Leverkus, A.B. et al., 2018. Salvage logging effects on regulating and supporting ecosystem services — a systematic map. Canadian Journal of Forest Research, 48(9), pp.983–1000.

Available at http://dx.doi.org/10.21829/myb.2017.2311118

(Article begins on next page)

Canadian Journal of Forest Research
Revue canadienne de recherche forestière

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Journal:	*Canadian Journal of Forest Research*
Manuscript ID	cjfr-2018-0114.R1
Manuscript Type:	Review
Date Submitted by the Author:	n/a
Complete List of Authors:	Leverkus, Alexandro B; Universidad de Alcalá Rey Benayas, José María; Universidad de Alcalá Castro, Jorge; University of Granada Boucher, Dominique; Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du P.E.P.S., P.O. Box 10380, Stn. Sainte-Foy, Québec City, Québec, Canada, ; Brewer, Steve; Univ. of Mississippi, Dept. of Biology Collins, Brandon; University of California Berkeley, Donato, Daniel; Washington State Dept. of Nat. Res. Fraver, Shawn; University of Maine, School of Forest Resources Kishchuk, Barbara; Natural Resources Canada, Canadian Forest Service, Science Policy Integration Branch Lee, Eun-Jae; Urban Planning Research Group, Daejeon Sejong Research Institute Lindenmayer, David; Australian National University, Lingua, Emanuele; University of Padua Macdonald, Ellen; Department of Renewable Resources, University of Alberta Marzano, Raffaella; Department DISAFA, University of Torino Rhoades, Charles; US Forest Service Royo, Alejandro; USDA Forest Service, Thorn, Simon; Technische Universität München, Department of Ecology and Ecosystem Management Wagenbrenner, Joseph; USDA Forest Service, Pacific Southwest Research Station Waldron, Kaysandra; Centre for Forest Research, Université Laval, Sciences du bois et de la forêt Wohlgemuth, Thomas; RU Forest Dynamics, Swiss Federal Institute for Forest, Snow and Landscape Research WSL Gustafsson, Lena; Department of Ecology, Swedish University of Agricultural Sciences (SLU)
Keyword:	Salvage harvesting, sanitation logging, wildfire, insect outbreak, windthrow
Is the invited manuscript for consideration in a Special Issue? :	N/A

Salvage logging effects on regulating and supporting ecosystem services – A systematic map

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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.

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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. 2016), 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).

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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. 2004a).

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 unrecognised– 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 above-mentioned 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, post-bark beetle salvage logging lodgepole pine forests in Colorado commonly reduces canopy fuels and regenerates new stands without negatively effecting native plant diversity or soil productivity (Collins et al. 2011, 2012, Fornwalt et al. 2017, 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 categorised according to whether they affect:

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

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Eliminado: Removal of woody material is the primary objective of most salvage logging operations, whether for timber extraction or for fuel reduction (Müller et al. 2018).

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

Eliminado: The large amounts of dead or weakened wood created by disturbances constitute the habitat and resource base for numerous taxa.

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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 categorised 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 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. 2016), and this is likely also the case regarding the responses to salvage logging (Leverkus and Castro 2017).

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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. 2011b), 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.

Eliminado: <#>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). As a result, it can influence post-disturbance forest regeneration and stand development and affect all four kinds of ecosystem services.

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 synthesise 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 intervention? 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 (CEBC 2010) and several other texts (Sutherland et al. 2004b, 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. 2015a).

Research question

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?

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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. The final search string (Table S1) was established after the scoping exercise described in the protocol (Leverkus et al. 2015a). The search in WoS was initially made on 18 Aug 2015 and updated on 5 May 2017 to encompass all studies published until 31 Dec 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/ Water Resources, and in Scopus to Agricultural and Biological Sciences/ Environmental Science/ Earth and Planetary Sciences/ Multidisciplinary.

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 US Forest Service (http://www.treesearch.fs.fed.us/). We also searched in Google Scholar. For complete search terms, see Table S1.

As supplementary bibliographic searches, the reference lists of relevant articles (review articles and books) were screened for additional articles to complement the list of articles identified using the search terms. A list of the publications was sent to all the authors of this systematic map, most of who 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.

Eliminado: Authors of relevant articles were contacted to clarify study designs or provide additional data.

Study inclusion criteria

To be considered for the review, 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 where 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

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unsalvaged areas of Control-Intervention (CI) and Before-After-Control-Intervention (BACI) designs.

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

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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 the titles, two members of the review 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 the titles. After screening the titles, the word "salvage" was searched in the titles, keywords and abstracts of all 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). In cases where 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 of the studies were assessed as well as the study-site descriptions (including tables and figures). Relevant articles were categorised 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 both to the methodology and to 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.

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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 randomised 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 randomisation in the allocation of treatments to spatial units. This is 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. Studies with pseudo-replicated designs were placed in this category. 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 such studies 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 very 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

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designs, and the response variables that were measured. For a detailed description of the data included in the systematic map database, see Appendix A1.

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 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 A2. 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).

The following results are presented at the level 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 A1), and others at the level of stand types within study sites or within publications (for example, in cases where more than one stand was addressed in a

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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. 2015a, 2015b)]. 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 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

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America, there were nearly twice as many publications from the U.S.A 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 like wildfire in regions at the frontline of land-use change, such as 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

Eliminado: Disturbance and salvage logging descriptions

Bajado [4]: 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).

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likely generated more public and political demand for understanding the various implications of wildfire as compared to 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), has 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 largely depend 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 the *Systematic map database and coding strategy* section in Appendix A1). 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 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 half a 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 like wildfire. For example, post-fire logging may have 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 ± 1SD) 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 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

Eliminado: These averages were 1.1 ± 0.8 years for wildfire, 4.4 ± 3.7 years for insect outbreaks, and 1.7 ± 0.8 years for wind disturbance (Fig 5B).

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 categorised in excess of 90%. Salvage logging intensity ranged between 25 and 100%, and it averaged 80 ± 24% (including up to 4 values per publication). Average intensities were 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 A1). 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 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). This has long been acknowledged in

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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 like forming 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 in 10 studies. Ground-based yarding was mentioned in 20 studies, and by helicopter in two studies. Extraction of wood by helicopter is well known to reduce soil impacts compared to ground-based yarding. However, helicopter use is extremely costly; this, combined with the low economic value of disturbance-affected timber and depressed price that typically follow large disturbance events, are likely reasons for the scant mentions of helicopters.

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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 A3.

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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 sub-units 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 (Table S2). As a result, we do not discard the possibility that some of those excluded studies could provide valuable insights despite pseudo-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. 2015a).

In 11 of the 49 studies, the selection of stands for management intervention was at least under partial control by the researchers and thus included randomisation 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 minimise 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 where 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 randomisation, 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

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reports the conceptualisation of a randomised complete block design that, however, could not be turned to practice due to legal constraints and which resulted in a pseudo-replicated design comparing salvaged private forest *vs* 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), so that 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 and one post-insect) 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. 2016), 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). It should also be noted that 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, such as the US Forest Service, are required by law to

Bajado [5]: 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).

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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 primary productivity. Cover of pits and mounds, as well as cover of deadwood, may be used as indicators of the microclimatic and micro-topographic habitat availability and heterogeneity. Bare soil cover could be an indicator of available seedbed in measurements made right 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

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Eliminado: , many studies characterised long-term through decomposition (Marañón-Jiménez and Castro 2013, Molinas González et al. 2017). It can also ameliorate microclimatic conditions to enhance tree regeneration (Castro et al. 2011) and help reduce herbivory by large ungulates (Leverkus et al. 2015b). 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, the aim of deadwood characterisation 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 that was excluded from the map for design-related reasons 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 characterisation 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 also can 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. 2011a) 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 due to the existence of a recent review on the topic (Thorn et al. 2018), we did include vegetation as an indicator of the recovery of ecosystem structure, habitat, and soil retention.

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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

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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

Subido [2]: In summary, 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 the studies on ecosystem services (Boerema et al. 2016), 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).

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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 substantial 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.
- The effect of disturbance type on the ecological effects of salvage logging.

Acknowledgments

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.

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Tables

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

Continent	Country	N Publications	N Studies	N multi-site 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

Figure captions

Figure 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 colonisation 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); (2) = Castro et al. (2012); (3) = Leverkus et al. (2016); (4) = Leverkus and Castro (2017).

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

Figure 3. Cumulative number of publications per disturbance type included in this systematic map.

Figure 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, Table S3). Inset: Korean Peninsula.

Figure 5. Disturbance and salvage logging characteristics. A) Disturbance severity considered in the analysed 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 analysed publications. This includes 1-4 points per publication. Note that this applies to the Intervention 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/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 are: for fire 53, 51 and 69 (panels A, B and C, respectively); for insect outbreaks 15, 13 and 15; and for wind 31, 26 and 21 for wind.

Figure 6. The number of spatially independent salvage logging replicate units used in the 90 publications, classified by disturbance type.

Figure 7. Number of publications that reported different measured response variables, for each disturbance type. Nutrient= biological indicators of nutrient cycling; Carbon= non-wood carbon pool; Water= drinking water quality; Erosion= soil

erosion by wind or water; Invasives= Invasive and/or exotic species; Cover= ground cover, including cover of vegetation; Resilience= capacity to regenerate after subsequent wildfire (i.e. wildfire after salvage logging); Riparian= riparian ecosystem functioning; Dispersal= seed dispersal; Soil chem.= soil chemical properties; Soil phys.= soil physical properties; Deadwood= stand structure and deadwood amount and characteristics; Temp.= air, water or soil temperature; Regen.= tree regeneration; Vegetation= Vegetation composition. 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.

Supporting Information

Appendix A1. **Systematic map database and data coding strategy**

Appendix A2. **Literature searches and screening –Results**

Appendix A3. **Stand characteristics –Results and Discussion**

Table S1. **Search strings used in the systematic map.**

Table S2. **Publications excluded at full-text screening and reasons for exclusion.**

Table S3. **Systematic Map Database.** For details on coding and variable names, see Appendix A1.

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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 synthesise the results of individual studies. Systematic maps help managers identify the literature on a topic that is most relevant to their needs. They also identify knowledge clusters and knowledge gaps to suggest future systematic review lines and suggest topics for further empirical study.

Here, we aim to collate the studies 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 understanding of 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 intervention?

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Characteristics of included publications

Página 19: [3] Eliminado Alex 01/05/18 22:51

Distribution of studies

The publications included in the database were overwhelmingly concentrated in North America and Europe, with only two publications from another continent and no representation of the tropics or the Southern Hemisphere. Even within these two geographic clusters, the publications were not equally distributed. In North America, there were nearly twice as many publications from the U.S.A than from Canada, and even Canadian publications were more abundant than those of 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 like wildfire in regions at the frontline of land-use change, such as 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 carried out 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 density 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 nor spoken at a sufficient level of proficiency to facilitate publication in indexed journals.

The geographic distribution of the publications was strongly clustered in two continents (Fig 4): most came from North America, followed by Europe, and one from each of the Middle East and East Asia (Table 1).

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Most studies (36) were established within the perimeter of a single disturbance event, thereby establishing the disturbance as the constraint on the inference population. Two studies (one post-fire and one post-insect) included two disturbance events, four included four events, one included five, one included 14, and one included 20 (all these were 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. True replication of salvage logging within studies was generally below N = 10 (Fig 6). We present this information at the scale of publications because some publications of the same studies made use of different subsets of the larger design, leading to different replication across publications (e.g., Leverkus et al. 2014, 2016).

Página 30: [5] Eliminado **Alex** **02/05/18 13:44**

Tree regeneration was the most frequent response variable, and it was addressed by 51% of the publications (Fig 7). Second in frequency, 42% of the publications included estimations of ground cover (e.g. percent cover of vegetation, rocks, bare ground, pits and mounds, etc.). Third, 41% of the publications measured variables linked to the remaining deadwood, such as the number of snags or the amount of downed woody debris of different diameter, species, and/ or decay classes. Some of these studies focused on the habitat that the wood provides for living organisms, some on habitat structure, others on the C sink that it represents, and others on the quantity, quality and distribution of fuels in the face of subsequent wildfires. Fourth, 28% of publications analysed the recovering non-tree vegetation. Fifth, 26% included measurements of soil physical properties, such as moisture, compaction, shear strength, and penetrability. The remaining response variable categories were addressed by <15% of the publications, and the number of studies addressing them, separated by disturbance type, can be found in Fig 7. 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.

Discussion

Página 30: [6] Eliminado	Alex	02/05/18 13:24

Distribution of studies

The publications included in the database were overwhelmingly concentrated in North America and Europe, with only two publications from another continent and no representation of the tropics or the Southern Hemisphere. Even within these two geographic clusters, the publications were not equally distributed. In North America, there were nearly twice as many publications from the U.S.A than from Canada, and even Canadian publications were more abundant than those of 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.

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Disturbance characteristics

The most frequent disturbance type that defined our study population was wildfire. In 2000, a USDA review (McIver and Starr 2000) highlighted several mechanisms through which burnt forests could be particularly vulnerable to subsequent logging disturbance, including effects on burnt soil and vegetation. The report also noted a lack of empirical evidence regarding the consequences of salvage 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 also produces some unique ecological responses, such as significant reductions in small-diameter aboveground biomass, as well as direct and indirect wildlife mortality. This, combined with the direct impacts of wildfire on those living in or near fire-prone forests and spectacular images in the media that suggest death and destruction, has likely generated more public and political demand for understanding the various implications of wildfire as compared to windstorms or insect outbreaks, including impacts related to subsequent salvage logging. However, logging after some large storms such as Vivian (1990) and Lothar (1999) in Switzerland (Kramer et al. 2014), and after massive insect outbreaks throughout western North America (Collins et al. 2011), has 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), and addressing questions related to post-disturbance management is a logical response to increasingly prevalent situations.

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. Many ecological responses to disturbances largely depend on their severity, which highlights the relevance of studying the response to disturbance, and to subsequent logging, under different degrees of severity. 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). Whereas 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 sacrificing replication. Of course, this is not always possible, and it hinges on the spatial scale at which disturbance severity varies.

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 fire near 2016 Fort McMurray in Canada, which affected more than half a million ha). Salvage logging is, however, quite often performed in areas affected by small- or medium-scale disturbances, which are common in Europe. 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 relationship between disturbance extent, the extent and intensity of salvage logging, and the ecological response to disturbance and subsequent salvage logging.

Intervention

Ecological responses to salvage logging are often predicted to vary with the time elapsed between the disturbance and logging, particularly in the case of discrete disturbance events like wildfire. For example, post-fire logging may have 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 of 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 on the ecosystem response. Burnt stands were generally those salvage logged most quickly, followed by wind-affected stands. 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. Insect outbreaks most often take several years to develop, during which 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 methods employed in salvage logging operations and their intensity also likely define 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 like forming ruts that fill with water and create persistent aquatic habitat (Ernst et al. 2016). Extraction of wood by helicopter is well known to reduce soil impacts compared to ground-based yarding. However, helicopter use is extremely costly; this, combined with the low economic value of disturbance-affected timber and depressed price that typically follow large disturbance events, are likely reasons why helicopters were only mentioned in two of the 49 included studies.

Finally, the intensity of salvage logging can be a crucial factor explaining salvage logging effects, as identified six decades ago (Roy 1956). Due to this awareness, land managers can –and in some situations do– implement Best Management Practices to reduce potential negative salvage logging effects on soil, vegetation and water, such as by restricting wet season and steep slope operations or by favouring mechanical operations over winter snowpack. The studies in the systematic map included a wide range of salvage logging intensity for the three disturbance types considered here, although intensity was mostly categorised in excess of 90%. 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 intensities were established, ranging from 0 to 100% (Ritchie et al. 2013). The authors further assessed the effect of 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). This has long been acknowledged in traditional green-tree silviculture, where the retention forestry approach was created under the acknowledgement that commercial clearcutting can greatly differ from that of forestry operations that leave behind structures that favour the continuity of the forest ecosystem (Gustafsson et al. 2012, Lindenmayer et al. 2012). Only seven out of 49 studies were designed to compare different logging intensity levels, which highlights the need to better address salvage logging throughout a range of logging intensity. The need for salvage operations to generate profits, something more difficult to achieve than in green-tree silviculture, could be a limitation in this regard. Nevertheless, the potential benefits of the retention of biological legacies (Franklin et al. 2000) during post-disturbance harvest operations should be more profoundly explored.

Study designs

In most studies, salvage logging was not performed experimentally, which provided several advantages and disadvantages. Salvage logging was generally described as a process to achieve management objectives rather than to conduct research. Such reasons generate 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 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 minimise such bias. In addition, some of the studies –both experimental and non-experimental– 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.

True replication is another important factor reducing the potential for bias. In this regard, it should be noted that replication of the salvage logging intervention was generally low. Most studies addressed this issue by establishing hierarchical sampling designs (i.e. with several sub-units 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 (Appendix I). As a result, we do not exclude the possibility that some of those excluded studies could provide valuable insights despite the pseudo-replication, yet for the purpose of inclusion in the systematic map we decided to stick to the study inclusion criteria established in the protocol aimed at reducing the potential for bias (Leverkus et al. 2015a).

Experimental design, with appropriate replication at the scale of management and randomised allocation of treatments to spatial units, can also minimise bias resulting from spatial variation. In eleven studies, researchers designed the salvage logging experiment. One good example of such an experiment is the one established after the Summit Fire in Oregon: it included randomisation, 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 reports the design of a randomised complete block design that, however, could not be turned to practice due to legal constraints and which resulted in a pseudo-replicated design comparing salvaged private forest *vs* unsalvaged public land (Slesak et al. 2015) –hence leading to exclusion from our systematic map. The downside of experiments that are under the control of researchers is that the logging intervention was generally performed under close compliance with environmental prescriptions (e.g., Ne'eman et al. 1997, McIver and Ottmar 2007, Leverkus et al. 2014), so that 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). As a result, it is difficult to apply strict, identical quality criteria to all the included 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.

Response variables

In summary, s

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The map presented here provides the first systematic account on the scientific evidence of ecosystem responses to salvage logging. It

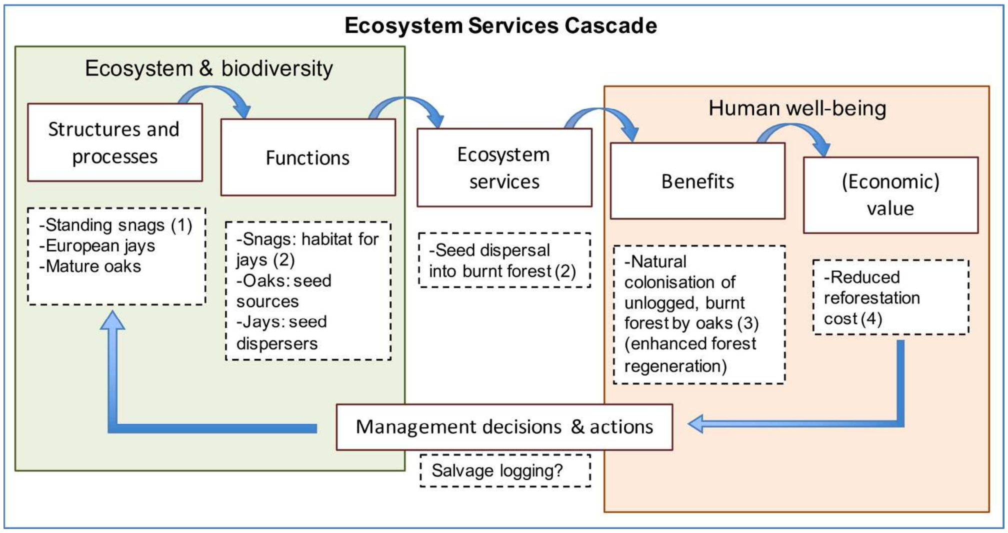

Figure 1. Ecosystem services cascade illustrated for the case of seed dispersal by European jays within a post-fire management experimental setting. The diagram shows the link between the biophysical and the human well-being components of ecosystem services. Particular elements of the ecosystem perform 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 colonisation 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); (2) = Castro et al. (2012); (3) = Leverkus et al. (2016); (4) = Leverkus and Castro (2017).

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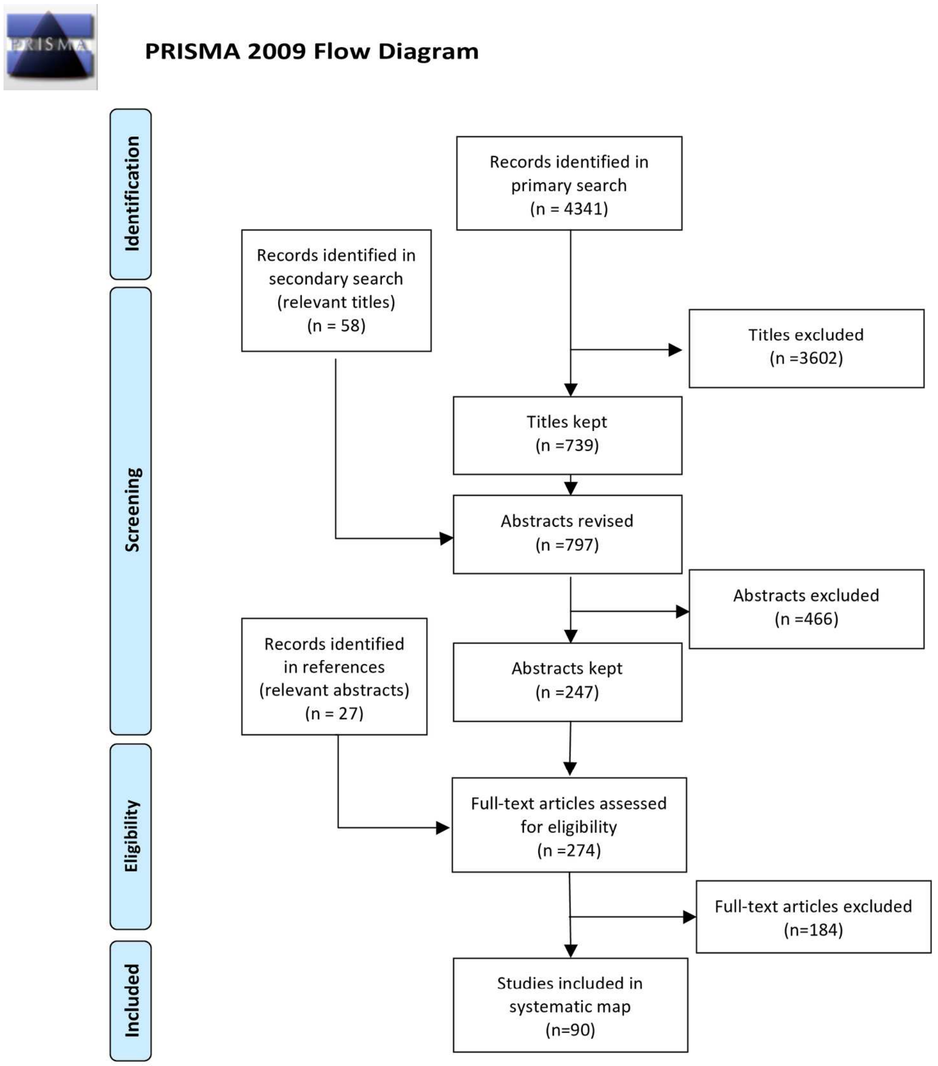
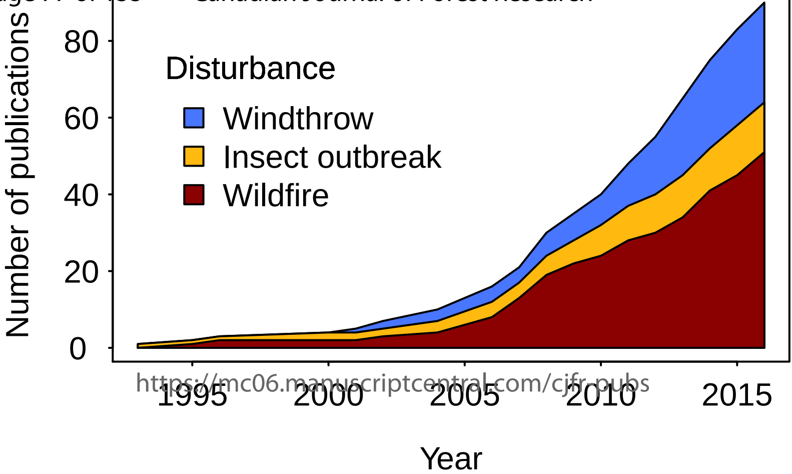


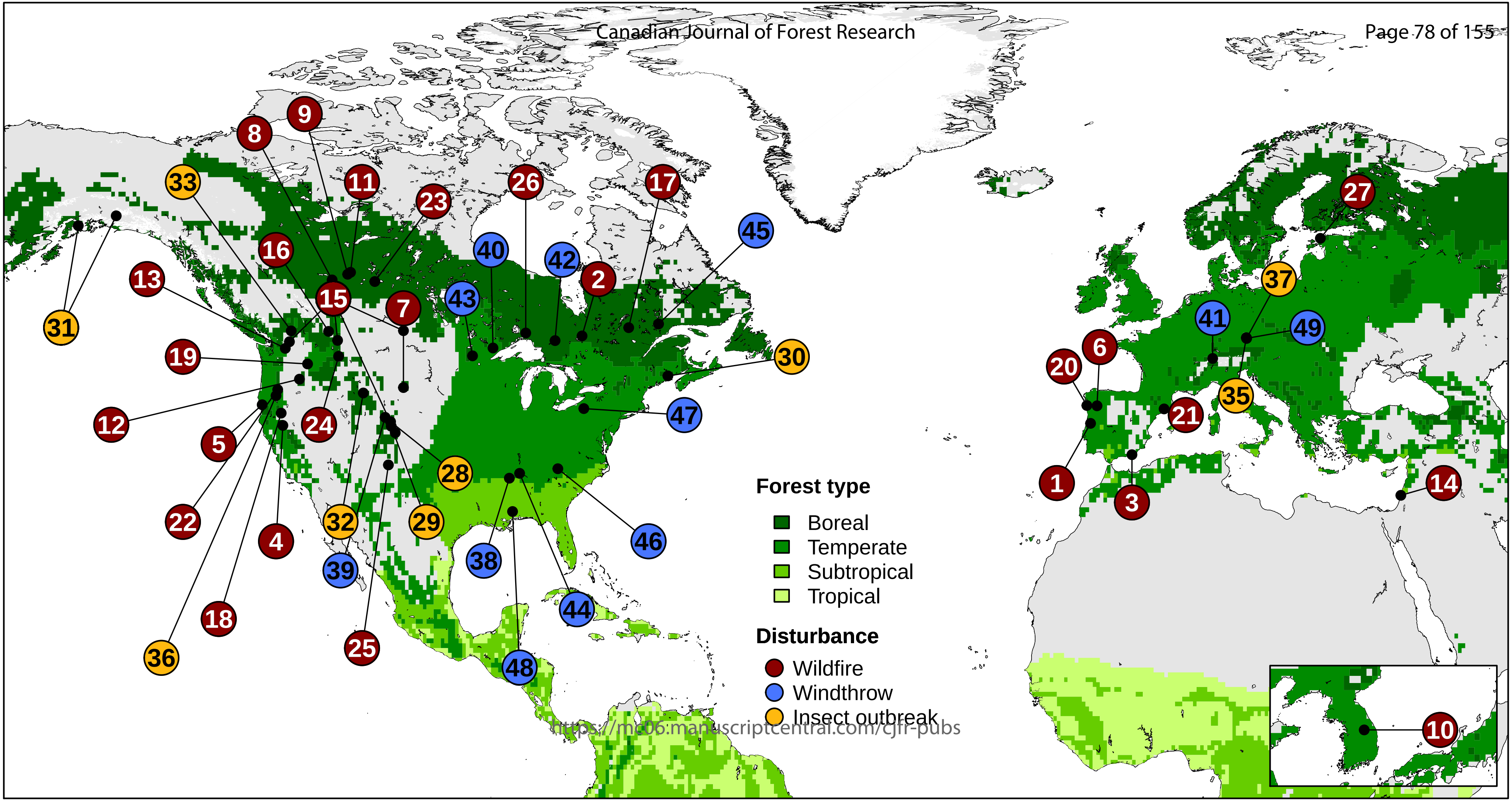
Adapted From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). *P*referred *R*eporting *I*tems for *S*ystematic Reviews and *M*eta-*A*nalyses: The PRISMA Statement. PLoS Med 6(6): e1000097. doi:10.1371/journal.pmed1000097

For more information, visit www.prisma-statement.org.

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

172x222mm (300 x 300 DPI)


Number of publications
0
20
40
60
80
Disturbance
Windthrow
Insect outbreak
Wildfire
1995
2000
2005
2010
2015
Year


Forest type
🟩 Boreal
🟩 Temperate
🟩 Subtropical
🟩 Tropical
Disturbance
● Wildfire
● Windthrow
● Insect outbreak
1
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3
4
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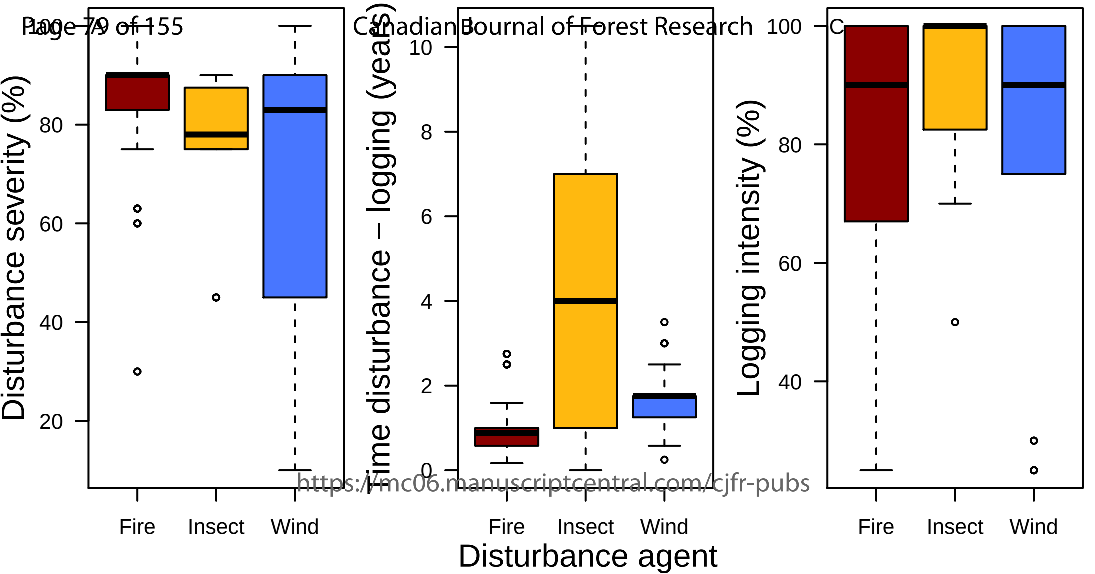
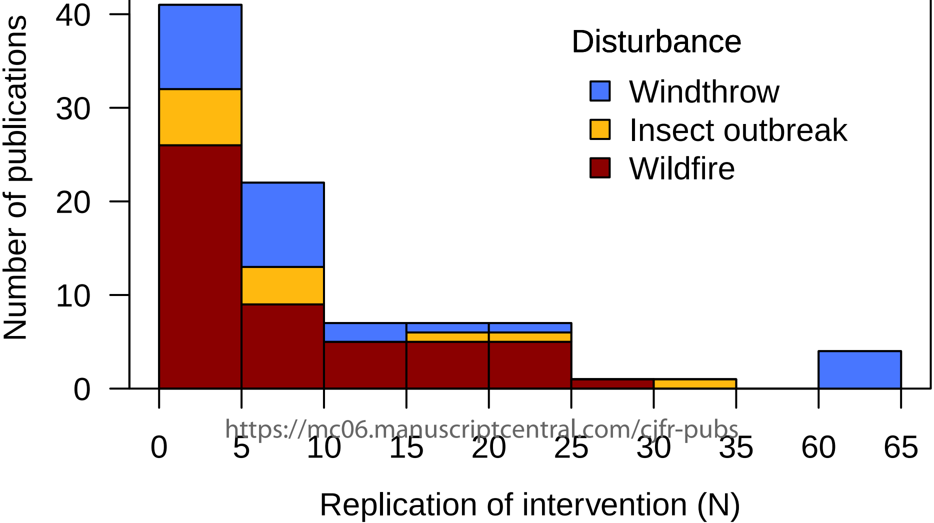

A
100
80
60
40
20
Disturbance severity (%)
Fire
Insect
Wind
B
10
8
6
4
2
0
Time disturbance – logging (years)
Fire
Insect
Wind
C
100
80
60
40
Logging intensity (%)
Fire
Insect
Wind
Disturbance agent


Number of publications
0
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Disturbance
Windthrow
Insect outbreak
Wildfire
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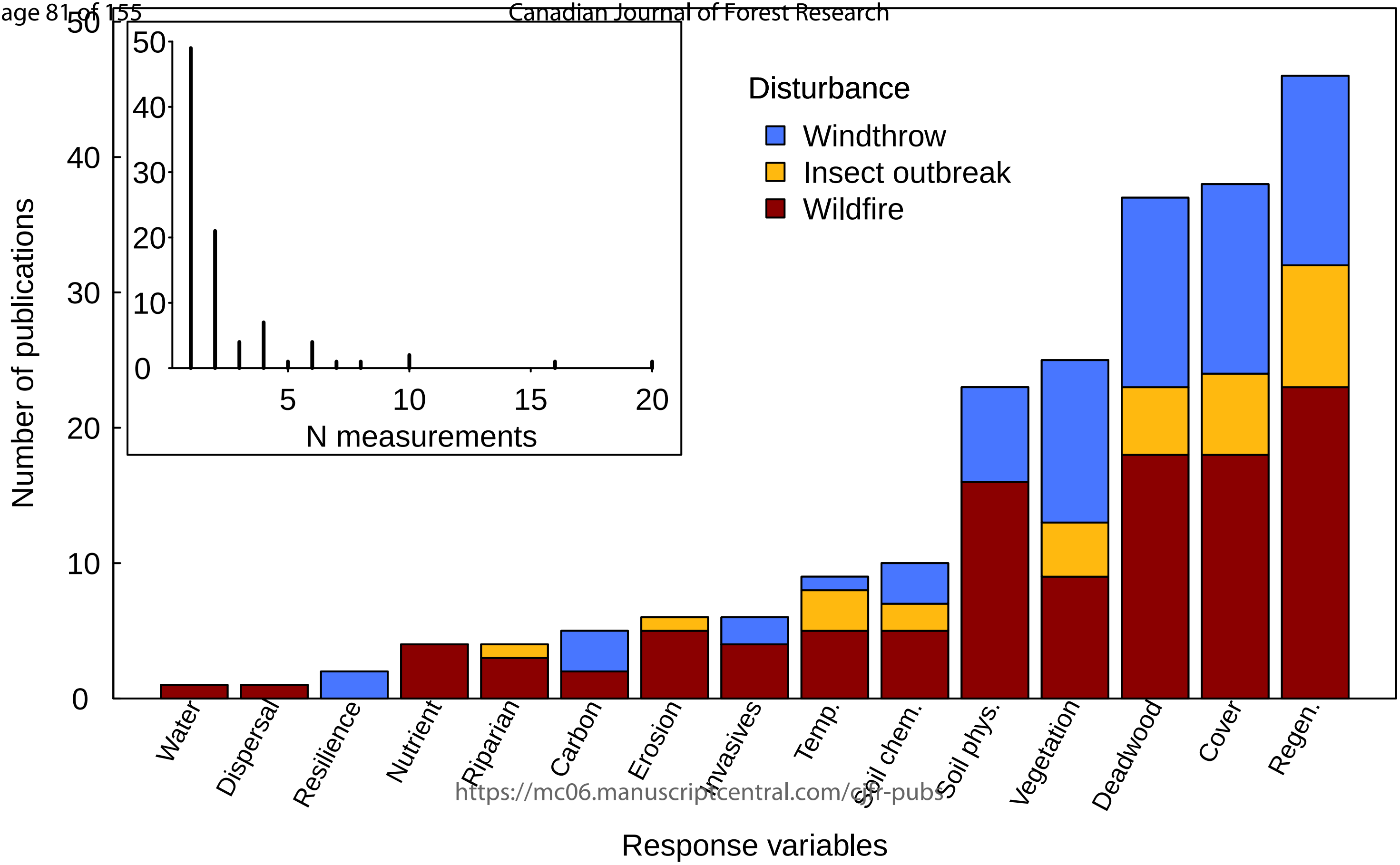
65
Replication of intervention (N)



Number of publications
0
10
20
30
40
50
N measurements
5
10
15
20
Disturbance
🟦 Windthrow
🟨 Insect outbreak
🟥 Wildfire
Water
Dispersal
Resilience
Nutrient
Riparian
Carbon
Erosion
Invasives
Temp.
Soil chem.
Soil phys.
Vegetation
Deadwood
Cover
Regen.
Response variables

Appendix A1

Supporting information for Leverkus et al., Salvage logging effects on regulating and supporting ecosystem services – A systematic map

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 which 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 (Table A3) 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, from different publications related to the same study, or directly from the authors; however, not all 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 obtention of the publication. This was one of the following: a) Primary search (in Web of Science or Scopus); b) Secondary search (in specialised 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.

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 percentage of basal area or of trees that were removed. For descriptive purposes, we transformed qualitative indicators to percentages as follows. The intensity category “Moderate to low” was given 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 the methods that were mentioned. We categorised 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 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, Fellet-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, 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 categorised this information into three broad categories: a) young forest (<50 years old), b) mature forest (50-99 years), and c) old forest (≥100 years).

13. Dominant canopy species. We recorded the name of the species dominating the studied stands. In case there was more than one, we recorded up to five dominant species, and above this amount we specified that it was a mixed stand. In cases where 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. Randomisation. We recorded whether salvage logging was under control of the researchers, with randomisation in the allocation of treatments to spatial units. Column: Randomisation.

15. Type of design: Control-Intervention, Before-After-Control-Intervention, or a mixture of both approaches. Before-After 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 subsequent disturbances). 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 in each study. 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 activity related to nutrient cycling, g) vegetation, h) soil erosion [by wind or water], i) abundance of exotic or invasive species, j) air, soil or water temperature, 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, o) drinking water quality.

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Appendix A2

Supporting information for Leverkus et al., Salvage logging effects on regulating and supporting ecosystem services – A systematic map

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 of the main text). The search in Scopus provided additional 70 non-duplicated publications, adding to 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 value of the kappa test κ = 0.47, indicating only "moderate" agreement among reviewers and thus heterogeneity in the application of inclusion criteria (Landis and Koch 1977). After revising the inclusion criteria and performing the test again, the new kappa 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. A total of 63 articles was randomly selected for independent evaluation by three members of the review team. The values that were obtained were κ = 0.68 (ABL & LG), κ = 0.43 (LG & JC) and κ = 0.43 (JC & ABL). After discussing the criteria again and reassessing abstract inclusion, the obtained kappa 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).

Of the full-text articles assessed, 90 were kept and 184 were excluded for the reasons outlined in Table A1 in this file (see Supplementary Table S2 for references of excluded publications and reasons for exclusion). 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 a recent, 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 A1). 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.

Table A1. Reasons for exclusion from the systematic map at full-text screening

Reason for exclusion*	Criterion type	N 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
B-A design	Inclusion	3
Methods not well described	Validity	1
Language	Inclusion	1
Total		184

* 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.

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Appendix A3

Supporting information for Leverkus et al., Salvage logging effects on regulating and supporting ecosystem services – A systematic map

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 A2 (below) 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 A3). At the publication level, quaking aspen (*Populus tremuloides*) was the most frequent dominant species among broadleaved tree species and lodgepole pine (*Pinus contorta*) among conifers (Table A3). *Pinus* was by far the most frequent genus, with 67 cases, followed by *Picea* (32 cases), *Populus* (24 cases), *Abies* (14 cases), *Fagus* and *Pseudotsuga* (each 6 cases). Wind was the disturbance type where the largest number of dominant broadleaf species was included among the identified studies (n = 10, *vs* n = 4 for wildfire or insect outbreak; Table 3). 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 A3).

Table A2. 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*	2	7	1	1

*N/A= information not available

Table A3. Distribution of publications relative to disturbance type and the occurrence of dominant tree species

	Disturbance type (N of publications)			
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
N species†	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 x *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
N species†	15	11	10	24
Mixed broadleaves*	0	0	2	2
Mixed conifers*	1	0	1	2
Mixed conifers and broadleaves*	0	0	1	1

*Included more than five dominant species in individual stands

†Number of species with non-zero values

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 the dynamics of conifer forests (Mutch 1970, Kuuluvainen and Ankala 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*) were by far the most frequent genus that dominated the study areas, with 66 cases, 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 like *P. halepensis* in the Mediterranean and to cold-resistant ones like *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 be expected not 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, since 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).

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Salvage logging effects on regulating and supporting ecosystem services – A systematic map

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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.

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. 2016), 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. 2004a).

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 unrecognised–

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 above-mentioned 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, post-bark beetle salvage logging lodgepole pine forests in Colorado commonly reduces canopy fuels and regenerates new stands without negatively effecting native plant diversity or soil productivity (Collins et al. 2011, 2012, Fornwalt et al. 2017, 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 categorised according to whether they affect:

a) The physical structure of ecosystems. An immediate consequence of logging is the reduction in parameters such as standing and downed woody debris, 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 dead wood 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 categorised 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 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. 2016), 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. 2011b), 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 synthesise 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 intervention? 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 (CEBC 2010) and several other texts (Sutherland et al. 2004b, 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. 2015a).

Research question

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. The final search string (Table S1) was established after the scoping exercise described in the protocol (Leverkus et al. 2015a). The search in WoS was initially made on 18 Aug 2015 and updated on 5 May 2017 to encompass all studies published until 31 Dec 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/ Water Resources, and in Scopus to Agricultural and Biological Sciences/ Environmental Science/ Earth and Planetary Sciences/ Multidisciplinary.

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 US Forest Service (http://www.treesearch.fs.fed.us/). We also searched in Google Scholar. For complete search terms, see Table S1.

As supplementary bibliographic searches, the reference lists of relevant articles (review articles and books) were screened for additional articles to complement the list of articles identified using the search terms. A list of the publications was sent to all the authors of this systematic map, most of who 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 review, 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 where 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 a major driver 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 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 the titles, two members of the review 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 the titles. After screening the titles, the word "salvage" was searched in the titles, keywords and abstracts of all 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). In cases where 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 of the studies were assessed as

well as the study-site descriptions (including tables and figures). Relevant articles were categorised 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 both to the methodology and to 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 randomised 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 randomisation in the allocation of treatments to spatial units. This is 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. Studies with pseudo-replicated designs were placed in this category. 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 such studies 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 very 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 A1.

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 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 A2. 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).

The following results are presented at the level 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 A1), and others at the level of stand types within study sites or within publications (for example, in cases where 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. 2015a, 2015b)]. 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 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 U.S.A 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 like wildfire in regions at the frontline of land-use change, such as 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 to 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), has 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 largely depend 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 the *Systematic map database and coding strategy* section in Appendix A1). 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 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 half a 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 like wildfire. For example, post-fire logging may have 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 ± 1SD) 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 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 categorised in excess of 90%. Salvage logging intensity ranged between 25 and 100%, and it averaged 80 ± 24% (including up to 4 values per publication). Average intensities were 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 A1). 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 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). This has long been acknowledged in traditional green-tree silviculture, where 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 to 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).

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 like forming 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 in 10 studies. Ground-based yarding was mentioned in 20 studies, and by helicopter in two studies. Extraction of wood by helicopter is well known to reduce soil impacts compared to ground-based yarding. However, helicopter use is extremely costly; this, combined with the low economic value of disturbance-affected timber and depressed price that typically follow large disturbance events, are likely reasons for the scant mentions 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 A3.

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 sub-units 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 (Table S2). As a result, we do not discard the possibility that some of those excluded studies could provide valuable insights despite pseudo-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. 2015a).

In 11 of the 49 studies, the selection of stands for management intervention was at least under partial control by the researchers and thus included randomisation 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 minimise 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 where 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 randomisation, 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 reports the conceptualisation of a randomised complete block design that, however, could not be turned to practice due to legal constraints and which resulted in a pseudo-replicated design comparing salvaged private forest *vs* 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), so that 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 and one post-insect) 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. 2016), 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). It should also be noted that 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, such as the US 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 primary productivity. Cover of pits and mounds, as well as cover of deadwood, may be used as indicators of the microclimatic and micro-topographic habitat availability and heterogeneity. Bare soil cover could be an indicator of available seedbed in measurements made right 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-term through decomposition (Marañón-Jiménez and Castro 2013, Molinas González et al. 2017). It can also ameliorate microclimatic conditions to enhance tree regeneration (Castro et al. 2011) and help reduce herbivory by large ungulates (Leverkus et al. 2015b). 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, the aim of deadwood characterisation 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 that was excluded from the map for design-related reasons 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 characterisation 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 also can 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. 2011a) 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 due to the existence of a recent review on the topic (Thorn et al. 2018), 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 substantial 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.
- The effect of disturbance type on the ecological effects of salvage logging.

Acknowledgments

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.

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Tables

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

Continent	Country	N Publications	N Studies	N multi-site 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

Figure captions

Figure 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 colonisation 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); (2) = Castro et al. (2012); (3) = Leverkus et al. (2016); (4) = Leverkus and Castro (2017).

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

Figure 3. Cumulative number of publications per disturbance type included in this systematic map.

Figure 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, Table S3). Inset: Korean Peninsula.

Figure 5. Disturbance and salvage logging characteristics. A) Disturbance severity considered in the analysed 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 analysed publications. This includes 1-4 points per publication. Note that this applies to the Intervention 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/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 are: for fire 53, 51 and 69 (panels A, B and C, respectively); for insect outbreaks 15, 13 and 15; and for wind 31, 26 and 21 for wind.

Figure 6. The number of spatially independent salvage logging replicate units used in the 90 publications, classified by disturbance type.

Figure 7. Number of publications that reported different measured response variables, for each disturbance type. Nutrient= biological indicators of nutrient cycling; Carbon= non-wood carbon pool; Water= drinking water quality; Erosion= soil

erosion by wind or water; Invasives= Invasive and/or exotic species; Cover= ground cover, including cover of vegetation; Resilience= capacity to regenerate after subsequent wildfire (i.e. wildfire after salvage logging); Riparian= riparian ecosystem functioning; Dispersal= seed dispersal; Soil chem.= soil chemical properties; Soil phys.= soil physical properties; Deadwood= stand structure and deadwood amount and characteristics; Temp.= air, water or soil temperature; Regen.= tree regeneration; Vegetation= Vegetation composition. 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.

Supporting Information

Appendix A1. **Systematic map database and data coding strategy**

Appendix A2. **Literature searches and screening –Results**

Appendix A3. **Stand characteristics –Results and Discussion**

Table S1. **Search strings used in the systematic map.**

Table S2. **Publications excluded at full-text screening and reasons for exclusion.**

Table S3. **Systematic Map Database.** For details on coding and variable names, see Appendix A1.