NRC Research Press

REVIEW

Salvage logging effects on regulating and supporting ecosystem services — a systematic map

Alexandro B. Leverkus, José María Rey Benayas, Jorge Castro, Dominique Boucher, Stephen Brewer, Brandon M. Collins, Daniel Donato, Shawn Fraver, Barbara E. Kishchuk, Eun-Jae Lee, David B. Lindenmayer, Emanuele Lingua, Ellen Macdonald, Raffaella Marzano, Charles C. Rhoades, Alejandro Royo, Simon Thorn, Joseph W. Wagenbrenner, Kaysandra Waldron, Thomas Wohlgemuth, and Lena Gustafsson

Abstract: Wildfires, insect outbreaks, and windstorms are increasingly common forest disturbances. Post-disturbance management often involves salvage logging, i.e., the felling and removal of the affected trees; however, this practice may represent an additional disturbance with effects on ecosystem processes and services. We developed a systematic map to provide an overview of the primary studies on this topic and created a database with information on the characteristics of the retrieved publications, including information on stands, disturbance, intervention, measured outcomes, and study design. Of 4341 retrieved publications, 90 were retained in the systematic map. These publications represented 49 studies, predominantly from North America and Europe. Salvage logging after wildfire was addressed more frequently than after insect outbreaks or windstorms. Most studies addressed logging after a single disturbance event, and replication of salvaged stands rarely exceeded 10. The most frequent response variables were tree regeneration, ground cover, and deadwood characteristics. This document aims to help managers find the most relevant primary studies on the ecological effects of salvage logging. It also aims to identify and discuss clusters and gaps in the body of evidence, relevant for scientists who aim to synthesize previous work or identify questions for future studies.

Key words: salvage harvesting, sanitation logging, wildfire, insect outbreak, windthrow.

Résumé : Les feux de forêt, les épidémies d'insectes et les tempêtes de vent sont des perturbations forestières de plus en plus fréquentes. À la suite d'une perturbation, l'aménagement implique souvent une coupe de récupération, c.-à-d., l'abattage et le prélèvement des arbres endommagés. Cependant, cette pratique peut constituer une perturbation additionnelle et avoir des effets sur les services et processus de l'écosystème. Nous avons développé une carte systématique destinée à fournir un aperçu des études originales sur ce sujet et créé une base de données contenant de l'information sur les caractéristiques des publications retenues, incluant des informations sur les peuplements, la perturbation, l'intervention, les résultats mesurés et la méthodologie de l'étude. Des 4341 publications trouvées, 90 ont été retenues dans la carte systématique. Ces publications représentaient 49 études menées principalement en Amérique du Nord et en Europe. La coupe de récupération après feu a été étudiée plus fréquemment qu'après des épidémies d'insectes ou des tempêtes de vent. La plupart des études portaient sur la coupe après une seule perturbation et le nombre de répétitions de peuplements récupérés dépassait rarement 10. Les variables réponse les plus fréquentes étaient la régénération de la strate arborescente, le couvert végétal et les caractéristiques du bois mort. Ce document

Received 27 March 2018. Accepted 14 May 2018.

A.B. Leverkus and J.M. Rey Benayas. Departamento de Ciencias de la Vida, UD Ecología, Edificio de Ciencias, Universidad de Alcalá, Alcalá de Henares, Spain.
J. Castro. Departamento de Ecología, Facultad de Ciencias, Universidad de Granada, Granada, Spain.
D. Boucher. Centre de foresterie des Laurentides, Service Canadien des Forêts, Ressources Naturelles Canada, Québec (Que.), Canada.
S. Brewer. Department of Biology, University of Mississippi, Oxford, Miss., USA.
B.M. Collins. Center for Fire Research and Outreach, University of California Berkeley, Berkeley, Calif., USA.
D. Donato. School of Environmental and Forest Sciences, University of Washington, Seattle, Wash., USA.
S. Fraver. School of Forest Resources, University of Maine, Orono, Maine, USA.
B.E. Kishchuk. Science Policy Integration Branch, Canadian Forest Service, Natural Resources Canada, Ottawa, Ont., Canada.
E.-J. Lee. Urban Planning Research Group, Daejeon Sejong Research Institute, Jung-gu, Daejeon, Korea.
D.B. Lindenmayer. Fenner School of Environment and Society, The Australian National University, Canberra, Australia.
E. Lingua. Department TESAF, University of Padova, Legnaro (PD), Italy.
E. Macdonald. Department of Renewable Resources, University of Alberta, Edmonton, Alta., Canada.
R. Marzano. Department DISAFA, University of Torino, Grugliasco (TO), Italy.
C.C. Rhoades. Rocky Mountain Research Station, USDA Forest Service, Fort Collins, Colo., USA.
A. Royo. Northern Research Station, USDA Forest Service, Irvine, Penn., USA.
S. Thorn. Field Station Fabrikschleichach, Department of Animal Ecology and Tropical Biology (Zoology III), Julius-Maximilians-University Würzburg, Rauhenebrach, Bavaria, Germany.
J.W. Wagenbrenner. Pacific Southwest Research Station, USDA Forest Service, Arcata, Calif., USA.
K. Waldron. Department of Wood and Forest Sciences, Université Laval, Québec (Que.), Canada.
T. Wohlgemuth. Research Unit Forest Dynamics, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zuercherstrasse 111, CH-8903 Birmensdorf, Switzerland.
L. Gustafsson. Department of Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden.
Corresponding author: Alexandro B. Leverkus (email: alexandro.leverkus@uah.es).

Can. J. For. Res. **48**: 983–1000 (2018) dx.doi.org/10.1139/cjfr-2018-0114

vise à aider les gestionnaires à trouver les études les plus pertinentes portant sur les effets écologiques de la coupe de récupération. Il vise aussi à identifier et examiner les points forts et les lacunes parmi l'ensemble des arguments pertinents pour les scientifiques qui cherchent à synthétiser les travaux antérieurs ou à identifier les sujets de futures études. [Traduit par la Rédaction]

Mots-clés : coupe de récupération, coupe d'assainissement, feu de forêt, épidémie d'insectes, chablis.

Introduction

Large, episodic, severe forest disturbances such as those caused by wildfires, insect outbreaks, and windstorms are part of the natural dynamics of forest ecosystems across the world (Noss et al. 2006; Turner 2010; Johnstone et al. 2016). However, the frequency, severity, and extent of such disturbances have increased in recent decades due to anthropogenic activity (Seidl et al. 2017) and are predicted to further increase in the future (Schelhaas et al. 2003; Kurz et al. 2008; Pausas and Fernández-Muñoz 2012; Seidl et al. 2017). As a result, it is crucial to identify and adopt management strategies that promote regeneration and maintain ecosystem functions of post-disturbance forests, whether through active intervention or passive management (Crouzeilles et al. 2017). A common post-disturbance management approach in many parts of the world is salvage logging, i.e., the widespread felling and removal of the affected trees (McIver and Starr 2000; Lindenmayer et al. 2008; Thorn et al. 2018). Salvage logging has been reported after wildfires (Lindenmayer et al. 2018), volcanic eruptions (Titus and Householder 2007), insect infestations (Thorn et al. 2017), windstorms (Waldron et al. 2014), and ice storms (Sun et al. 2012). It is frequent in disturbed production forests but also common in protected forests in some parts of the world (Schiermeier 2016; Leverkus et al. 2017; Müller et al. 2018). However, there is concern that the additional logging-related disturbance can imperil ecosystem recovery and affect biodiversity and ecosystem services (Karr et al. 2004; Beschta et al. 2004; Donato et al. 2006; Lindenmayer et al. 2008). Besides the mechanical disturbance, salvage logging affects ecosystems through the removal and modification of large amounts of biological legacies, i.e., the organisms, organic materials, and organically generated environmental patterns that persist through a disturbance and constitute the baseline for post-disturbance recovery and regeneration (Franklin et al. 2000).

The most frequent motivation for salvage logging across the world is the recovery of some part of the economic value of the forest (Müller et al. 2018). Tree-killing disturbances trigger a set of processes that can rapidly reduce the timber value due to reductions in wood quality (e.g., stain, decay, and the activity of insect borers) and to pulses in wood supply to the market (Prestemon and Holmes 2010). Rapid post-disturbance harvest is a frequent response to disturbance that aims to avoid further deterioration of the damaged wood (Prestemon and Holmes 2010; Lewis and Thompson 2011). In some parts of the world such as regions of North America, large-scale wildfires and insect outbreaks have become so frequent that salvage logging is no longer a hasty response to unexpected events but rather constitutes an expected source of wood to fill market demands (Mansuy et al. 2015). However, the logging of disturbed forests is not profitable in all cases (e.g., Leverkus et al. 2012), and it may also aim to fulfil other management objectives. Salvage logging can target the reduction of the risk of subsequent disturbances such as pest outbreaks and wildfire through the elimination of the substrate or fuel generated by the initial disturbance (Schroeder and Lindelöw 2002; Collins et al. 2012). The simplification of post-disturbance ecosystem structure through the removal of fallen trunks is intended to ease subsequent active restoration activities such as reforestation (Leverkus et al. 2012; Man et al. 2013). Finally, there is a general negative aesthetic perception of disturbed forests that may be offset by removing the visual evidence of what is generally considered a "calamity" (Noss and Lindenmayer 2006). However, these motivations are not always based on scientific evidence, but rather on traditional practices, perceptions, and deductions, as is often the case in conservation-related decision-making (Pullin et al. 2004; Sutherland et al. 2004).

The lack of scientific evidence on the effects of salvage logging was highlighted in 2000 (McIver and Starr 2000). In 2004, Lindenmayer and colleagues (Lindenmayer et al. 2004) called for a revision of post-disturbance management policies, arguing that salvage logging can have long-lasting negative effects on biodiversity, undermine the — largely unrecognized — ecological benefits of natural disturbances, and impair ecosystem recovery. Numerous studies were established in subsequent years to assess the ecological consequences of this practice, covering a wide array of disturbance types and severities, biomes, forest compositions, logging methods, and response variables (Thorn et al. 2018). As a result, the abovementioned motivations for salvage logging have been challenged (e.g., wildfire risk (Donato et al. 2006) and economics (Leverkus et al. 2012)), and many other effects of this practice have been described (e.g., Lindenmayer et al. 2008; Beghin et al. 2010; Priewasser et al. 2013; Wagenbrenner et al. 2015; Hernández-Hernández et al. 2017). Nonetheless, under some circumstances, salvage logging can meet both management and conservation objectives and address societal concerns. For example, salvage logging after bark beetle infestation of lodgepole pine forests in Colorado commonly reduces canopy fuels and regenerates new stands without negatively affecting native plant diversity or soil productivity (Collins et al. 2011, 2012; Fornwalt et al. 2018; Rhoades et al. 2018). As a consequence, controversy surrounding salvage logging among managers, environmentalists, politicians, and academics remains lively (Schiermeier 2016; Leverkus et al. 2017; Lindenmayer et al. 2017; Müller et al. 2018).

The ecological impacts of salvage logging can broadly be categorized according to whether they affect the following.

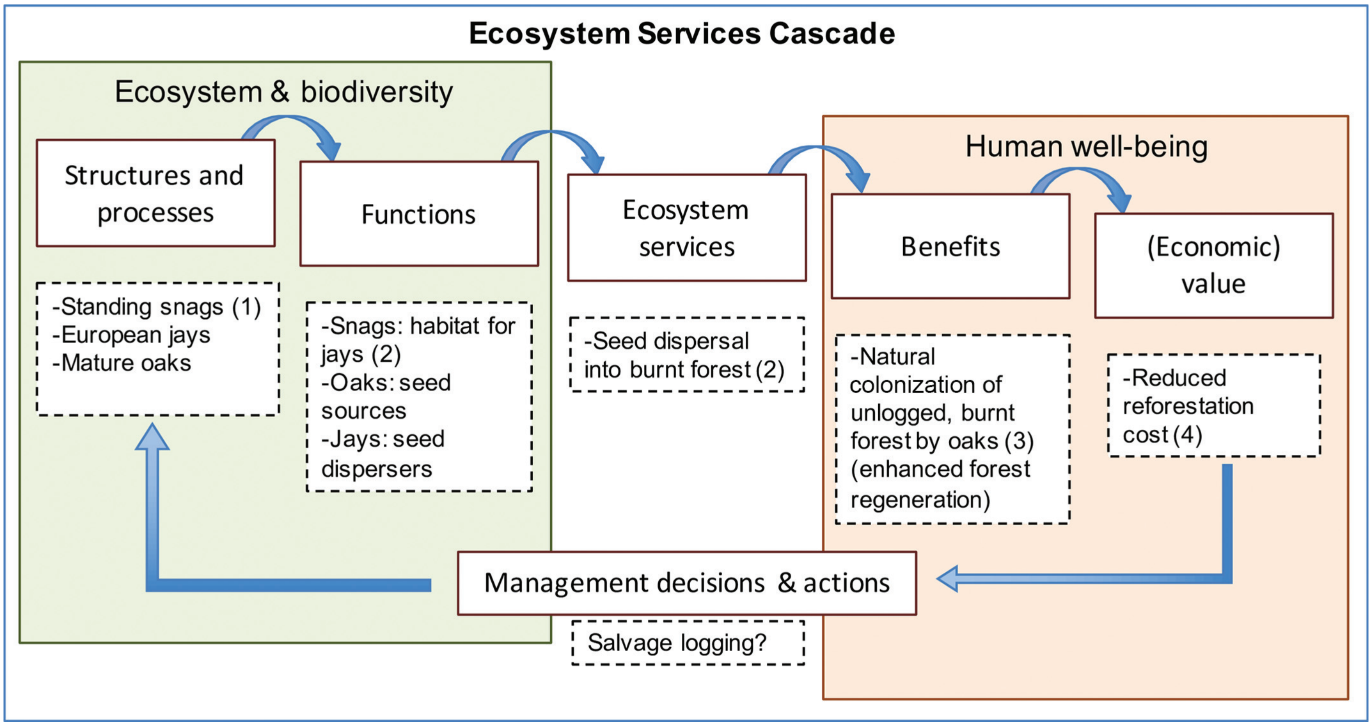
(*a*) The physical structure of ecosystems — An immediate consequence of logging is the reduction in parameters such as standing and downed woody material, living canopy cover, and habitat structural complexity (Lee et al. 2008; Waldron et al. 2013; Peterson et al. 2015).

(*b*) Particular elements of the biota and species assemblages — The removal of deadwood can affect many species, particularly deadwood-dependent taxa (as concluded in a recent global review on this topic; Thorn et al. 2018).

(*c*) Forest regeneration capacity — Salvage logging has the potential to alter residual growing stock, soil seed bed, canopy and soil seed banks, and species interactions such as competition, seed dispersal, seed predation, and herbivory (Greene et al. 2006; Collins et al. 2010; Puerta-Piñero et al. 2010; Castro et al. 2012; Castro 2013).

(*d*) Key ecosystem processes and services — Ecosystem services are the benefits that people obtain from ecosystems; they are the link between particular elements of the ecosystem or functions that they perform (i.e., the biophysical component), the benefits that society obtains, and ultimately, the value placed on them (i.e., the human well-being component; Fig. 1; Haines-Young and Potschin 2010). They are categorized into provisioning, cultural, regulating, and supporting services (Millennium Ecosystem Assessment 2003). As outlined above, salvage logging is most often conducted to recover the value of the affected wood. In the

Fig. 1. Ecosystem services cascade illustrated for the case of seed dispersal by European jays (*Garrulus glandarius* L.) within a post-fire management experimental setting. The diagram shows the link between the biophysical and the human well-being components of ecosystem services. Particular elements of the ecosystem perform functions that produce benefits for society via an ecosystem service. Society places a value on these benefits, whether economic or not. The resulting value feeds back to affect the ecosystem elements through management decisions. In the example (shown in the dashed boxes below each component of the conceptual diagram), burnt snags represent a supporting element for the seed caching activity of a major seed disperser, whose activity yields natural colonization of the burnt area and reduces the economic cost of reforestation. Appreciation of this value can enhance the likelihood that snags be retained in post-fire management. Figure adapted from Haines-Young and Potschin (2010), Martín-López et al. (2014), and Leverkus and Castro (2017). References in the diagram: (1), Molinas-González et al. (2017*b*); (2), Castro et al. (2012); (3), Leverkus et al. (2016); (4), Leverkus and Castro (2017). [Colour online.]



case of timber and other provisioning services, the human well-being component is often well defined and quantified. However, salvage logging also may affect cultural, regulating, and supporting ecosystem services throughout the ecosystem services cascade. This implies that some of the effects outlined in (*a*), (*b*), and (*c*) can also be considered to fall into the category of ecosystem services (Fig. 1; Leverkus and Castro 2017). In the case of supporting and regulating services, the biophysical component is usually better understood than the human well-being component (Boerema et al. 2017), and this is likely also the case regarding the responses to salvage logging (Leverkus and Castro 2017).

Although ecosystem services have seldom been explicitly addressed in the scientific literature on salvage logging, they provide a common framework that allows balancing economic benefits from timber against the wide array of ecological variables that are also affected by post-disturbance management (Leverkus and Castro 2017). This framework represents an ecosystem approach (Secretariat of the Convention on Biological Diversity 2000), i.e., the consideration of multiple benefits provided by ecosystems — rather than only market values — to guide sustainable management decisions.

Salvage logging can affect ecosystem services by altering processes such as soil erosion and hydrological regimes (Wagenbrenner et al. 2016), nutrient cycling (Kishchuk et al. 2015), carbon sequestration (Serrano-Ortiz et al. 2011), seed dispersal (Castro et al. 2012), vegetation cover (Macdonald 2007), tree regeneration (Castro et al. 2011; Marzano et al. 2013; Boucher et al. 2014), resistance to invasive species (Holzmueller and Jose 2012), resilience to subsequent disturbances (Fraver et al. 2011), and many others (McIver and Starr 2000; Karr et al. 2004; Beschta et al. 2004; Lindenmayer and Noss 2006; Lindenmayer et al. 2008). Some authors argue that ecological responses to salvage logging may result in synergistic effects due to the two successive disturbance events (the natural disturbance and then logging) occurring close in time (Van Nieuwstadt et al. 2001; Wohlgemuth et al. 2002; Karr et al. 2004; Lindenmayer et al. 2004; DellaSala et al. 2006; Lindenmayer and Noss 2006). Others have found that environmental drivers other than salvage logging are more important in determining ecosystem regeneration (Kramer et al. 2014; Peterson and Dodson 2016; Royo et al. 2016; Rhoades et al. 2018). Further, studies often report contradictory results, and there is currently no comprehensive, global assessment of the studies that have addressed salvage logging effects on ecosystem processes.

Systematic maps aim to collate the empirical evidence on particular topics and describe the characteristics of the studies on those topics (James et al. 2016). In contrast to systematic reviews, they do not aim to synthesize the results of individual studies. Rather, they help managers identify the literature on a topic that is most relevant to their needs, as well as knowledge clusters and knowledge gaps to suggest future systematic review lines and topics for further empirical study.

Here, we provide a systematic map addressing the ecological effects of salvage logging with a focus on regulating and supporting ecosystem services. The focus on ecosystem services intends to leverage the relevance and applicability of academic studies for non-academic stakeholders, including land managers who face the question of how to manage disturbed forests, as well as the general public. A global overview of this subject that also addresses potential reasons for heterogeneity in the effects measured by different studies could aid managers and policy-makers worldwide in finding the necessary scientific information to make decisions regarding salvage logging. Such decisions require answering questions such as "Is salvage logging likely to enhance the recovery of disturbed forests under particular forest types and disturbance conditions?" and "Does the trade-off between provisioning and other kinds of ecosystem services result in a positive overall balance for specific management interventions?". We describe the state of the literature that addresses these questions.

Materials and methods

We followed the guidelines for systematic reviews in environmental management as prescribed by the Collaboration for Environmental Evidence (Centre for Evidence-Based Conservation 2010) and several other texts (Sutherland et al. 2004; Pullin and Stewart 2006; Koricheva et al. 2013; James et al. 2016). The methods described below are an expansion of those presented in our protocol (Leverkus et al. 2015*a*).

Research questions

We established a search strategy to identify the studies answering the following primary research question:

Does post-disturbance salvage logging affect regulating and supporting ecosystem services?

This question implies the following key elements:

- Population: forests affected by one of the following disturbances: windstorms, pest insect outbreaks, or wildfire
- Intervention: salvage logging, i.e., the harvesting of trees from areas after disturbance events
- Comparator: forests after disturbance where no salvage logging was conducted
- Outcome: variables that could be regarded as indicators of regulating or supporting ecosystem services.

We expected that the studies collectively would provide varying and apparently contradictory answers to the primary research question. To search for potential reasons underlying this heterogeneity, we considered the secondary research question:

Does the response of ecosystem services to post-disturbance salvage logging vary with the

- type and severity of the disturbance?
- geographic region?
- intensity, method, or timing of salvage logging?
- forest type?
- type of study design?

Literature searches

The primary literature search was conducted in English in Web of Science (WoS) and Scopus with the aim of answering the primary research question. The terms were searched in titles, abstracts, and keywords and were based on the population and the intervention elements. The final search string (Supplementary Table S1[1]) was established after the scoping exercise described in the protocol (Leverkus et al. 2015*a*). The search in WoS was initially made on 18 August 2015 and updated on 5 May 2017 to encompass all studies published until 31 December 2016. In WoS, the search was restricted to the fields of environmental sciences and ecology, forestry, biodiversity conservation, zoology, plant sciences, meteorology and atmospheric sciences, entomology, and water resources. In Scopus, the search was restricted to agricultural and biological sciences, environmental science, earth and planetary sciences, and multidisciplinary studies.

We performed secondary searches to find other publications, including grey literature, with simplified population and intervention terms. These searches were made in the Directory of Open Access Journals (https://doaj.org/), the CABI database of forest science (http://www.cabi.org/forestscience/), and websites of the Canadian Forest Service (http://cfs.nrcan.gc.ca/publications) and the USDA Forest Service (http://www.treesearch.fs.fed.us/). We also searched in Google Scholar. For complete search terms, see Supplementary Table S1[1].

As supplementary bibliographic searches, the reference lists of relevant articles (review articles and books) were screened for additional articles to complement the list identified using the search terms. A list of the publications was sent to all of the authors of this systematic map, most of whom have research experience on salvage logging. Authors were asked to identify relevant articles that were omitted from the search, and these articles were then assessed against the study inclusion criteria, as described next.

Study inclusion criteria

To be considered for the systematic map, studies had to be empirical and fulfil each of the following inclusion criteria:

(*a*) Relevant population: forest after wildfire, insect outbreak, or windstorm disturbance. Prescribed burning was not considered, as such fires tend to burn at lower intensity than uncontrolled wildfires.

(*b*) Relevant intervention: salvage logging. Different methods of wood extraction and intensities of intervention were considered. We excluded studies in which salvage logging was confounded with other subsequent interventions such as tree planting or insecticide application that were not conducted in the comparator.

(*c*) Relevant comparator: forest disturbed by the same disturbance event but not subject to salvage logging. We did not consider areas of disturbed forest prior to logging as a comparator (i.e., before–after (BA) study designs), as post-disturbance ecosystems are highly dynamic and the effects of salvage logging could be confounded with the effects of the time elapsed since the disturbance. As comparators, we considered the disturbed but unsalvaged areas of control–intervention (CI) and before–after control–intervention (BACI) designs.

(*d*) Relevant outcome: response variable that could broadly be regarded as a regulating or supporting ecosystem service. As it was expected that ecosystem services would rarely be directly addressed, we used variables considered to be indicators or proxies for ecosystem services (e.g., the quality of stream water for water purification, the abundance of seed dispersers for seed dispersal, plant biomass or cover for primary productivity, or the abundance of invasive species for invasion resistance). We also included studies addressing post-disturbance tree regeneration such as seedling density, survival, and growth. Provisioning ecosystem services such as timber were excluded because they are tightly linked to market conditions, which can vary considerably across locations and time. Rather than neglecting the importance of such ecosystem services (which are major drivers of the decision to salvage log disturbed forests), our intention was to complement the list of ecosystem services that can be affected by this practice. We also excluded cultural services because we expected few studies on this topic. Also, any variables directly related to the number of standing trees were excluded on the basis that the intervention directly aims at their extraction and reductions are thus a logical outcome. Finally, biodiversity was not included in

---

[1] Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2018-0114.

the systematic map because such responses were thoroughly reviewed in a recent meta-analysis (Thorn et al. 2018).

We did not explicitly impose geographic restrictions on the studies, although the searches were restricted to publications in English.

Article screening

The relevance of the articles resulting from the searches of the literature was assessed through a stepwise elimination procedure. The articles were screened in the following steps:

1. Each title was read in the first step, and articles with irrelevant titles were discarded. This step was completed in a conservative way to avoid discarding any potentially relevant publications. Before screening all of the titles, two members of the team (ABL and LG) screened 401 titles and the difference in outcomes was assessed through a kappa test. As the results indicated heterogeneity of application of selection criteria (see Results), the inclusion criteria were discussed again prior to screening all of the titles. After screening the titles, the word "salvage" was searched in the titles, keywords, and abstracts of all of the papers that were recorded as irrelevant based on title. Their titles were screened again under a more inclusive approach, and those considered potentially relevant were re-included for the next step.
2. The abstracts of articles with relevant titles were read in the second step, and articles with irrelevant abstracts were discarded. To be classified as relevant in this step, the abstracts had to fulfil the inclusion criteria *a*, *b*, and *c*. When there was doubt about the relevance of a publication, it was kept for the next step. Three authors (ABL, JC, and LG) initially revised 63 randomly chosen abstracts, and kappa tests were again used to assess and improve homogeneity of application of inclusion criteria.
3. The articles with potentially relevant abstracts were read in full. At this stage, articles failing to fulfil any one of the study inclusion criteria were discarded. To select studies that fulfilled inclusion criterion *d*, the main objectives and the sampling methods of the studies were assessed, as well as the study-site descriptions (including tables and figures). Relevant articles were categorized according to the study quality assessment criteria defined below.

Study quality and validity assessment

Quality appraisal is not a necessary process in systematic mapping (James et al. 2016). Nevertheless, based on the retrieved literature, we identified some quality issues related to both the methodology and the reporting in individual publications that provided insight into the validity of the publication for inclusion in the map. First, regarding quality in reporting, the lack of proper description of the study site and the sampling methods (i.e., not possible to assess study inclusion criteria and (or) study validity based on methodological quality due to deficiencies in reporting) led to study exclusion.

The remaining studies were placed in the following three broad categories based on methodological quality:

1. Empirical studies with treatments applied at appropriate spatial scales and with true replication at the scale of management operations and with randomized allocation of treatments to spatial units. An appropriate scale was considered as one that would generally be used in post-disturbance management under local conditions or that would reasonably allow the measured responses to appear.
2. Studies as in (1) above, but without randomization in the allocation of treatments to spatial units. This was often the case, as the authors of the retrieved articles rarely had control over the salvage logging process. This quality aspect is relevant from the point of view of susceptibility to bias and it should be considered in subsequent systematic reviews. Although we did not use this criterion to reject studies in this systematic map, we did record whether the spatial units where the intervention and the comparator were established were chosen by the researchers (see Systematic map database, below).
3. Empirical studies without true replication or at inappropriate spatial scales. One of the most frequent cases was that of one disturbance event affecting a reserve (unsalvaged comparator) and adjacent, unprotected forest (salvaged intervention area). Such designs are highly susceptible to confounding factors related to the management history and objectives of the different management ("treatment") units and hence to bias, so we decided to exclude them from the systematic map. As a matter of consistency, we also eliminated all other studies that contained only one true replicate unit per treatment. It should be noted that in some studies, the degree of true replication was hard to assess from the study site descriptions, and in other cases, there was ambiguity in what could be considered true replication. In such cases, other articles from the same sites were assessed and, where necessary, authors were contacted to clarify their study designs.

Systematic map database and data coding strategy

We constructed a database with information relative to each publication, which included bibliographic information and data related to the secondary research questions. This encompassed data on stand, disturbance, and salvage logging characteristics, study designs, and the response variables that were measured. For a detailed description of the data included in the systematic map database, see Appendix A.

Calculations and graphical output were produced in R (version 3.3.1; R Core Team 2016).

Results and discussion

Literature searches

We retrieved 4341 publications from the primary searches (Fig. 2). A total of 274 publications was assessed at full-text length, and 90 were kept in this systematic map (Fig. 2; see Supplementary Table S2[1] for publications excluded at this stage and the reasons for exclusion). For detailed descriptions of the results of the literature searches and screening, see Appendix B. The remainder of the systematic map is primarily grounded on the 90 publications that were kept, which are included in the systematic map database (Supplementary Table S3[1]; also available online with open access, see Leverkus et al. 2018).

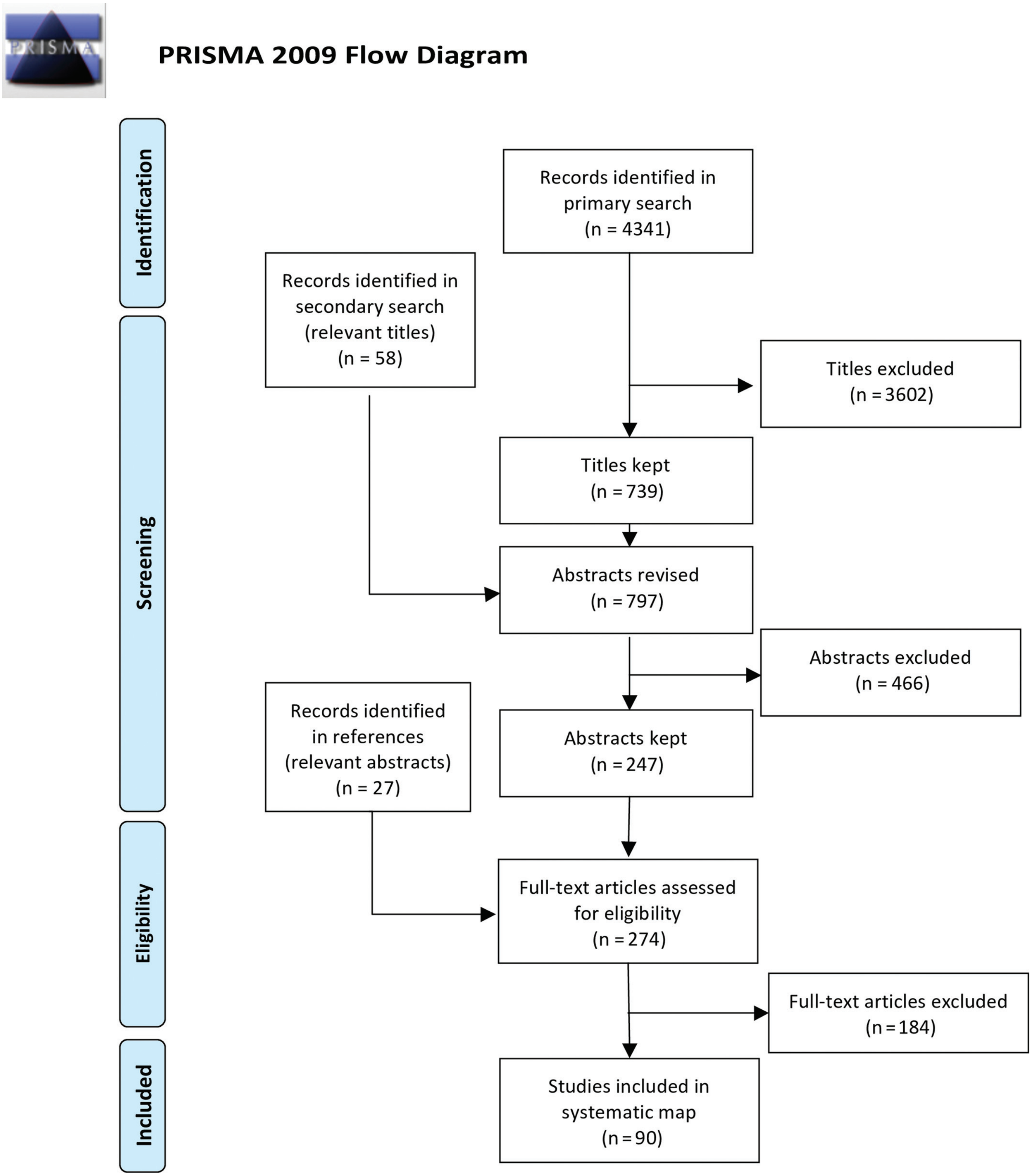
The following results are presented at the level that we considered most relevant for each addressed characteristic: some at the level of publications ($n = 90$), others at the level of studies ($n = 49$) (see Appendix A), and others at the level of stand types within study sites or within publications (for example, in cases in which more than one stand was addressed in a single study; $n > 49$). The level of each result is always indicated in the text, and the database allows assessing any data at any desired level.

Origin and distribution of publications

Of the 90 publications included in the systematic map database, 81 were obtained from the primary search in the Web of Science. The cumulative number of publications has increased dramatically in the last two decades and particularly in the last decade (Fig. 3).

The 90 publications resulted from 49 studies, including studies with multiple study sites. Individual studies produced an average of 1.8 ± 1.2 publications (mean ± SD; range: 1–6), although it should be noted that not all publications from all studies are included in this systematic map (e.g., some papers from the Bavarian Forest National Park in Germany that dealt with salvage logging effects on biodiversity were excluded (Beudert et al. 2015; Thorn et al.

Fig. 2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram. Shown are the number of publications retrieved in the literature searches and the number excluded in each step. Diagram adapted from Moher et al. (2009). [Colour online.]



2015*a*, 2015*b*)). Studies were generally established within one clearly defined study area such as a publicly owned forest (e.g., National Forest) with adjacent private forestland, but eight studies (yielding 12 publications) either addressed two or more study sites that were located in different regions (separated by more than 100 km; e.g., Wagenbrenner et al. 2015) or had a sampling design of regional scale with multiple sites (e.g., Priewasser et al. 2013) (Table 1).

The publications included in the database were overwhelmingly concentrated in North America and Europe, with only two

Fig. 3. Cumulative number of publications per disturbance type included in this systematic map. [Colour online.]

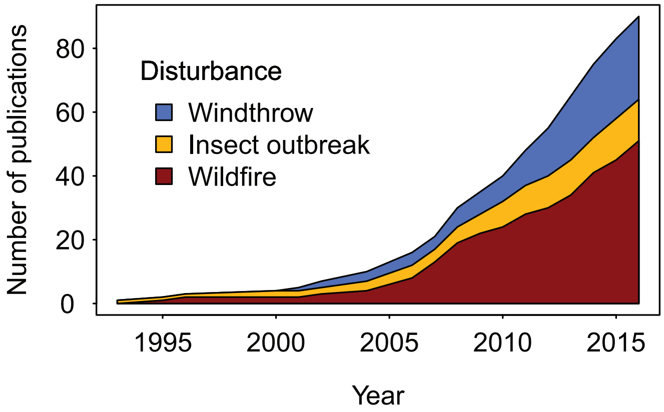


Table 1. Distribution of publications and study sites across geographic areas.

Continent	Country	No. of publications	No. of studies	No. of multisite studies
North America	USA	42	25	3
	Canada	25	12	4
Europe	Spain	10	4	0
	Switzerland	4	1	1
	Germany	2	2	0
	Portugal	2	1	1
	Estonia	1	1	0
	Czech Republic	2	1	0
Asia	Israel	1	1	0
	South Korea	1	1	0
Total		90	49	9

publications from another continent and no representation from the tropics or the Southern Hemisphere (Fig. 4; Table 1). Even within these two geographic clusters, the publications were not equally distributed. In North America, there were nearly twice as many publications from the United States than from Canada, and even publications from Canada were more abundant than those from all Europe (where half of the publications came from Spain). One could predict that studies on post-disturbance logging would occur more frequently in places where more natural disturbance occurs or where natural disturbance is more often followed by logging. However, disturbances are common across forests globally (Seidl et al. 2017), and there is no obvious reason to consider that the countries not included in the systematic map lack salvage logging.

A possible explanation for the paucity of studies in the tropics lies in differences in human-related causes and consequences of disturbances across regions. Disturbances such as wildfire in regions at the frontline of land-use change, as in many tropical regions, often constitute an instrument for deforestation and land conversion rather than a natural process followed by regeneration. In contrast, developed countries have generally reached more stable land uses, so that disturbed forests will be expected to regrow, either for production or for nature conservation. In this way, assessing the effects of salvage logging on ecosystems makes more sense in cases where management or conservation objectives are to maintain forest cover, as is more often the case in Europe and North America than in other regions. Even in the few exceptions where salvage logging was addressed in tropical areas, the research was conducted by foreign researchers (Van Nieuwstadt et al. 2001). Most of the studies outside these two zones, including studies in Chile (Smith-Ramírez et al. 2014) and Australia (Blair et al. 2016), failed to pass the inclusion criteria regarding the relevance of response variables. Other non-mutually exclusive reasons for the predominance of European and North American studies, as highlighted in a systematic map on active interventions for biodiversity conservation (Bernes et al. 2015), are (*a*) the large extents of forest, (*b*) the greater abundance of researchers and availability of funding, and (*c*) the large emphasis on research in ecology and environmental management in Europe and North America. Finally, an important factor could be the language selected for the literature search (English), which was originally aimed at identifying scientific studies from over the world but was biased against studies from nations where English is either not the official language or not spoken at a sufficient level of proficiency to facilitate publication in indexed journals.

Disturbance characteristics

Wildfire was the most frequent disturbance type, with 51 publications (27 studies), followed by wind (26 publications, 12 studies), and insect outbreaks (13 publications, 11 studies). McIver and Starr (2000) conducted a review that highlighted several mechanisms through which burnt forests could be particularly vulnerable to subsequent logging disturbance, including effects on burnt soil and vegetation. This review also noted a lack of empirical evidence regarding the consequences of post-fire logging, which triggered numerous research projects on logging after wildfire (e.g., McIver and McNeil (2006); Donato et al. (2006); Castro et al. (2010)). Wildfire produces some unique ecological responses such as significant reductions in small-diameter aboveground biomass, as well as direct and indirect wildlife mortality. Wildfire also generates direct impacts on people living in or near fire-prone forests and spectacular images in the media. These factors have likely generated more public and political demand for understanding the various implications of wildfire as compared with windstorms or insect outbreaks, including impacts related to subsequent salvage logging. However, logging after large storms (e.g., Kramer et al. 2014) and after massive insect outbreaks (e.g., Collins et al. 2011) have recently attracted increasing attention. The three kinds of disturbances addressed here have increased — and will likely continue to increase — in frequency and extent due to climate change and other factors related to ecosystem conversion and changes in land-use intensity (Seidl et al. 2017). Addressing questions related to post-disturbance management is a logical response to increasingly prevalent situations.

Many ecological responses to disturbances depend largely on disturbance severity, which highlights the relevance of studying the response to disturbance and to subsequent logging under different degrees of severity. The severity of natural disturbance among the retrieved publications ranged between 10% and 100% (Fig. 5A; note the limitations in these data described in Appendix A). We found that wildfire was generally described as having greater disturbance severity than insect outbreaks or windstorms. Studies on logging after wildfire or insect outbreaks were generally tightly clustered at high severity values, whereas disturbance severity by wind was less severe and more variable. Most of the studies included in the systematic map were performed within patches subject to disturbances of specific severity, thereby controlling for this factor as much as possible. In only a few cases (8 out of 49) did the studies directly address disturbance severity as an explanatory variable, either through the selection of stands within different degrees of severity (e.g., Brewer et al. 2012) or by sampling severity gradients within plots (e.g., Royo et al. 2016). Although the selection of plots of different disturbance severity is an appropriate way to increase the robustness of the study design, it may come at the cost of lower replication. In contrast, measuring disturbance severity at smaller scales as a covariate can help increase the explanatory power of management variables without

Fig. 4. Location of the individual studies included in the systematic map. Number codes are indicated for reference (column Site_ref in the systematic map database, Supplementary Table S3[1]). Inset: Korean Peninsula.

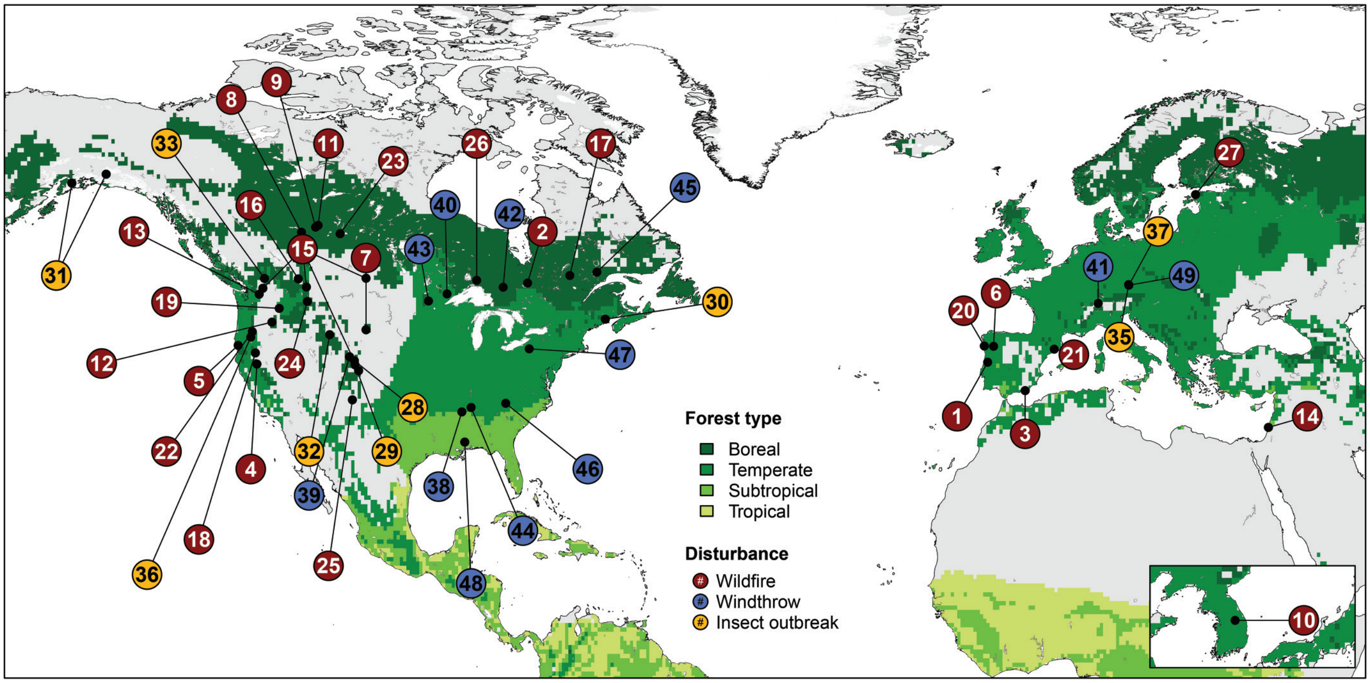
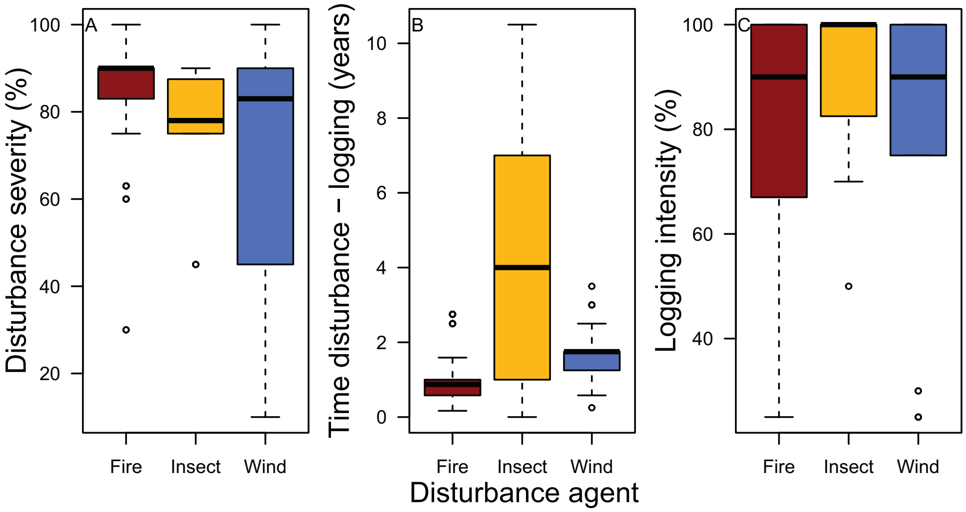


Fig. 5. Disturbance and salvage logging characteristics. (A) Disturbance severity considered in the analyzed publications. This includes 1–3 points per publication, according to whether one general disturbance severity was reported or the publication explicitly included sampling areas of different severity levels. (B) Time elapsed between the disturbance and subsequent salvage logging. Each data point represents one publication. (C) Logging intensity in the analyzed publications. This includes 1–4 points per publication. Note that this applies to the Intervention element only, as each publication also included a Comparator with 0% logging intensity. In all plots, the thick horizontal lines are medians, and the boxes indicate the first and third quartiles of the values. Whiskers are either the minimum to maximum values or 1.5 times the interquartile range of the data, in which case outliers are shown as points. The values of disturbance severity and logging intensity are broad approximations. Sample sizes for the graphics (panels A, B, and C, respectively): for fire, 53, 51, and 69; for insect outbreaks, 15, 13, and 15; and for wind, 31, 26, and 21. [Colour online.]



sacrificing replication. Of course, this is not always possible, and it hinges on the spatial scale at which disturbance severity varies and the spatial scale required to accurately assess the response variable of interest.

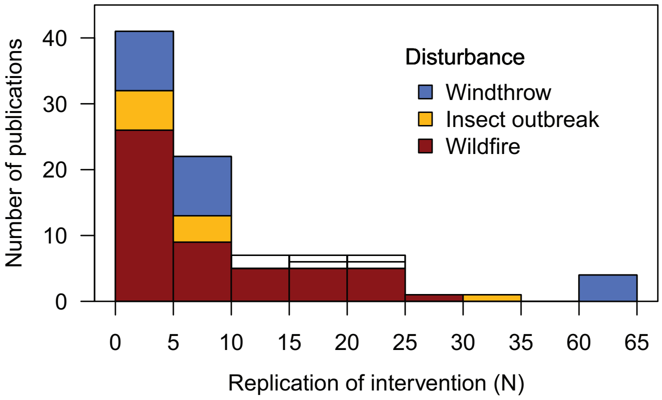
We did not collect information on the spatial extent of the disturbances because in many cases this information was not available. However, it can be argued that large disturbances will generally attract more research and provide opportunities for greater replication. For example, disturbances in North America commonly affect large areas (e.g., the 2016 fire near Fort McMurray, Canada, which affected more than 0.5 million ha). Salvage logging is, however, quite often performed in areas affected by small- or medium-scale disturbances, which are common in Europe and tend to be confined to areas with pre-existing road infrastructure. Scientific studies performed in these areas might suffer from constraints in the sampling design (thus leading to exclusion from the systematic map), but in these situations, logging intensity is likely to reach 100% across the disturbed area. As a consequence, subjects worthy of in-depth analysis that are not covered by this systematic map include the relationships among disturbance extent, the extent and intensity of salvage logging, and the ecological response to disturbance and subsequent salvage logging.

Intervention characteristics

Ecological responses to salvage logging are often considered to vary with the time elapsed between the disturbance and logging, particularly in the case of discrete disturbance events such as wildfire. For example, post-fire logging may have a greater impact on soils if it is conducted directly after wildfire because it may delay post-fire recovery (Wagenbrenner et al. 2016). If logging occurs during or after the first growing season, natural regeneration can be most severely affected due to the physical destruction of resprouting stems and emerging seedlings (Martínez-Sánchez et al. 1999; Castro et al. 2011). The studies included in the systematic map most often included information on when logging was conducted, yet individual studies did not explicitly test the effect of different timing of salvage logging. Salvage logging took place between immediately and 10.5 years following the disturbance, with an average of 1.8 ± 2.0 (mean ± 1 SD) years across publications. Burnt stands were generally those salvage logged most quickly (after 1.1 ± 0.8 years), followed by wind-affected stands (1.7 ± 0.8 years; Fig. 5B). In the case of disturbance by insects, salvage logging often started several years after the beginning of the outbreak, and the variability in the timing of salvage logging was much greater than for the other two disturbance types (4.4 ± 3.7 years). Insect outbreaks most often take several years to develop, during which time each tree goes through several stages of decline (Sullivan et al. 2010), and logging can take place at any stage from before the beginning of the outbreak — pre-emptive logging, not addressed here — to logging after several years of infestation. Logging is sometimes conducted in an attempt to prevent the infestation of particular stands or the expansion of insect populations (Müller et al. 2018), and in other cases, it is performed to avoid wood decay or the accumulation of fuel once the stand has been affected. These are likely reasons for the greater variability in the timing of salvage logging related to insect outbreaks than after disturbance by fire or wind.

The intensity of salvage logging can be another crucial factor explaining salvage logging effects, as already identified more than six decades ago (Roy 1956). The studies in the systematic map included a wide range of salvage logging intensity for the three disturbance types considered, although intensity was mostly categorized in excess of 90%. Salvage logging intensity ranged between 25% and 100% and averaged 80% ± 24% (including up to four values per publication). Average intensity was 79% ± 24% for wildfire, 90% ± 15% for insect outbreaks, and 79% ± 27% for wind damage (Fig. 5C; as with disturbance severity, note the limitations in these data, described in Appendix A). In some cases, the effect of different logging intensity was assessed within individual studies; this often included qualitative differences in logging practices such as the removal of slash or the retention of standing dead trees. Notably, in one experimental study, stands under five classes of logging intensity were established, ranging from 0% to 100% (Ritchie et al. 2013). The authors further assessed the effect of the amount of basal area retained, which explained the variation in some of the response variables better than the categorical experimental factor (Ritchie et al. 2013). Such studies can provide important insights into the responses to salvage logging and can evaluate the effectiveness of best management practices, as logging — and other disturbances — may not necessarily produce generalizable effects but rather effects that vary nonlinearly according to disturbance intensity or severity (Buma 2015; Foster et al. 2016; Leverkus et al. 2018*a*). This has long been acknowledged in traditional green-tree silviculture in which the retention forestry approach was created under the acknowledgement that the effects of commercial clearcutting can be greatly mitigated by leaving behind structures that favour the continuity of the forest ecosystem (Gustafsson et al. 2012; Lindenmayer et al. 2012). The rapid deterioration of wood quality following disturbance-induced mortality reduces the profitability of salvage operations compared with green-tree silviculture, and this could be a limitation for retention approaches. Nevertheless, the potential benefits of the retention of biological legacies (Franklin et al. 2000) during post-disturbance harvest operations should be more profoundly explored (Lindenmayer et al. 2018; Thorn et al. 2018).

Fig. 6. The number of spatially independent salvage logging replicate units used in the 90 publications, classified by disturbance type. [Colour online.]



The methods employed in salvage logging operations can also modulate the effect of the intervention. For example, mechanized harvesting equipment is more likely to compact soils than manual cutting with chainsaws, but it may also produce novel, positive effects such as the formation of ruts that fill with water and create persistent aquatic habitat (Ernst et al. 2016). Logging operations were often not described well enough in publications included in the systematic map to identify logging methods, sometimes because the operations were not observed by the researchers. Harvesting with feller–bunchers was mentioned in 15 studies (not publications), and manual cutting was mentioned in 10 studies. Ground-based yarding was mentioned in 20 studies, and yarding by helicopter was mentioned in two studies. Extraction of wood by helicopter is well known to reduce soil impacts compared with ground-based yarding. However, helicopter use is extremely costly; this and the low economic value of disturbance-affected timber and the depressed price that typically follows large disturbance events are likely reasons for the scant use of helicopters.

Stand characteristics

Of the 49 studies included in the systematic map, 11 were established in broadleaf forests or included broadleaf stands, 33 were established in or included conifer stands, 10 included mixed stands, and 3 included combinations of stand types without differentiation. In most cases, the stands fell into the "mature" category. There were 37 tree species dominating or co-dominating the stands addressed in the retrieved publications. For further details on the characteristics of stands among the retrieved studies, see Appendix C.

Characteristics of study designs

True replication is an important factor reducing the potential for bias of individual studies. True replication of salvage logging generally did not exceed $N = 10$ stands (Fig. 6; presented at the scale of publications because some publications of the same studies made use of different subsets of a larger design, e.g., Leverkus et al. 2014, 2016). Most studies addressed the issue of low replication by establishing hierarchical sampling designs (i.e., with several subunits within salvage and control units) and by controlling the effects of potentially confounding co-variables. These strategies were also employed in many of the studies that were excluded due to lack of true replication (Supplementary Table S2[1]). As a result, we do not discard the possibility that some of those excluded studies could provide valuable insights despite the lack of true replication, yet for the purpose of inclusion in the systematic map, we elected to stay with the study inclusion criteria established in the protocol aimed at reducing the potential for bias (Leverkus et al. 2015*a*).

In 11 of the 49 studies, the selection of stands for management intervention was at least under partial control by the researchers and included randomization in the allocation of treatments to spatial units. In the rest of the studies, researchers made use of areas that were either salvaged or left unsalvaged to achieve management objectives rather than to conduct research. Both approaches provided several advantages and disadvantages. Non-experimental studies have a risk of bias between intervention and comparator stands, for example, due to the selection of more productive stands, or those nearest to roads, for salvage operations. Further, the choice not to salvage log particular stands is sometimes justified by reasons such as fiscal constraints and litigation; stream, hillside, and habitat protection; or inaccessibility (McGinnis et al. 2010), highlighting the potential for bias. Still, in non-experimental studies, care was generally taken to select salvaged and unsalvaged stands of similar pre-disturbance conditions to minimize such bias. In addition, some studies controlled for random spatial variation by implementing a BACI design, i.e., by measuring how the response variables changed over time from pre-logging to post-logging and in stands with and without the salvage logging intervention, thus providing a robust method for addressing bias. Such a BACI design was implemented in 36% of the 11 studies in which salvage logging was performed experimentally and in 19% of the 37 non-experimental studies. One good example of experimental design is the one established after the Summit Fire in Oregon, which included randomization, blocking, treatments applied at an appropriate spatial scale, replication, consideration of disturbance severity and salvage logging intensity, and a BACI sampling design (McIver and Ottmar 2007). Such studies are extremely difficult to implement, as exemplified by one paper that reported the conceptualization of a randomized complete block design that, however, could not be turned to practice due to legal constraints and that resulted in a pseudo-replicated design comparing salvaged private forest with unsalvaged public land (Slesak et al. 2015), hence leading to exclusion from our systematic map.

Not all true experimental studies are necessarily ideal, and some can suffer problems of inappropriate spatial scale and lack of replication (e.g., Francos et al. 2018), but such problems were not detected in the retrieved studies. However, a general disadvantage of experiments that were under the control of researchers is that the logging intervention was typically performed in close compliance with environmental prescriptions (e.g., Ne'eman et al. 1997; McIver and Ottmar 2007; Leverkus et al. 2014), thus the intervention may have lesser effects than under non-experimental, "real-world" management. Besides, some non-experimental studies had the advantage that they could be conducted at spatial scales larger than what would be possible under experimental approaches by selecting several disturbance patches with and without intervention that fulfilled certain criteria across entire regions or countries (Priewasser et al. 2013; Águas et al. 2014). In this systematic map, most studies (36) were established within the perimeter of a single disturbance event, thereby establishing the disturbance as the constraint on the inference population. However, two studies (one post-fire study and one post-insect study) included two disturbance events, four included four events, one included five, one included 14, and one included 20 (all post-fire). Three studies on post-windthrow logging addressed one disturbance event (e.g., one storm) but within 7, 11, or 30 spatially independent blowdown patches; one study assessed 90 individual patches caused by two storms.

As a corollary of the previous discussion, it is difficult to apply strict, identical quality criteria to all studies, and there is not one single ideal study design. We consider all studies included in this systematic map to be of sufficient quality for providing relevant information under certain conditions.

Characteristics of the responses

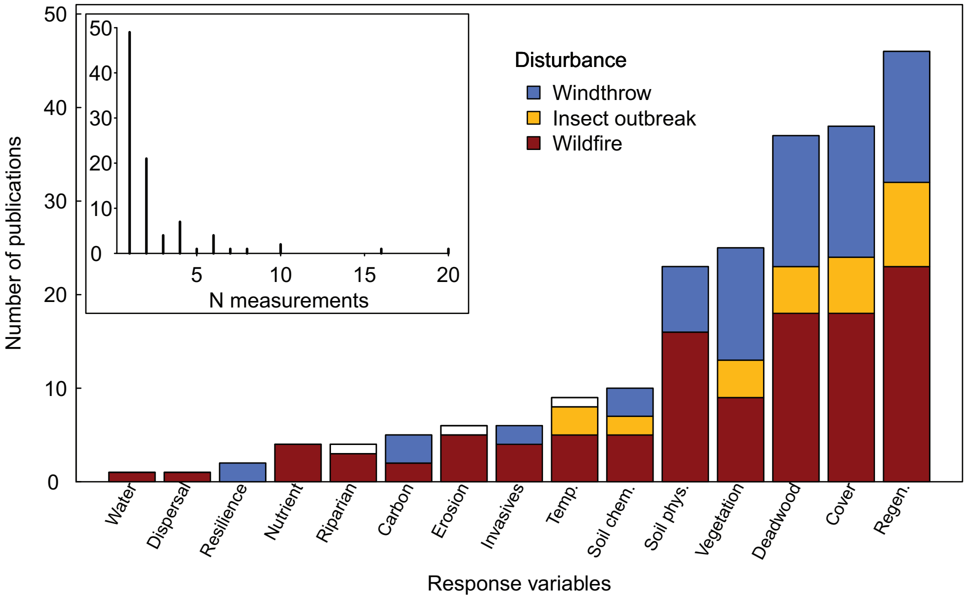
Studies explicitly focusing on the response of ecosystem services to salvage logging were scant. Most publications addressed ecosystem elements and structures, fewer studied ecosystem functions, and very few addressed the human well-being component of ecosystem services directly (Fig. 1). This is consistent with the findings of a global literature review on ecosystem service studies (Boerema et al. 2017), and it highlights the need to better address the human component of salvage logging effects to improve the transferability of results to management decisions (Leverkus and Castro 2017). On the other hand, most of the publications (79%) included data on one or two measurements of the response variable undertaken at different times, and the maximum was 20 measurements (Fig. 7, inset). Four publications included continuous measurements taken over 3 or 6 years.

The most frequent response variables examined were related to tree regeneration (addressed by 51% of the publications; Fig. 7). These included the density, basal area, growth, and survival of trees established after disturbance. This was no surprise, as establishment of trees is perhaps the most direct indicator of the recovery of the previous ecosystem. Further, some agencies, e.g., the USDA Forest Service, are required by law to monitor and rectify tree regeneration failure associated with management activities. In many situations, lack of appropriate regeneration means that trees would have to be planted, so that natural regeneration provides direct value for society (Fig. 1). In fact, as early as in 1956, a report (Roy 1956) already advised "When you find good reproduction, protect it. Try to save the high costs of artificial regeneration."

Second in importance were the response variables related to ground cover (addressed by 42% of publications). Typically, this would include vegetation cover, a useful measure of protection from soil erosion or of primary productivity. Cover of pits and mounds, as well as cover of deadwood, may be used as indicators of the microclimatic and microtopographic habitat availability and heterogeneity. Bare soil cover could be an indicator of available seedbed in measurements made immediately after the disturbance or of ground disturbance and lack of regeneration in both early and subsequent measurements. Finally, skid trail cover would indicate soil disturbance and compaction.

The third most frequent response variable type was related to the availability and characteristics of deadwood (addressed by 41% of publications). This included snags, downed logs, branches, and twigs, often separated by species, size, and decay stage. Deadwood after disturbance is an important component associated with many post-disturbance specialists, including birds and beetles (Thorn et al. 2018). Standing trees can act as habitat for species that live in tree hollows (Lindenmayer and Possingham 1996) and as perches or visual cues for seed dispersers (Castro et al. 2012; Cavallero et al. 2013). Deadwood constitutes a pool of nutrients that is released to the soil in the mid and long terms through decomposition (Marañón-Jiménez and Castro 2013; Molinas-González et al. 2017*a*). It can also ameliorate microclimatic conditions to enhance tree regeneration (Castro et al. 2011) and help reduce herbivory by large ungulates (Leverkus et al. 2015*b*). However, there is also a risk that the wood left behind by disturbance constitutes the means of propagation of a subsequent disturbance such as wildfire or insect outbreaks. As a result, in many studies,

Fig. 7. Number of publications that reported different measured response variables, for each disturbance type. Water, drinking water quality; Dispersal, seed dispersal; Resilience, capacity to regenerate after subsequent wildfire (i.e., wildfire after salvage logging); Nutrient, biological indicators of nutrient cycling; Riparian, riparian ecosystem functioning; Carbon, non-wood carbon pool; Erosion, soil erosion by wind or water; Invasives, invasive and (or) exotic species; Temp., air, water, or soil temperature; Soil chem., soil chemical properties; Soil phys., soil physical properties; Vegetation, vegetation composition; Deadwood, stand structure and deadwood amount and characteristics; Cover, ground cover, including cover of vegetation; Regen., tree regeneration. Note that biodiversity responses were excluded from the systematic map. Inset: distribution of publications according to the number of individual measurements taken for the response variables. Both *y*-axes have the same meaning. [Colour online.]



the aim of deadwood characterization was to assess the amount and features of fuels, including the modelling of future fuel characteristics and of potential fire behaviour (McIver and Ottmar 2007; Keyser et al. 2009; Donato et al. 2013; Hood et al. 2017). One publication with a chronosequence approach provides a thorough assessment of the time frames at which fuels are enhanced or reduced by salvage logging (Peterson et al. 2015). In fact, risk reduction of subsequent disturbance is one of the main justifications for salvage logging (Müller et al. 2018), including fire but also the risk of bark beetle outbreaks after windstorms (Leverkus et al. 2017) and other linked disturbances (Buma 2015). Nevertheless, we identified only two studies addressing resilience to subsequent wildfire as a response variable (Fraver et al. 2011; Buma and Wessman 2012). This is likely due to the complex concatenation of disturbance events required to assess such a variable empirically: it requires both intervention and comparator stands to be followed by the same subsequent disturbance and compliance with the additional criteria established in our protocol. Fuel characterization and modelling of fire behaviour are thus logical ways to address such questions, and our systematic map may have left out relevant studies in this regard. Conversely, the amount of deadwood can also be used as an indicator of the size of the carbon pool in disturbed ecosystems. The trade-off between C retention and wildfire prevention can be solved by assessing the C cycle directly (Serrano-Ortiz et al. 2011) or by focusing independently on recalcitrant C pools (large trees, snags, coarse wood, and soil) and labile fuels (understory shrubs, fine wood, and duff) (Powers et al. 2013); the studies in the systematic map generally allow this approach due to the explicit consideration of different size classes.

The fourth most frequent type of response variable was non-tree vegetation (beyond mere percent cover values; addressed by 28% of publications). Although we avoided including biodiversity responses in this map, we did include vegetation as an indicator of the recovery of ecosystem structure, habitat, and soil retention.

Next, soil physical and chemical properties (addressed by 26% of publications) included measurements related to soil fertility. The remaining response variable categories were addressed by <15% of the publications (Fig. 7). Both erosion control and the abundance of exotic or invasive species were addressed in only six publications, which is surprising given that they constitute some of the core concerns of managers after natural disturbances. Negative results and the absence of invasive species could partially explain the lack of published results on this topic (e.g., Leverkus et al. 2014). Next, non-deadwood C pool was addressed in five studies. Biological indicators of nutrient cycling and riparian ecosystem functioning were addressed in four publications. Again, the latter variable comes as one of the main concerns regarding salvage logging, yet with very little research (Karr et al. 2004). This likely has to do with the spatial scale defined for inclusion in the systematic map (that of salvage logging intervention), which excluded several studies implemented at the scale of watersheds and with problems of replication. Only one study addressed seed dispersal and one addressed drinking water quality (perhaps the one publication most clearly focusing on the human well-being side of the ecosystem services cascade; Fig. 1). Avalanche protection in steep hills is another important ecosystem service affected by salvage logging (Wohlgemuth et al. 2017), yet it was not included in the systematic map as a response because the one study addressing it (Schönenberger et al. 2005) lacked replication.

Conclusions

The systematic map presented here provides a rigorous account of the empirical studies addressing the effects of salvage logging on supporting and regulating ecosystem services that fulfil some qualitative requirements. It shows that substantial research has been conducted in the last two decades, particularly after the publication of an article in Science in 2004 calling for a careful revision of post-disturbance management practices (Lindenmayer et al. 2004). Our systematic map is based on a comprehensive and systematic screening of the scientific literature on post-disturbance logging written in English and considers a range of stand, disturbance, and logging characteristics and of outcomes. It should help managers and policy-makers identify the most relevant studies addressing the effects of salvage logging and thus spare them the work of searching from scratch. It is also relevant for scientists who aim to synthesize previous work and it identifies knowledge gaps to help direct future work. For example, we identified a large geographic gap across all continents except Europe and North America. We also found that there has been only very limited research focusing on the link between ecosystem elements and processes and the benefits and values for human society, which ultimately define many management schemes. It should also be noted that very few of the retrieved studies specifically addressed the effects of deadwood retention. Whereas small-scale retention is nowadays a well-known practice in green-tree harvesting and much research has been conducted on the topic (Fedrowitz et al. 2014), the benefits of such practices in disturbed forests are not yet well known and require additional research (Lindenmayer et al. 2018; Thorn et al. 2018). Finally, the systematic map identified some areas with substantial research where systematic review or meta-analysis can be performed:

- the effect of salvage logging on recalcitrant vs. labile deadwood components (i.e., C pool vs. fuel loads) and how these vary over time;
- the effect of salvage logging on tree regeneration;
- the effect of the time between disturbance and subsequent logging on response variables; and
- the effect of disturbance type on the ecological effects of salvage logging.

Acknowledgements

ABL acknowledges postdoctoral funding from the Spanish Ministerio de Economía y Competitividad (FJCI-2015-23687) and mobility grant (CAS17/00374) from Ministerio de Educación, Cultura y Deporte. Additional funding was provided by projects P12-RNM-2705 from Junta de Andalucía, CGL2014-53308-P of the Spanish Government, and Remedinal 3 (S2013/MAE-2719) of the Madrid Government.

References

Águas, A., Ferreira, A., Maia, P., Fernandes, P.M., Roxo, L., Keizer, J., Silva, J.S., Rego, F.C., and Moreira, F. 2014. Natural establishment of *Eucalyptus globulus* Labill. in burnt stands in Portugal. For. Ecol. Manage. **323**: 47–56. doi:10.1016/j.foreco.2014.03.012.

Beghin, R., Lingua, E., Garbarino, M., Lonati, M., Bovio, G., Motta, R., and Marzano, R. 2010. *Pinus sylvestris* forest regeneration under different post-fire restoration practices in the northwestern Italian Alps. Ecol. Eng. **36**(10): 1365–1372. doi:10.1016/j.ecoleng.2010.06.014.

Bernes, C., Jonsson, B.G., Junninen, K., Lõhmus, A., Macdonald, E., Müller, J., and Sandström, J. 2015. What is the impact of active management on biodiversity in boreal and temperate forests set aside for conservation or restoration? A systematic map. Environ. Evidence, **4**: 25. doi:10.1186/s13750-015-0050-7.

Beschta, R.L., Rhodes, J.J., Kauffman, J.B., Gresswell, R.E., Minshall, G.W., Karr, J.R., Perry, D.A., Hauer, F.R., and Frissell, C.A. 2004. Postfire management on forested public lands of the Western United States. Conserv. Biol. **18**(4): 957–967. doi:10.1111/j.1523-1739.2004.00495.x.

Beudert, B., Bässler, C., Thorn, S., Noss, R., Schröder, B., Dieffenbach-Fries, H., Foullois, N., and Müller, J. 2015. Bark beetles increase biodiversity while maintaining drinking water quality. Conserv. Lett. **8**(4): 272–281. doi:10.1111/conl.12153.

Blair, D.P., McBurney, L.M., Blanchard, W., Banks, S.C., and Lindenmayer, D.B. 2016. Disturbance gradient shows logging affects plant functional groups more than fire. Ecol. Appl. **26**(7): 2280–2301. doi:10.1002/eap.1369. PMID:27755744.

Boerema, A., Rebelo, A.J., Bodi, M.B., Esler, K.J., and Meire, P. 2017. Are ecosystem services adequately quantified? J. Appl. Ecol. **54**(2): 358–370. doi:10.1111/1365-2664.12696.

Boucher, D., Gauthier, S., Noël, J., Greene, D.F., and Bergeron, Y. 2014. Salvage logging affects early post-fire tree composition in Canadian boreal forest. For. Ecol. Manage. **325**: 118–127. doi:10.1016/j.foreco.2014.04.002.

Brewer, J.S., Bertz, C.A., Cannon, J.B., Chesser, J.D., and Maynard, E.E. 2012. Do natural disturbances or the forestry practices that follow them convert forests to early-successional communities? Ecol. Appl. **22**(2): 442–458. doi:10.1890/11-0386.1. PMID:22611846.

Buma, B. 2015. Disturbance interactions: characterization, prediction, and the potential for cascading effects. Ecosphere, **6**: art70. doi:10.1890/ES15-00058.1.

Buma, B., and Wessman, C.A. 2012. Differential species responses to compounded perturbations and implications for landscape heterogeneity and resilience. For. Ecol. Manage. **266**: 25–33. doi:10.1016/j.foreco.2011.10.040.

Castro, J. 2013. Postfire burnt-wood management affects plant damage by ungulate herbivores. Int. J. For. Res. **2013**: 965461. doi:10.1155/2013/965461.

Castro, J., Moreno-Rueda, G., and Hódar, J.A. 2010. Experimental test of postfire management in pine forests: Impact of salvage logging versus partial cutting and nonintervention on bird-species assemblages. Conserv. Biol. **24**(3): 810–819. doi:10.1111/j.1523-1739.2009.01382.x. PMID:20015262.

Castro, J., Allen, C.D., Molina-Morales, M., Marañón-Jiménez, S., Sánchez-Miranda, Á., and Zamora, R. 2011. Salvage logging versus the use of burnt wood as a nurse object to promote post-fire tree seedling establishment. Restor. Ecol. **19**(4): 537–544. doi:10.1111/j.1526-100X.2009.00619.x.

Castro, J., Puerta-Piñero, C., Leverkus, A.B., Moreno-Rueda, G., and Sánchez-Miranda, A. 2012. Post-fire salvage logging alters a key plant–animal interaction for forest regeneration. Ecosphere, **3**(10): art90. doi:10.1890/ES12-00089.1.

Cavallero, L., Raffaele, E., and Aizen, M.A. 2013. Birds as mediators of passive restoration during early post-fire recovery. Biol. Conserv. **158**: 342–350. doi:10.1016/j.biocon.2012.10.004.

Centre for Evidence-Based Conservation (CEBC). 2010. Guidelines for Systematic Reviews in Environmental Management. Version 4.0. Centre for Evidence-Based Conservation, Bangor, UK.

Collins, B.J., Rhoades, C.C., Underhill, J., and Hubbard, R.M. 2010. Post-harvest seedling recruitment following mountain pine beetle infestation of Colorado lodgepole pine stands: a comparison using historic survey records. Can. J. For. Res. **40**(12): 2452–2456. doi:10.1139/X10-172.

Collins, B.J., Rhoades, C.C., Hubbard, R.M., and Battaglia, M.A. 2011. Tree regeneration and future stand development after bark beetle infestation and harvesting in Colorado lodgepole pine stands. For. Ecol. Manage. **261**(11): 2168–2175. doi:10.1016/j.foreco.2011.03.016.

Collins, B.J., Rhoades, C.C., Battaglia, M.A., and Hubbard, R.M. 2012. The effects of bark beetle outbreaks on forest development, fuel loads and potential fire behavior in salvage logged and untreated lodgepole pine forests. For. Ecol. Manage. **284**: 260–268. doi:10.1016/j.foreco.2012.07.027.

Crouzeilles, R., Ferreira, M.S., Chazdon, R.L., Lindenmayer, D.B., Sansevero, J.B.B., Monteiro, L., Iribarrem, A., Latawiec, A.E., and Strassburg, B.B.N. 2017. Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. Sci. Adv. **3**: e1701345. doi:10.1126/sciadv.1701345. PMID:29134195.

DellaSala, D.A., Karr, J.R., Schoennagel, T., Perry, D., Noss, R.F., Lindenmayer, D., Beschta, R., Hutto, R.L., Swanson, M.E., and Evans, J. 2006. Post-fire logging debate ignores many issues. Science, **314**: 51–52. PMID:17023633.

Donato, D.C., Fontaine, J.B., Campbell, J.L., Robinson, W.D., Kauffman, J.B., and Law, B.E. 2006. Post-wildfire logging hinders regeneration and increases fire risk. Science, **311**: 352. doi:10.1126/science.1122855. PMID:16400111.

Donato, D.C., Simard, M., Romme, W.H., Harvey, B.J., and Turner, M.G. 2013. Evaluating post-outbreak management effects on future fuel profiles and stand structure in bark beetle-impacted forests of Greater Yellowstone. For. Ecol. Manage. **303**: 160–174. doi:10.1016/j.foreco.2013.04.022.

Ernst, R., Hölting, M., Rodney, K., Benn, V., Thomas-Caesar, R., and Wegmann, M. 2016. A frog's eye view: logging roads buffer against further diversity loss. Front. Ecol. Environ. **14**(7): 353–355. doi:10.1002/fee.1314.

Fedrowitz, K., Koricheva, J., Baker, S.C., Lindenmayer, D.B., Palik, B., Rosenvald, R., Beese, W., Franklin, J.F., Kouki, J., Macdonald, E., Messier, C., Sverdrup-Thygeson, A., and Gustafsson, L. 2014. Can retention forestry help conserve biodiversity? A meta-analysis. J. Appl. Ecol. **51**: 1669–1679. doi:10.1111/1365-2664.12289. PMID:25552747.

Fornwalt, P.J., Rhoades, C.C., Hubbard, R.M., Harris, R.L., Faist, A.M., and Bowman, W.D. 2018. Short-term understory plant community responses to salvage logging in beetle-affected lodgepole pine forests. For. Ecol. Manage. **409**: 84–93. doi:10.1016/j.foreco.2017.10.056.

Foster, C.N., Sato, C.F., Lindenmayer, D.B., and Barton, P.S. 2016. Integrating theory into disturbance interaction experiments to better inform ecosystem management. Global Change Biol. **22**(4): 1325–1335. doi:10.1111/gcb.13155.

Francos, M., Pereira, P., Alcañiz, M., and Úbeda, X. 2018. Post-wildfire management effects on short-term evolution of soil properties (Catalonia, Spain, SW-Europe). Sci. Total Environ. **633**: 285–292. doi:10.1016/j.scitotenv.2018.03.195. PMID:29574372.

Franklin, J.F., Lindenmayer, D., MacMahon, J.A., McKee, A., Magnuson, J., Perry, D.A., Waide, R., and Foster, D. 2000. Threads of continuity. Conserv. Pract. **1**(1): 8–17. doi:10.1111/j.1526-4629.2000.tb00155.x.

Fraver, S., Jain, T., Bradford, J.B., D'Amato, A.W., Kastendick, D., Palik, B., Shinneman, D., and Stanovick, J. 2011. The efficacy of salvage logging in reducing subsequent fire severity in conifer-dominated forests of Minnesota, USA. Ecol. Appl. **21**: 1895–1901. doi:10.1890/11-0380.1. PMID:21939032.

Greene, D.F., Gauthier, S., Noël, J., Rousseau, M., and Bergeron, Y. 2006. A field experiment to determine the effect of post-fire salvage on seedbeds and tree regeneration. Front. Ecol. Environ. **4**(2): 69–74. doi:10.1890/1540-9295(2006)004[0069:AFETDT]2.0.CO;2.

Gustafsson, L., Baker, S.C., Bauhus, J., Beese, W.J., Brodie, A., Kouki, J., Lindenmayer, D.B., Lõhmus, A., Martínez Pastur, G., Messier, C., Neyland, M., Palik, B., Sverdrup-Thygeson, A., Volney, W.J.A., Wayne, A., and Franklin, J.F. 2012. Retention forestry to maintain multifunctional forests: a world perspective. Bioscience, **62**(7): 633–645. doi:10.1525/bio.2012.62.7.6.

Haines-Young, R., and Potschin, M. 2010. The links between biodiversity, ecosystem services and human well-being. *In* Ecosystem ecology: a new synthesis. *Edited by* D.G. Raffaelli and C.L. Frid. Cambridge University Press. pp. 110–139. doi:10.1017/CBO9780511750458.007.

Hernández-Hernández, R., Castro, J., Del Arco-Aguilar, M., Fernández-López, Á.B., and González-Mancebo, J.M. 2017. Post-fire salvage logging imposes a new disturbance that retards succession: the case of bryophyte communities in a Macaronesian laurel forest. Forests, **8**(7): 252. doi:10.3390/f8070252.

Holzmueller, E.J., and Jose, S. 2012. Response of the invasive grass *Imperata cylindrica* to disturbance in the southeastern forests, USA. Forests, **3**(4): 853–863. doi:10.3390/f3040853.

Hood, P.R., Nelson, K.N., Rhoades, C.C., and Tinker, D.B. 2017. The effect of salvage logging on surface fuel loads and fuel moisture in beetle-infested lodgepole pine forests. For. Ecol. Manage. **390**: 80–88. doi:10.1016/j.foreco.2017.01.003.

James, K.L., Randall, N.P., and Haddaway, N.R. 2016. A methodology for systematic mapping in environmental sciences. Environ. Evidence, **5**: 7. doi:10.1186/s13750-016-0059-6.

Johnstone, J.F., Allen, C.D., Franklin, J.F., Frelich, L.E., Harvey, B.J., Higuera, P.E., Mack, M.C., Meentemeyer, R.K., Metz, M.R., Perry, G.L., Schoennagel, T., and Turner, M.G. 2016. Changing disturbance regimes, ecological memory, and forest resilience. Front. Ecol. Environ. **14**(7): 369–378. doi:10.1002/fee.1311.

Karr, J.R., Rhodes, J.J., Minshall, G.W., Hauer, F.R., Beschta, R.L., Frissell, C.A., and Perry, D.A. 2004. The effects of postfire salvage logging on aquatic ecosystems in the American West. Bioscience, **54**(11): 1029–1033. doi:10.1641/0006-3568(2004)054[1029:TEOPSL]2.0.CO;2.

Keyser, T.L., Smith, F.W., and Shepperd, W.D. 2009. Short-term impact of post-fire salvage logging on regeneration, hazardous fuel accumulation, and understorey development in ponderosa pine forests of the Black Hills, SD, USA. Int. J. Wildland Fire, **18**: 451–458. doi:10.1071/WF08004.

Kishchuk, B.E., Thiffault, E., Lorente, M., Quideau, S., Keddy, T., and Sidders, D. 2015. Decadal soil and stand response to fire, harvest, and salvage-logging disturbances in the western boreal mixedwood forest of Alberta, Canada. Can. J. For. Res. **45**: 141–152. doi:10.1139/cjfr-2014-0148.

Koricheva, J., Gurevitch, J., and Mengersen, K. (*Editors*). 2013. Handbook of meta-analysis in ecology and evolution. Princeton University Press, Princeton and Oxford.

Kramer, K., Brang, P., Bachofen, H., Bugmann, H., and Wohlgemuth, T. 2014. Site factors are more important than salvage logging for tree regeneration after wind disturbance in Central European forests. For. Ecol. Manage. **331**: 116–128. doi:10.1016/j.foreco.2014.08.002.

Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T., and Safranyik, L. 2008. Mountain pine beetle and forest carbon feedback to climate change. Nature, **452**: 987–990. doi:10.1038/nature06777. PMID:18432244.

Lee, E.-J., Lee, W.-S., and Rhim, S.-J. 2008. Characteristics of small rodent populations in post-fire silvicultural management stands within pine forest. For. Ecol. Manage. **255**(5–6): 1418–1422. doi:10.1016/j.foreco.2007.10.055.

Leverkus, A.B., and Castro, J. 2017. An ecosystem services approach to the ecological effects of salvage logging: valuation of seed dispersal. Ecol. Appl. **27**(4): 1057–1063. doi:10.1002/eap.1539. PMID:28342237.

Leverkus, A.B., Puerta-Piñero, C., Guzmán-Álvarez, J.R., Navarro, J., and Castro, J. 2012. Post-fire salvage logging increases restoration costs in a Mediterranean mountain ecosystem. New For. **43**(5–6): 601–613. doi:10.1007/s11056-012-9327-7.

Leverkus, A.B., Lorite, J., Navarro, F.B., Sánchez-Cañete, E.P., and Castro, J. 2014. Post-fire salvage logging alters species composition and reduces cover, richness, and diversity in Mediterranean plant communities. J. Environ. Manage. **133**: 323–331. doi:10.1016/j.jenvman.2013.12.014. PMID:24412981.

Leverkus, A.B., Gustafsson, L., Rey Benayas, J.M., and Castro, J. 2015*a*. Does post-disturbance salvage logging affect the provision of ecosystem services? A systematic review protocol. Environ. Evidence, **4**: 16. doi:10.1186/s13750-015-0042-7.

Leverkus, A.B., Rojo, M., and Castro, J. 2015*b*. Habitat complexity and individual acorn protectors enhance the post-fire restoration of oak forests via seed sowing. Ecol. Eng. **83**: 276–280. doi:10.1016/j.ecoleng.2015.06.033.

Leverkus, A.B., Rey Benayas, J.M., and Castro, J. 2016. Shifting demographic conflicts across recruitment cohorts in a dynamic post-disturbance landscape. Ecology, **97**(10): 2628–2639. doi:10.1002/ecy.1527. PMID:27859134.

Leverkus, A.B., Jaramillo-López, P.F., Brower, L.P., Lindenmayer, D.B., and Williams, E.H. 2017. Mexico's logging threatens butterflies. Science, **358**(6366): 1008. doi:10.1126/science.aar3826. PMID:29170226.

Leverkus, A.B., Lindenmayer, D.B., Thorn, S., and Gustafsson, L. 2018*a*. Salvage logging in the world's forests: interactions between natural disturbance and logging need recognition. Global Ecology and Biogeography. In press. doi:10.1111/geb.12772.

Leverkus, A.B., Rey Benayas, J.M., Castro, J., Boucher, D., Brewer, S., Collins, B.M., Donato, D., Fraver, S., Kishchuk, B.E., Lee, E.-J., Lindenmayer, D.B., Lingua, E., Macdonald, E., Marzano, R., Rhoades, C.C., Royo, A., Thorn, S., Wagenbrenner, J.W., Waldron, K., Wohlgemuth, T., and Gustafsson, L. 2018*b*. Systematic map database for Salvage logging effects on regulating and supporting ecosystem services. A systematic map. doi:10.21950/AAD6R3, e-cienciaDatos, V2.

Lewis, K., and Thompson, D. 2011. Degradation of wood in standing lodgepole pine killed by mountain pine beetle. Wood Fiber Sci. **43**(2): 130–142.

Lindenmayer, D.B., and Noss, R.F. 2006. Salvage logging, ecosystem processes, and biodiversity conservation. Conserv. Biol. **20**(4): 949–958. doi:10.1111/j.1523-1739.2006.00497.x. PMID:16922212.

Lindenmayer, D.B., and Possingham, H.P. 1996. Ranking conservation and timber management options for Leadbeater's possum in Southeastern Australia using population viability analysis. Conserv. Biol. **10**(1): 235–251. doi:10.1046/j.1523-1739.1996.10010235.x.

Lindenmayer, D.B., Foster, D.R., Franklin, J.F., Hunter, M.L., Noss, R.F., Schmiegelow, F.A., and Perry, D. 2004. Salvage harvesting policies after natural disturbance. Science, **303**: 1303. doi:10.1126/science.1093438. PMID:14988539.

Lindenmayer, D.B., Burton, P.J., and Franklin, J.F. 2008. Salvage logging and its ecological consequences. Island Press, Washington, D.C.

Lindenmayer, D.B., Franklin, J.F., Lõhmus, A., Baker, S.C., Bauhus, J., Beese, W., Brodie, A., Kiehl, B., Kouki, J., Pastur, G.M., Messier, C., Neyland, M., Palik, B., Sverdrup-Thygeson, A., Volney, J., Wayne, A., and Gustafsson, L. 2012. A major shift to the retention approach for forestry can help resolve some global forest sustainability issues. Conserv. Lett. **5**(6): 421–431. doi:10.1111/j.1755-263X.2012.00257.x.

Lindenmayer, D., Thorn, S., and Banks, S. 2017. Please do not disturb ecosystems further. Nat. Ecol. Evol. **1**: 0031. doi:10.1038/s41559-016-0031.

Lindenmayer, D.B., McBurney, L., Blair, D., Wood, J., and Banks, S.C. 2018. From unburnt to salvage logged: quantifying bird responses to different levels of disturbance severity. J. Appl. Ecol. In press. doi:10.1111/1365-2664.13137.

Macdonald, S.E. 2007. Effects of partial post-fire salvage harvesting on vegetation communities in the boreal mixedwood forest region of northeastern Alberta, Canada. For. Ecol. Manage. **239**(1–3): 21–31. doi:10.1016/j.foreco.2006.11.006.

Man, R., Chen, H.Y.H., and Schafer, A. 2013. Salvage logging and forest renewal affect early aspen stand structure after catastrophic wind. For. Ecol. Manage. **308**: 1–8. doi:10.1016/j.foreco.2013.07.039.

Mansuy, N., Thiffault, E., Lemieux, S., Manka, F., Paré, D., and Lebel, L. 2015. Sustainable biomass supply chains from salvage logging of fire-killed stands: a case study for wood pellet production in eastern Canada. Appl. Energy, **154**: 62–73. doi:10.1016/j.apenergy.2015.04.048.

Marañón-Jiménez, S., and Castro, J. 2013. Effect of decomposing post-fire coarse woody debris on soil fertility and nutrient availability in a Mediterranean ecosystem. Biogeochemistry, **112**(1–3): 519–535. doi:10.1007/s10533-012-9744-x.

Martínez-Sánchez, J.J., Ferrandis, P., de las Heras, J., and Herranz, J.M. 1999. Effect of burnt wood removal on the natural regeneration of *Pinus halepensis* after fire in a pine forest in Tus valley (SE Spain). For. Ecol. Manage. **123**: 1–10. doi:10.1016/S0378-1127(99)00012-2.

Martín-López, B., Gómez-Baggethun, E., García-Llorente, M., and Montes, C. 2014. Trade-offs across value-domains in ecosystem services assessment. Ecol. Indic. **37**: 220–228. doi:10.1016/j.ecolind.2013.03.003.

Marzano, R., Garbarino, M., Marcolin, E., Pividori, M., and Lingua, E. 2013. Deadwood anisotropic facilitation on seedling establishment after a stand-replacing wildfire in Aosta Valley (NW Italy). Ecol. Eng. **51**: 117–122. doi:10.1016/j.ecoleng.2012.12.030.

McGinnis, T.W., Keeley, J.E., Stephens, S.L., and Roller, G.B. 2010. Fuel buildup and potential fire behavior after stand-replacing fires, logging fire-killed trees and herbicide shrub removal in Sierra Nevada forests. For. Ecol. Manage. **260**(1): 22–35. doi:10.1016/j.foreco.2010.03.026.

McIver, J.D., and McNeil, R. 2006. Soil disturbance and hill-slope sediment transport after logging of a severely burned site in Northeastern Oregon. West. J. Appl. For. **21**: 123–133.

McIver, J.D., and Ottmar, R. 2007. Fuel mass and stand structure after post-fire logging of a severely burned ponderosa pine forest in northeastern Oregon. For. Ecol. Manage. **238**(1–3): 268–279. doi:10.1016/j.foreco.2006.10.021.

McIver, J.D., and Starr, L. 2000. Environmental effects of postfire logging: Literature review and annotated bibliography. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon, Gen. Tech. Rep. PNW-GTR-486. doi:10.2737/PNW-GTR-486.

Millennium Ecosystem Assessment. 2003. MA conceptual framework. *In* Ecosystems and human well-being: a framework for assessment. Island Press, Washington, D.C. pp. 25–36.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., and The PRISMA Group. 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. **6**(7): e1000097. doi:10.1371/journal.pmed.1000097. PMID:19621072.

Molinas-González, C., Castro, J., and Leverkus, A.B. 2017*a*. Deadwood decay in a burnt Mediterranean pine reforestation. Forests, **8**: 158. doi:10.3390/f8050158.

Molinas-González, C.R., Leverkus, A.B., Marañón-Jiménez, S., and Castro, J.

2017*b*. Fall rate of burnt pines across an elevational gradient in a Mediterranean mountain. Eur. J. For. Res. **136**(3): 401–409. doi:10.1007/s10342-017-1040-9.

Müller, J., Noss, R., Thorn, S., Bässler, C., Leverkus, A.B., and Lindenmayer, D. 2018. Increasing disturbance demands new policies to conserve intact forest. Conserv. Lett. doi:10.1111/conl.12449.

Ne'eman, G., Perevolotsky, A., and Schiller, G. 1997. The management implications of the Mt. Carmel research project. Int. J. Wildland Fire, **7**(4): 343–350. doi:10.1071/WF9970343.

Noss, R.F., and Lindenmayer, D.B. 2006. The ecological effects of salvage logging after natural disturbance. Conserv. Biol. **20**(4): 946–948. doi:10.1111/j.1523-1739.2006.00498.x.

Noss, R.F., Franklin, J.F., Baker, W.L., Schoennagel, T., and Moyle, P.B. 2006. Managing fire-prone forests in the western United States. Front. Ecol. Environ. **4**: 481–487. doi:10.1890/1540-9295(2006)4[481:MFFITW]2.0.CO;2.

Pausas, J.G., and Fernández-Muñoz, S. 2012. Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. Clim. Change, **110**(1–2): 215–226. doi:10.1007/s10584-011-0060-6.

Peterson, D.W., and Dodson, E.K. 2016. Post-fire logging produces minimal persistent impacts on understory vegetation in northeastern Oregon, USA. For. Ecol. Manage. **370**: 56–64. doi:10.1016/j.foreco.2016.04.004.

Peterson, D.W., Dodson, E.K., and Harrod, R.J. 2015. Post-fire logging reduces surface woody fuels up to four decades following wildfire. For. Ecol. Manage. **338**: 84–91. doi:10.1016/j.foreco.2014.11.016.

Powers, E.M., Marshall, J.D., Zhang, J., and Wei, L. 2013. Post-fire management regimes affect carbon sequestration and storage in a Sierra Nevada mixed conifer forest. For. Ecol. Manage. **291**: 268–277. doi:10.1016/j.foreco.2012.07.038.

Prestemon, J.P., and Holmes, T.P. 2010. Economic impacts of hurricanes on forest owners. *In* Advances in threat assessment and their application to forest and rangeland management. *Edited by* J.M. Pye, M.H. Rauscher, Y. Sands, D.C. Lee, and J.S. Beatty. USDA Forest Service, Pacific Northwest and Southern Research Stations, Portland, Oregon, Gen. Tech. Rep. PNW-GTR-802. pp. 207–221.

Priewasser, K., Brang, P., Bachofen, H., Bugmann, H., and Wohlgemuth, T. 2013. Impacts of salvage-logging on the status of deadwood after windthrow in Swiss forests. Eur. J. For. Res. **132**(2): 231–240. doi:10.1007/s10342-012-0670-1.

Puerta-Piñero, C., Sánchez-Miranda, A., Leverkus, A., and Castro, J. 2010. Management of burnt wood after fire affects post-dispersal acorn predation. For. Ecol. Manage. **260**(3): 345–352. doi:10.1016/j.foreco.2010.04.023.

Pullin, A.S., and Stewart, G.B. 2006. Guidelines for systematic review in conservation and environmental management. Conserv. Biol. **20**(6): 1647–1656. doi:10.1111/j.1523-1739.2006.00485.x. PMID:17181800.

Pullin, A.S., Knight, T.M., Stone, D.A., and Charman, K. 2004. Do conservation managers use scientific evidence to support their decision-making? Biol. Conserv. **119**(2): 245–252. doi:10.1016/j.biocon.2003.11.007.

R Core Team. 2016. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: http://www.R-project.org/.

Rhoades, C.C., Pelz, K.A., Fornwalt, P.J., Wolk, B.H., and Cheng, A.S. 2018. Overlapping bark beetle outbreaks, salvage logging and wildfire restructure a lodgepole pine ecosystem. Forests, **9**(3): 101. doi:10.3390/f9030101.

Ritchie, M.W., Knapp, E.E., and Skinner, C.N. 2013. Snag longevity and surface fuel accumulation following post-fire logging in a ponderosa pine dominated forest. For. Ecol. Manage. **287**: 113–122. doi:10.1016/j.foreco.2012.09.001.

Roy, D.F. 1956. Salvage logging may destroy Douglas-fir reproduction. USDA Forest Service, California Forest and Range Experiment Station, Berkeley, Calif., Res. Note 107.

Royo, A.A., Peterson, C.J., Stanovick, J.S., and Carson, W.P. 2016. Evaluating the ecological impacts of salvage logging: can natural and anthropogenic disturbances promote coexistence? Ecology, **97**(6): 1566–1582. doi:10.1890/15-1093.1. PMID:27459786.

Schelhaas, M.J., Nabuurs, G.J., and Schuck, A. 2003. Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Biol. **9**: 1620–1633. doi:10.1046/j.1365-2486.2003.00684.x.

Schiermeier, Q. 2016. Polish scientists protest over plan to log in Białowieża Forest. Nature, **530**: 393. doi:10.1038/530394a. PMID:26911758.

Schönenberger, W., Noack, A., and Thee, P. 2005. Effect of timber removal from windthrow slopes on the risk of snow avalanches and rockfall. For. Ecol. Manage. **213**(1–3): 197–208. doi:10.1016/j.foreco.2005.03.062.

Schroeder, L.M., and Lindelöw, A. 2002. Attacks on living spruce trees by the bark beetle *Ips typographus* (Col. Scolytidae) following a storm-felling: a comparison between stands with and without removal of wind-felled trees. Agric. For. Entomol. **4**: 47–56. doi:10.1046/j.1461-9563.2002.00122.x.

Secretariat of the Convention on Biological Diversity. 2000. Sustaining life on Earth: how the Convention on Biological Diversity promotes nature and human well-being. Secretariat of the Convention on Biological Diversity, Montreal, Quebec, Canada.

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T.A., and Reyer, C.P.O. 2017. Forest disturbances under climate change. Nat. Clim. Change, **7**(6): 395–402. doi:10.1038/nclimate3303.

Serrano-Ortiz, P., Marañón-Jiménez, S., Reverter, B.R., Sánchez-Cañete, E.P., Castro, J., Zamora, R., and Kowalski, A.S. 2011. Post-fire salvage logging reduces carbon sequestration in Mediterranean coniferous forest. For. Ecol. Manage. **262**(12): 2287–2296. doi:10.1016/j.foreco.2011.08.023.

Slesak, R.A., Schoenholtz, S.H., and Evans, D. 2015. Hillslope erosion two and three years after wildfire, skyline salvage logging, and site preparation in southern Oregon, USA. For. Ecol. Manage. **342**: 1–7. doi:10.1016/j.foreco.2015.01.007.

Smith-Ramírez, C., Maturana, V., Gaxiola, A., and Carmona, M. 2014. Salvage logging by indigenous people in a Chilean conifer forest. For. Sci. **60**(6): 1100–1106. doi:10.5849/forsci.12-079.

Sullivan, T.P., Sullivan, D.S., Lindgren, P.M.F., and Ransome, D.B. 2010. Green-tree retention and life after the beetle: stand structure and small mammals 30 years after salvage harvesting. Silva Fenn. **44**(5): 749–774.

Sun, Y., Gu, L., Dickinson, R.E., and Zhou, B. 2012. Forest greenness after the massive 2008 Chinese ice storm: integrated effects of natural processes and human intervention. Environ. Res. Lett. **7**(3): 035702. doi:10.1088/1748-9326/7/3/035702.

Sutherland, W.J., Pullin, A.S., Dolman, P.M., and Knight, T.M. 2004. The need for evidence-based conservation. Trends Ecol. Evol. **19**(6): 305–308. doi:10.1016/j.tree.2004.03.018. PMID:16701275.

Thorn, S., Bässler, C., Bernhardt-Römermann, M., Cadotte, M., Heibl, C., Schäfer, H., Seibold, S., and Müller, J. 2015*a*. Changes in the dominant assembly mechanism drives species loss caused by declining resources. Ecol. Lett. **19**(2): 109–215. doi:10.1111/ele.12548.

Thorn, S., Hacker, H.H., Seibold, S., Jehl, H., Bässler, C., and Müller, J. 2015*b*. Guild-specific responses of forest Lepidoptera highlight conservation-oriented forest management — implications from conifer-dominated forests. For. Ecol. Manage. **337**: 41–47. doi:10.1016/j.foreco.2014.10.031.

Thorn, S., Bässler, C., Svoboda, M., and Müller, J. 2017. Effects of natural disturbances and salvage logging on biodiversity — lessons from the Bohemian Forest. For. Ecol. Manage. **388**: 113–119. doi:10.1016/j.foreco.2016.06.006.

Thorn, S., Bässler, C., Brandl, R., Burton, P.J., Cahall, R., Campbell, J.L., Castro, J., Choi, C.-Y., Cobb, T., Donato, D.C., Durska, E., Fontaine, J.B., Gauthier, S., Hebert, C., Hothorn, T., Hutto, R.L., Lee, E.-J., Leverkus, A.B., Lindenmayer, D.B., Obrist, M.K., Rost, J., Seibold, S., Seidl, R., Thom, D., Waldron, K., Wermelinger, B., Winter, M.-B., Zmihorski, M., and Müller, J. 2018. Impacts of salvage logging on biodiversity: a meta-analysis. J. Appl. Ecol. **55**: 279–289. doi:10.1111/1365-2664.12945. PMID:29276308.

Titus, J.H., and Householder, E. 2007. Salvage logging and replanting reduce understory cover and richness compared to unsalvaged–unplanted sites at Mount St. Helens, Washington. West. North Am. Nat. **67**(2): 219–231. doi:10.3398/1527-0904(2007)67[219:SLARRU]2.0.CO;2.

Turner, M.G. 2010. Disturbance and landscape dynamics in a changing world. Ecology, **91**(10): 2833–2849. doi:10.1890/10-0097.1. PMID:21058545.

Van Nieuwstadt, M.G.L., Sheil, D., and Kartawinata, K. 2001. The ecological consequences of logging in the burned forests of East Kalimantan, Indonesia. Conserv. Biol. **15**(4): 1183–1186. doi:10.1046/j.1523-1739.2001.0150041183.x.

Wagenbrenner, J.W., MacDonald, L.H., Coats, R.N., Robichaud, P.R., and Brown, R.E. 2015. Effects of post-fire salvage logging and a skid trail treatment on ground cover, soils, and sediment production in the interior western United States. For. Ecol. Manage. **335**: 176–193. doi:10.1016/j.foreco.2014.09.016.

Wagenbrenner, J.W., Robichaud, P.R., and Brown, R.E. 2016. Rill erosion in burned and salvage logged western montane forests: Effects of logging equipment type, traffic level, and slash treatment. J. Hydrol. **541**: 889–901. doi:10.1016/j.jhydrol.2016.07.049.

Waldron, K., Ruel, J.C., and Gauthier, S. 2013. Forest structural attributes after windthrow and consequences of salvage logging. For. Ecol. Manage. **289**: 28–37. doi:10.1016/j.foreco.2012.10.006.

Waldron, K., Ruel, J.C., Gauthier, S., De Grandpré, L., and Peterson, C.J. 2014. Effects of post-windthrow salvage logging on microsites, plant composition and regeneration. Appl. Veg. Sci. **17**(2): 323–337. doi:10.1111/avsc.12061.

Wohlgemuth, T., Kull, P., and Wüthrich, H. 2002. Disturbance of microsites and early tree regeneration after windthrow in Swiss mountain forests due to the winter storm Vivian 1990. For. Snow Landsc. Res. **77**(1): 17–47.

Wohlgemuth, T., Schwitter, R., Bebi, P., Sutter, F., and Brang, P. 2017. Post-windthrow management in protection forests of the Swiss Alps. Eur. J. For. Res. **136**: 1029–1040. doi:10.1007/s10342-017-1031-x.

Appendix A. Systematic map database and data coding strategy

Databases for systematic maps are usually encouraged at the level of individual study sites (James et al. 2016). However, due to the characteristics of the retrieved studies, we decided that the most coherent presentation of the data would be at the publication level. This was, on the one hand, because some publications included two to several disturbance events and (or) study sites across a region. Also, some study sites resulted in multiple publications that used different subsets of the overall experimental design. In these cases, some variables such as forest type or replication varied even within one study site (e.g., Castro et al. 2012;

Leverkus et al. 2014), and our database (Supplementary Table S3) thus provides detailed information for each publication. Despite the publication-level structure of the database, we included one column with the name of the study site(s) of each publication to allow relating publications from the same study and obtaining study-level summary information.

We aimed to populate the database with information items from each publication (see below), either directly from the publication or from different publications related to the same study or directly from the authors; however, not all of this information was always available and exceptions were noted in the database with "NA". For each publication, the database includes:

1. Bibliographic information. Columns: Authors, Year, Title, Publication, Volume and pages, DOI.
2. Source of the publication. This was one of the following: (*a*) primary search (in Web of Science or Scopus); (*b*) secondary search (in specialized search engines and websites); (*c*) supplementary search (in reference lists of review articles and other publications). Column: Source.
3. Location of the study. Columns: Country, Region/State, X, Y.
4. Name of the study site. This variable aims to relate different publications in the database to each other due to them addressing the same study. Columns: Site, Site_ref (the latter relates to Fig. 4).
5. We also recorded whether a study addressed one or multiple study sites or sites across a geographic region. Column: Regional or multi-site (y = yes; n = no).
6. Type of disturbance: wildfire, insect outbreak, or windstorm. Column: Disturbance type.
7. Disturbance severity. This was obtained in a coarse way through indications of percent tree mortality or percent basal area dead or through qualitative indications. Where a severity range was provided, we recorded the median of that range. Some studies only provided a qualitative estimation of severity. On the basis of our experience in the relationship between qualitative and quantitative estimates in the retrieved publications and with the aim of describing the retrieved literature in homogeneous terms, we attributed the following severity percentages to them: Low, 30%; Low to moderate, 45%; Moderate, 60%; Moderate to high or Mixed or Variable, 75%; High, 90%; and Severe, 100%. Where one publication explicitly addressed sampling areas of different severities, we included all values in separate columns. Note that disturbance severity can be spatially quite variable and that we only provide one median value per publication or per severity class within each publication. Columns: Disturbance Severity (mean percentage, provided for all publications), Disturbance Severity "b" (for publications that explicitly addressed a second level of severity), and Disturbance Severity "c" (for publications that explicitly addressed a third level of severity). NA values in the latter columns indicate that the publication did not explicitly address a second or third disturbance severity level.
8. Time between disturbance and logging. We obtained the time (in years) elapsed between the disturbance and logging. As for disturbance severity, we recorded median values in the cases for which a range of values was provided. This was because some studies included a range of time periods, for example, due to disturbance not happening in one discrete moment but over a period of time (particularly insect outbreaks), salvage logging occurring over some period of time, or lack of exact knowledge on when salvage logging took place. Column: Time disturbance–logging.
9. Logging intensity. Similar to the data on disturbance severity, we obtained an approximation of logging intensity through quantitative or qualitative indications available in the publications. The quantitative indications referred to the percent basal area or percent trees that were removed. For descriptive purposes, we transformed qualitative indicators to percentages as follows: intensity category Moderate to low, 50%; Moderate or Variable, 75%; High, 90%; and Clearcut, 100%. When one publication explicitly addressed sampling areas of different logging intensity, we included all values in different columns. Columns: Logging intensity (mean percentage, provided for all publications), Logging intensity "b" (for publications that explicitly addressed a second level of intensity), Logging intensity "c" (for publications that explicitly addressed a third level of intensity), and Logging intensity "d" (for publications that explicitly addressed a fourth level of intensity). NA values in the latter columns indicate that the publication did not explicitly address a second, third, or fourth logging intensity level.
10. Logging method. We recorded any indication of machinery or methods employed in the felling and extraction of the wood. More than one method was employed in some studies, in which case we recorded all of the methods that were mentioned. We categorized these logging methods into manual cut or use of chainsaws; harvesting with feller–bunchers, harvesters, or similar machinery; ground-based yarding with skidders, tractors, log forwarders, cable, or winch; and helicopter yarding. In the database, we provide one column containing all of the methods mentioned in one publication (column Logging method) and six columns with entries on the use of each individual method (columns Tractor/Skidder/Forwarder; Feller–buncher; Winch/cable yarding; Helicopter; Manual cut/chainsaws; and Slash treatment).
11. Forest type. According to study descriptions, for each publication, we recorded whether it included broadleaf, conifer, and (or) mixed stands or a combination of these with no differentiation. The database contains four columns with binomial entries (1/0) for each of Broadleaf, Conifer, Mixed, and Scrambled (i.e., combination of stand types without differentiation). Individual studies may have values of 1 for one or more stand types.
12. Forest age before disturbance. We obtained information on the age of stands, which was generally provided as a number of years since previous stand-replacing disturbance. For consistency of information among studies, we classified this information into three broad categories: (*a*) young forest (<50 years old); (*b*) mature forest (50–99 years); and (*c*) old forest (≥100 years). Columns: Young, Mature, and Old.
13. Dominant canopy species. We recorded the name of the species dominating the studied stands. If there was more than one, we recorded up to five dominant species, and above this amount, we specified that it was a mixed stand. When one study included multiple stands of different composition, we recorded the names of all species dominating at least some of the stands. The names of all dominant species in any individual study are provided in the column "Main tree species". The presence of each individual species is provided with binomial entries in the columns "*Abies alba*" through "*Tsuga mertensiana*".
14. Randomization. We recorded whether there was randomization in the allocation of treatments to spatial units. Column: Randomization.
15. Type of design: Control–Intervention (CI), Before–After Control–Intervention (BACI), or a mixture of both approaches. BA designs without controls were excluded, as indicated in Study Inclusion Criteria. Column: Design (the entry CI/BACI indicates that each approach was used for a subset of the measurements).
16. Replication of population (disturbed forest). We recorded the number of disturbance events that defined the study population (i.e., excluding disturbances occurring after logging). In the case of wildfire, this was relatively easy to define. For insect outbreaks, we considered that one event affected a

whole region. As wind does not produce continuous disturbance surfaces as fire does, we also recorded the number of blowdown patches considered in windthrow studies. Column: N disturbed sites.

17. Replication of intervention. We assessed the number of spatially independent stands or patches that were salvage logged. This task was often difficult due to the great variability in the scale of studies, sampling strategies, and plot layouts. In designed experimental studies, the replication was easy to obtain, but in other studies, we provided a minimum number of replicates based on study site descriptions, maps, or contact with authors. Column: Replication SL.
18. Number of measurements. We recorded the number of times that field measurements were taken. Column: N measurements.
19. Response variables measured. We recorded whether each publication sampled each of the following: (*a*) stand structure and deadwood amount and characteristics, (*b*) tree regeneration, (*c*) ground cover (cover of plants, bare soil, rocks, etc.), (*d*) soil physical properties, (*e*) soil chemical properties, (*f*) biological indicators of nutrient cycling, (*g*) vegetation, (*h*) soil erosion (by wind or water), (*i*) abundance of exotic or invasive species (Exotics/invasives), (*j*) temperature (air, soil, water), (*k*) resilience to subsequent disturbance (e.g., tree regeneration after another, subsequent disturbance), (*l*) ecosystem C pools (excluding those in (*a*)), (*m*) riparian ecosystem functioning, (*n*) seed dispersal, and (*o*) drinking water quality.

References

Castro, J., Puerta-Piñero, C., Leverkus, A.B., Moreno-Rueda, G., and Sánchez-Miranda, A. 2012. Post-fire salvage logging alters a key plant–animal interaction for forest regeneration. Ecosphere, **3**(10): art90. doi:10.1890/ES12-00089.1.

James, K.L., Randall, N.P., and Haddaway, N.R. 2016. A methodology for systematic mapping in environmental sciences. Environ. Evidence, **5**: 7. doi:10.1186/s13750-016-0059-6.

Leverkus, A.B., Lorite, J., Navarro, F.B., Sánchez-Cañete, E.P., and Castro, J. 2014. Post-fire salvage logging alters species composition and reduces cover, richness, and diversity in Mediterranean plant communities. J. Environ. Manage. **133**: 323–331. doi:10.1016/j.jenvman.2013.12.014. PMID:24412981.

Appendix B. Literature searches and screening — results

The initial search in Web of Science provided 3979 results, with an additional 292 publications after the update in 2017 (Fig. 2). The search in Scopus provided an additional 70 non-duplicated publications, for a total of 4341. Of these, roughly 10% ($N = 401$) were randomly selected to assess homogeneity in the application of criteria among reviewers. This initial exercise, performed by ABL and LG, provided a kappa test value of $\kappa = 0.47$, indicating only "moderate" agreement among reviewers and thus heterogeneity in the application of inclusion criteria (Landis and Koch 1977). After revising the application of inclusion criteria and performing the test again, the new κ value was 0.69, which is considered "substantial" agreement (Landis and Koch 1977). The subsequent title selection resulted in 3649 titles being removed. Of these, 323 included the word "salvage" in the title, keywords, or abstract; their titles were again screened and 47 were brought back to the abstract selection phase. This resulted in 3602 titles being discarded and 739 being kept. The secondary search provided an additional 58 non-duplicated articles with a relevant title, yielding 797 abstracts to be reviewed.

Before abstract selection, homogeneity of application of inclusion criteria was again assessed. In total, 63 articles were randomly selected for independent evaluation by three members of the review team. The values that were obtained were $\kappa = 0.68$ (ABL & LG), $\kappa = 0.43$ (LG & JC), and $\kappa = 0.43$ (JC & ABL). After discussing the criteria again and reassessing abstract inclusion, the obtained κ values were 0.71, 0.62, and 0.72, respectively, so the process continued. Of the 797 abstracts, 466 were considered irrelevant and 247 were kept. An additional 27 studies with relevant titles and abstracts were obtained from the reference lists of selected articles and reviews on the topic. This resulted in a total of 274 full-length articles being assessed (Fig. 2).

Table B1. Reasons for exclusion from the systematic map at full-text screening.

Reason for exclusion[a]	Criterion type	No. of articles
No true replication	Validity	47
No appropriate response variable	Inclusion	38
Redundant data	Validity	18
No appropriate comparator	Inclusion	14
Not empirical study	Inclusion	13
Study design not appropriate	Validity	13
No appropriate population	Inclusion	11
Intervention confounded with other interventions	Inclusion	10
Paper not available		9
No appropriate intervention	Inclusion	6
BA (before–after) design	Inclusion	3
Methods not well described	Validity	1
Language	Inclusion	1
Total		184

[a] In cases where one study had more than one reason for exclusion, only the first unmet study inclusion/validity criterion (in the order described in the methods) was recorded.

Of the full-text articles assessed, 90 were kept and 184 were excluded for the reasons outlined in Table B1 (for references of excluded publications and reasons for exclusion, see Supplementary Table S2[1]). The most frequent cause for exclusion was the lack of true replication, which led to the exclusion of 47 articles. Second in frequency, 38 articles did not measure a response variable that was appropriate for this systematic map. These studies mostly focused on the response of individual organisms or biotic communities, and they were excluded only at the last stage of article screening (i.e., there was no limitation on the outcome in the search string and the articles were allowed to pass the title and abstract selection despite obvious focus on biodiversity components). We chose not to broaden the scope of this systematic map to include biodiversity as a response variable because this was the target of another global review (Thorn et al. 2018). Next, 18 of the retrieved studies included a response variable of interest, but the same data were also found in another publication by the same authors. This mostly included data related to study site descriptions (e.g., percent ground cover of vegetation and other cover categories) rather than dual publication of research outcomes. The five following reasons for exclusion relate to the lack of an appropriate design for inclusion (Table B1). We were not able to obtain nine full-text documents. One article was excluded because the methods were not described well enough to assess the inclusion criteria, and one was excluded because we lacked fluency in the publication's language (Slovenian) despite it having an abstract translation in English.

References

Landis, J.R., and Koch, G.G. 1977. The measurement of observer agreement for categorical data. Biometrics, **33**(1): 159–174. doi:10.2307/2529310. PMID: 843571.

Thorn, S., Bässler, C., Brandl, R., Burton, P.J., Cahall, R., Campbell, J.L., Castro, J., Choi, C.-Y., Cobb, T., Donato, D.C., Durska, E., Fontaine, J.B., Gauthier, S., Hebert, C., Hothorn, T., Hutto, R.L., Lee, E.-J., Leverkus, A.B., Lindenmayer, D.B., Obrist, M.K., Rost, J., Seibold, S., Seidl, R., Thom, D., Waldron, K., Wermelinger, B., Winter, M.-B., Zmihorski, M., and Müller, J. 2018. Impacts of salvage logging on biodiversity: a meta-analysis. J. Appl. Ecol. **55**: 279–289. doi:10.1111/1365-2664.12945. PMID:29276308.

Appendix C. Stand characteristics

Results

Of the 49 studies included in the systematic map, 11 were established in broadleaf forests or included broadleaf stands, 33 were established in or included conifer stands, 10 included mixed stands, and 3 included combinations of stand types without differentiation ("scrambled"). Regarding pre-disturbance forest age, 5 studies included young stands, 28 included mature stands, 12 included old stands, and 10 studies did not provide sufficient information to assess this variable. Note that these figures add to more than 49 (the number of studies included in the systematic map) because some studies included more than one stand type and (or) forest age. Table C1 shows the number of studies that included each stand type by stand age combination.

We recorded 37 tree species as dominating (or co-dominating) the canopy of individual stands in the included studies (Table C2). At the publication level, quaking aspen (*Populus tremuloides*) was the most frequent dominant species among broadleaved tree species and lodgepole pine (*Pinus contorta*) was the most frequent among conifers (Table C2). Wind was the disturbance type in which the largest number of dominant broadleaf species was included among the identified studies ($n = 10$ vs. $n = 4$ for wildfire or insect outbreak; Table C2). In contrast, wildfire studies contained the largest number of dominant conifer species ($n = 15$ vs. $n = 11$ for insect outbreaks and $n = 10$ for wind; Table C2).

Table C1. Number of studies containing stands of each stand type and age combination.

	Stand type (number of studies)			
Stand age	Broadleaf	Conifer	Mixed	Scrambled
Young	1	4	0	0
Mature	6	19	9	2
Old	2	8	2	0
N/A[a]	2	7	1	1

[a] N/A = information not available.

Table C2. Distribution of publications relative to disturbance type and the occurrence of dominant tree species.

	No. of publications by disturbance type			
Dominant tree species	Wildfire	Insect outbreak	Windthrow	Total
Broadleaves				
Acer rubrum	0	0	1	1
Acer saccharum	0	0	1	1
Betula papyrifera	0	1	1	2
Carya spp.	0	0	2	2
Eucalyptus globulus	2	0	0	2
Fagus grandifolia	0	0	1	1
Fagus sylvatica	0	1	4	5
Populus balsamifera	5	1	0	6
Populus spp.	0	0	1	1
Populus tremuloides	12	1	4	17
Prunus serotina	0	0	1	1
Quercus ilex	1	0	0	1
Quercus spp.	0	0	2	2
No. of species[a]	4	4	10	13
Conifers				
Abies alba	0	1	3	4
Abies balsamea	0	1	2	3
Abies grandis	1	0	0	1
Abies lasiocarpa	4	0	2	6
Larix occidentalis	1	0	0	1
Picea abies	0	3	4	7
Picea engelmannii	4	0	2	6
Picea glauca	7	1	0	8
Picea mariana	6	1	2	9
Picea spp.	0	1	0	1
Picea × *lutzii*	0	1	0	1
Pinus banksiana	5	0	4	8
Pinus contorta	7	6	3	16
Pinus densiflora	1	0	0	1
Pinus elliottii	0	0	1	1
Pinus halepensis	2	0	0	2
Pinus nigra	6	0	0	6
Pinus pinaster	11	0	0	11
Pinus ponderosa	12	2	0	14
Pinus spp.	0	1	0	1
Pinus sylvestris	4	0	0	4
Pinus taeda	0	0	2	2
Pseudotsuga menziesii	6	0	0	6
Tsuga mertensiana	0	1	0	1
No. of species[a]	15	11	10	24
Mixed broadleaves[b]	0	0	2	2
Mixed conifers[b]	1	0	1	2
Mixed conifers and broadleaves[b]	0	0	1	1

[a] Number of species with non-zero values.
[b] Included more than five dominant species in individual stands.

Discussion

Conifer stands were the most frequent forest type addressed by the studies on salvage logging. This can partially be explained by the abundance of studies in boreal or sub-boreal areas of North America and the fact that severe insect outbreaks often occur in forests with low species diversity such as the even-aged, lodgepole pine dominated forests of the Rocky Mountains. Wildfire is also a major driver of the dynamics of conifer forests (Mutch 1970; Kuuluvainen and Aakala 2011). Broadleaf species are also generally deciduous in temperate and boreal ecosystems, which makes them less susceptible to major wind disturbances occurring in winter (Mayer et al. 2005) and more likely to regenerate after defoliation by insects.

Among the conifers, pines (*Pinus*), with 66 cases, were by far the most frequent genus that dominated the study areas, followed by spruce (*Picea*, 32 cases), fir (*Abies*, 14 cases), and Douglas-fir (*Pseudotsuga*, 6 cases). The diversity of pine species and the genus' adaptation to broad climatic conditions such as drought-resistant species such as *P. halepensis* in the Mediterranean and cold-resistant ones such as *P. banksiana* in boreal North America explain its abundance. The most common dominant broadleaf genera were *Populus* (24 cases) and *Fagus* (6 cases). In combination, these genera span large portions of Europe and North America; this highlights the potential applicability of results from studies included in this systematic map to post-disturbance management in many places throughout these two regions. The distribution of forest age can also be considered representative of typical forest conditions in these regions. Most forests in developed nations are under some form of management and should thus not be expected to be in the "old" category, as documented by the systematic map. However, lack of understanding regarding the effects of disturbance and subsequent salvage logging on young forests represents a significant knowledge gap, as this forest age is relatively abundant. Although young and typically small-diameter trees are less susceptible to windthrow and insect attack, they are susceptible to wildfire and post-fire salvage logging despite their comparatively low wood volume (Leverkus et al. 2018).

References

Kuuluvainen, T., and Aakala, T. 2011. Natural forest dynamics in boreal Fennoscandia: a review and classification. Silva Fenn. **45**(5): 823–841. doi:10.14214/sf.73.

Leverkus, A.B., Lindenmayer, D.B., Thorn, S., and Gustafsson, L. 2018. Salvage logging in the world's forests: interactions between natural disturbance and logging need recognition. Global Ecology and Biogeography. In press. doi:10.1111/geb.12772.

Mayer, P., Brang, P., Dobbertin, M., Hallenbarter, D., Renaud, J.-P., Walthert, L., and Zimmermann, S. 2005. Forest storm damage is more frequent on acidic soils. Ann. For. Sci. **62**: 303–311. doi:10.1051/forest:2005025.

Mutch, R.W. 1970. Wildland fires and ecosystems–a hypothesis. Ecology, **51**(6): 1046–1051. doi:10.2307/1933631.s.