The only exception was wood-inhabiting fungi, where the average interval between first and final years of sampling was more than 5 years and effects of DW manipulation were non-significant in the first year but positive in the final year. Several other sensitivity tests were also performed to assess the robustness of our results to impacts of study design and validity, selection of studies and publication bias, but none of them revealed any major influence (Appendix S7).

Weighted meta-regression indicated that the positive response of saproxylic insect richness to DW manipulation became weaker with increasing enrichment of DW (Figure 3 and Table 3). However, this influence was probably mainly due to responses to addition/creation of DW tending to be weaker than responses to burning (Figure 3); the average DW enrichment was higher in the former cases (Table 2). When data from burning and DW addition/creation studies were analysed separately, we found no influence of DW enrichment on the response of saproxylic insect richness (results not shown). We also found no such influence on the abundance of saproxylic insects (all methods of DW manipulation analysed together), and no significant impacts on saproxylic insects of other potential effect modifiers (time since intervention, temperature and precipitation; see Table 3).

Subgroup analyses of the influence of forest types showed that the abundance and richness of saproxylic insects responded positively to DW manipulation in stands dominated by spruce (Picea) and pine (Pinus) but not in stands with a mixture of broadleaf and coniferous trees (Figure 4, but note the low n for this forest type). The abundance of saproxylic insects also showed a positive response in mixed coniferous forest. The climate zone had no significant influence on how the abundance of saproxylic insects responded to DW manipulation – positive responses were found in both temperate and boreal climates (Figure 4).

3.3 | Qualitative synthesis of tree-scale effects

Our systematic review included 32 “tree-scale” studies that involved manipulation of single trees or pieces of DW (Table S1), and which focused on comparing DW qualities rather than quantities, for example, logs versus snags, sun-exposed versus shaded logs, clustered versus aggregated snags, etc.

The addition and creation of DW were studied in several tree-scale experiments, and both short-term and longer term (8–12 years) effects on beetles and other insects, fungi and birds were reported (Table S1). Richness and abundance of examined species varied across tree species or with the placement of added DW (forest floor vs. canopy). In studies where created DW was compared to natural DW, the species richness (fungi) and abundance of species (beetles, wood-boring insects, woodpeckers) were mostly higher on created DW, but opposite and non-significant results were also reported. Several experiments compared effects of DW created with different methods (e.g. felling or girdling). According to these studies, there was no difference in the response of beetle richness between methods, but the response of beetle abundance was highly variable across studies. Also, the abundance of cavity-nesting birds did not differ between different DW creation methods, whereas the species richness of fungi was generally higher on logs compared to snags (in one study no difference was found).

Effects of burning of individual trees or logs were studied in only two experimental setups, one of them used by several studies, and only short-term results were reported (<4 years). According to these, burning had negative or no effects on the abundance and species richness of beetles but a positive effect on the abundance of Diptera on birch logs.
Species composition

In general, species assemblages showed significant effects of DW manipulation (Table S1). More specifically, most studies showed that species assemblages in burnt forest stands, or in stands with created or added DW, were different from assemblages in untreated stands. Similarly, in tree-scale studies, species assemblages often, but not always, differed between natural DW and created DW, as well as between different types of created or added DW (e.g. between logs and high stumps, or between different tree species).

4 | DISCUSSION

This first full systematic review on biodiversity effects of DW manipulation supports the view that treatments designed to increase the amount of DW are effective in terms of increasing the abundance and richness of DW-dependent species. This might not be surprising, since several studies have shown an overall correlation between DW amounts and associated biodiversity (meta-analysed by Lassauce, Paillet, Jactel, & Bouget, 2011). Interestingly, however, studies of prescribed burning showed positive effects on the abundance and richness of saproxylic insects that were at least as strong as those found for other interventions, despite the average DW enrichment being lower in the burning studies.
4.1 Amounts or diversity of DW

That burning seems to benefit saproxylic insects somewhat more efficiently than creation or addition of DW could be due to the fact that it results in higher heterogeneity of DW quality. Burning does not kill all trees immediately but damages, chars and weakens them and leaves most of the killed trees standing. This expands the variety of dead and dying trees as well as the range of decomposition stages (Siitonen, Martikainen, Punttila, & Rauh, 2000) and improves the continuity of DW which, in turn, results in increased diversity of microhabitats for saproxylic organisms. Our result, then, suggests that variation in DW quality may be more important for saproxylic organisms than the amount of DW per se. The relative importance of these two factors (DW quantity and quality) has been considered in the light of two competing hypotheses: the more-individuals hypothesis (Clarke & Gaston, 2006) and the habitat heterogeneity hypothesis (Tews et al., 2004), with a recent study by Seibold et al. (2016) finding support for the latter.

The technique of DW creation is obviously important for DW quality (e.g. Pasanen et al., 2018); thus, using diverse techniques might be an alternative to burning. A wide range of tools for DW manipulation have been available at least since the 1980s (Bull & Partridge, 1986; Cavalli & Mason, 2003). Some techniques, such as various forms of non-lethal girdling and veteranization of living trees, including pollarding (Jonsell, 2012; Sebek, Altman, Platek, & Cizek, 2013), could create a diversity of DW habitats that would persist over decades to centuries. We recognize, however, that some structures, such as cavity trees, remain challenging to create artificially (Rueegger, 2017), although substitutes such as man-made mould boxes could be useful (Carlsson, Bergman, Jansson, Ranius, & Milberg, 2016). We also recognize that certain structures (charred wood) are specific to burning only.

4.2 Tree species and forest types

Our stand-scale meta-analyses showed a consistent positive effect of DW enrichment on the abundance and species richness of saproxylic insects in coniferous forests, but in mixed forests the response was not significant. For mixed forests, however, the sample size was small and the confidence intervals very large (Figure 4). Several of the tree-scale studies in our review reported differences across tree species of treatment effects on species abundance and richness. Yet, our synthesis did not enable us to check whether such effects could be attributed solely to different species pools being associated with different tree species (Stokland et al., 2012). Species assemblages are likely to vary with the dominance of different tree species in a forest, but only one of the stand-scale studies in our review had
compared assemblages in conifer-dominated stands with those in mixed stands and none with those in broadleaf stands. For species assemblages in the tree-scale studies, however, the importance of tree species was evident; different tree species were generally inhabited by different saproxylic species, particularly where coniferous and broadleaf trees were compared.

4.3 | Time since intervention

The studies in our review were, in general, short-term compared to the time-scales of DW decomposition, which may extend over many decades. For groups such as saproxylic beetles, among which the majority of species colonize wood within a few years (Saint-Germain, Drapeau, & Buddle, 2007), short-term studies may be sufficient. In contrast, for wood-inhabiting fungi, which undergo species succession over decadal time-scales (e.g. Penttilä, Junninen, Punttila, & Siitonen, 2013), the evidence base is insufficient for a full evaluation of the effectiveness of DW manipulations. The importance of long time-scales was demonstrated by the difference we found between effects on fungi in the first and last years of sampling.

4.4 | Implications for policy/management

Our review suggests that manipulating DW can be an effective part of conservation management to support biodiversity in protected forests. Especially in areas with impoverished DW pools, it is likely that any enrichment will have marked positive effects on associated biodiversity. Additionally, the results support the view that DW diversity is important: a mix of DW qualities in terms of tree species, microclimatic position, diameter and decomposition stage should be favoured. The importance of DW diversity underlines the value of naturally disturbed forests for maintaining diverse DW-associated biota, as natural disturbances usually create a wide variety of DW types and thus unique habitats that should be left untouched (Lindenmayer, Thorn, & Banks, 2017).

At least for supporting saproxylic insects, prescribed burning seems to be a particularly useful method. Cavity-nesting birds, however, showed no response to burning, possibly because fire not only creates but also consumes snags, which are a key structure for many cavity-nesters (e.g. Harrod, Peterson, Povak, & Dodson, 2009). A reasonable strategy for cavity-nesters in protected forests should thus focus on minimizing snag losses and retaining naturally disturbed areas with abundant pools of snags in a landscape (e.g. Hutto, 2006).

We found a positive effect of DW enrichment on the abundance not only of rare insects but also of insects considered as pests. The risk of an increase in the populations of some pest species may be an inevitable consequence of conservation management for certain rare species. This risk, however, is highly dependent on tree species, pest species and the method of DW manipulation (Karvemo, Björkman, Johansson, Weslien, & Hjälten, 2017). Where the risk is considered high, some mitigating measures can be applied; for example, bark scratching of spruce could prevent an increase in spruce bark beetle populations (Thorn et al., 2016).

4.5 | Implications for research

Despite more than three decades of research and discussion on DW and conservation (Grove, 2002b; Speight, 1989), there are still gaps in our knowledge on biodiversity effects of DW manipulation in temperate and boreal forests. Geographically, the largest gap is in Asia (Figure 1) but also in other parts of the temperate and boreal zones the reviewed studies did not cover the full range of forest ecosystems; particularly if we consider the diversity of tree species, stand compositions and natural dynamics, ranging from patch-scale to stand-replacing dynamics. Given the large geographical distribution of broadleaf forests, it is unfortunate that our systematic review identified only seven relevant studies from such forests. Here, clearly more studies are required to enlarge the evidence base. We also urge researchers to measure the amount of DW before
manipulation, as this amount can be an important effect modifier (e.g. Kroll et al., 2012). Moreover, since DW created or added in protected forests often has limited diversity in terms of species, size and/or age (Johannesson, 2015; Pasanen, Junninen, & Kouki, 2014), more studies should consider the significance of DW quality and heterogeneity.

The included studies were strongly dominated by short-term investigations. What is short-term is context dependent, but given the decadal time-scale of tree decomposition, this is an unfortunate bias in the evidence base. Here, the main solution seems to be to stimulate researchers to return to their experiments and to ensure that sufficient information on the study design is documented, allowing a new generation of researchers to reassess conditions at old experimental sites (Seibold et al., 2015).

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AUTHORS’ CONTRIBUTIONS
All authors participated in designing the review and developing aims and research questions. J.S. extracted data and made most of the analyses, partly supported by C.B.; C.B., B.G.J., J.S., K.J. and J.M. drafted the manuscript, but all authors contributed to the draft and gave final approval for publication.

DATA ACCESSIBILITY
All extracted data and a narrative table including all the studies in this systematic review are available via the Dryad Digital Repository https://doi.org/10.5061/dryad.g2t6204 (Sandström et al., 2019).

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REFERENCES


DATA SOURCES

Full references to all included papers are available in our narrative, Appendix 6. The following short list indicates which papers we have included in our systematic review:

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<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Title</th>
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</thead>
<tbody>
<tr>
<td>Agnew &amp; Rao</td>
<td>2014</td>
<td>The creation of structural diversity</td>
</tr>
<tr>
<td>Aho</td>
<td>2006</td>
<td>Polton sekä harvennonsh-akkun ja tuotetun</td>
</tr>
<tr>
<td>Apigian, Dahlsten &amp; Stephens</td>
<td>2006</td>
<td>Fire and fire surrogate treatment effects</td>
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<td>Appelqvist &amp; Lindholm</td>
<td>2012</td>
<td>Vedinsekter i vitryggsmråden</td>
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<tr>
<td>Artman, Sutherland &amp; Downhower</td>
<td>2001</td>
<td>Prescribed burning to restore mixed</td>
</tr>
<tr>
<td>Aulén</td>
<td>1991</td>
<td>Increasing insect abundance by killing</td>
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<td>Baber, Kahl, Gossner... Bassler</td>
<td>2016</td>
<td>Disentangling the effects of forest-stand type</td>
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<td>Bagne &amp; Purcell</td>
<td>2011</td>
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<td>Experimental reduction of native vertebrate grazing</td>
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### Authors | Year | Title
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Hämäläinen, Kouki & Löhmus | 2014 | The value of retained Scots pines
Hämäläinen, Kouki & Löhmus | 2015 | Potential biodiversity impacts of forest biofuel
Jacobs, Spence & Langor | 2007 | Variable retention harvest of white spruce
Jacobs, Spence & Langor | 2007 | Influence of boreal forest succession
Joensuu, Heliövaara & Savolainen | 2008 | Risk of bark beetle damage in a spruce
Johansson, Gibb, Hilszczariski... Danell | 2006 | Conservation-oriented manipulations of coarse
Johansson, Gibb, Hjältén... Danell | 2007 | The effects of substrate manipulations
Johansson, Gibb, Hjältén... Danell | 2007 | Variable response of different functional groups
Jonsell, Nittérus & Stighäll | 2004 | Saproxylic beetles in natural and man-made
Junninen, Kouki & Renvall | 2008 | Restoration of natural legacies of fire in
Komonen & Alajoki | 2011 | Kirjanpainajatuhot luonnonhoidon jälkeen
Komonen & Kouki | 2008 | Do restoration fellings in protected forests
Komonen, Halme, Jäntti... Toivanen | 2014 | Created substrates do not fully mimic natural
Komonen, Kuntsi, Toivanen & Kotiaho | 2014 | Fast but ephemeral effects of ecological
Laarmann, Korjus, Sims... Stanturf | 2013 | Initial effects of restoring natural forest structures
Lindhe & Lindelöw | 2004 | Cut high stumps of spruce, birch, aspen
Lindhe, Åsenblad & Toresson | 2004 | Cut logs and high stumps of spruce, birch
Lindhe, Lindelöw & Åsenblad | 2005 | Saproxylic beetles in standing dead wood density
Lyons, Gaines, Lehmkuhl & Harrod | 2008 | Short-term effects of fire and fire surrogate
MacLean, Dracup, Gandiaga... Villard | 2015 | Experimental manipulation of habitat
Manning, Cunningham & Lindenmayer | 2013 | Bringing forward the benefits of coarse
Martikainen, Kouki, Heikkal... Lappalainen | 2006 | Effects of green tree retention and prescribed
Muona & Rutanen | 1994 | The short-term impact of fire on the beetle
Nadeau, Majka & Moreau | 2015 | Short-term response of coleopteran assemblages
Olsson, Jonsson, Hjältén & Ericson | 2011 | Addition of coarse woody debris - The early
Pasanen, Junninen & Kouki | 2014 | Restoring dead wood in forests diversifies

### Supporting Information

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