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

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1 Salvage logging effects on regulating and supporting
2 ecosystem services – A systematic map
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5 Alexandro B. Leverkus^{1*}, José María Rey Benayas¹, Jorge Castro², Dominique Boucher³,
6 Stephen Brewer⁴, Brandon M. Collins⁵, Daniel Donato⁶, Shawn Fraver⁷, Barbara E.
7 Kishchuk⁸, Eun-Jae Lee⁹, David B. Lindenmayer¹⁰, Emanuele Lingua¹¹, Ellen
8 Macdonald¹², Raffaella Marzano¹³, Charles C. Rhoades¹⁴, Alejandro Royo¹⁵, Simon
9 Thorn¹⁶, Joseph W. Wagenbrenner¹⁷, Kaysandra Waldron¹⁸, Thomas Wohlgemuth¹⁹, Lena
10 Gustafsson²⁰

11 ¹ Departamento de Ciencias de la Vida, UD Ecología, Edificio de Ciencias, Universidad
12 de Alcalá, Alcalá de Henares, Spain. josem.rey@uah.es

13 ² Departamento de Ecología, Facultad de Ciencias, Universidad de Granada, Granada,
14 Spain. jorge@ugr.es

15 ³ Centre de foresterie des Laurentides, Service Canadien des Forêts, Ressources Naturelles
16 Canada, Québec, Québec, Canada. dominique.boucher@canada.ca

17 ⁴ Department of Biology, University of Mississippi, Mississippi, USA.
18 jbrewer@olemiss.edu

19 ⁵ Center for Fire Research and Outreach, University of California Berkeley, California,
20 USA. bcollins@berkeley.edu

21 ⁶ School of Environmental and Forest Sciences, University of Washington, Seattle, WA,
22 USA. daniel.donato@dnr.wa.gov

1

- 23 ⁷ School of Forest Resources, University of Maine, Orono, Maine, USA.
24 shawn.fraver@maine.edu
- 25 ⁸ Science Policy Integration Branch, Canadian Forest Service, Natural Resources Canada,
26 Ottawa, Ontario, Canada. barbara.kishchuk@canada.ca
- 27 ⁹ Urban Planning Research Group, Daejeon Sejong Research Institute, Jung-gu, Daejeon,
28 Korea. 2lejae@hanmail.net
- 29 ¹⁰ Fenner School of Environment and Society, The Australian National University,
30 Canberra, Australia. David.Lindenmayer@anu.edu.au
- 31 ¹¹ Department TESAF, University of Padova, Legnaro (PD), Italy.
32 emanuele.lingua@unipd.it
- 33 ¹² Department of Renewable Resources, University of Alberta, Edmonton, Alberta,
34 Canada. emacдона@ualberta.ca
- 35 ¹³ Department DISAFA, University of Torino, Grugliasco (TO), Italy.
36 raffaella.marzano@unito.it
- 37 ¹⁴ Rocky Mountain Research Station, USDA Forest Service, Fort Collins, Colorado, USA.
38 crhoades@fs.fed.us
- 39 ¹⁵ Northern Research Station, USDA Forest Service, Irvine, PA, USA. aroyo@fs.fed.us
- 40 ¹⁶ Field Station Fabrikschleichach, Department of Animal Ecology and Tropical Biology
41 (Zoology III), Julius-Maximilians-University Würzburg, Rauhenebrach, Bavaria,
42 Germany. simon@thornonline.de
- 43 ¹⁷ Pacific Southwest Research Station, USDA Forest Service, Arcata, California, USA.
44 jwagenbrenner@fs.fed.us
- 45 ¹⁸ Department of Wood and Forest Sciences, Université Laval, Québec, QC, Canada.
46 kaysandra.waldron.1@ulaval.ca

2

47 ¹⁹ Research Unit Forest Dynamics, Swiss Federal Institute for Forest, Snow and
48 Landscape Research WSL, Zuercherstrasse 111, CH-8903 Birmensdorf, Switzerland.
49 thomas.wohlgemuth@wsl.ch

50 ²⁰ Department of Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden.
51 Lena.Gustafsson@slu.se

52

53 * Corresponding author: ABL. Departamento de Ciencias de la Vida, UD Ecología,
54 Edificio de Ciencias, Universidad de Alcalá, Alcalá de Henares, Spain. Tel. +34
55 622689928. E-mail: alexandro.leverkus@uah.es (ABL)

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58 **Abstract**

59 Wildfires, insect outbreaks, and windstorms are [increasingly](#) common forest disturbances,

Eliminado: that are increasing in importance

60 Post-disturbance management often involves salvage logging, i.e. the felling and removal

61 of the affected trees. However, this practice may represent an additional disturbance with

62 effects on ecosystem processes and services. We developed a systematic map to [provide](#)

Eliminado: identify

63 [an overview of](#) the primary studies on this topic, and created a database with information

64 on the characteristics of the retrieved publications, including information on stands,

65 disturbance, intervention, measured outcomes, and study design. Of 4341 retrieved

66 publications, 90 were retained in the systematic map. These publications represented 49

67 studies, predominantly from North America and Europe. Salvage logging after wildfire

68 was addressed more frequently than after insect outbreaks or windstorms. Most studies

69 addressed logging after a single disturbance event, and replication of salvaged stands

70 rarely exceeded 10. The most frequent response variables were tree regeneration, ground

71 cover, and deadwood characteristics. This document aims to help managers [find the most](#)

Eliminado: and decision-makers

72 relevant [primary studies on the ecological effects of salvage logging](#). It also [aims to](#)

Eliminado: information

Eliminado: to define

73 [identify and discuss](#) clusters and gaps in the body of evidence, relevant for scientists who

Eliminado: management strategies for disturbed forests grounded on a sound scientific basis

74 aim to synthesize previous work or identify questions for future studies.

Eliminado: shows

75

76

86 **Introduction**

87 Large, episodic, severe forest disturbances such as those caused by wildfires, insect
 88 outbreaks, and windstorms are part of the natural dynamics of forest ecosystems across the
 89 world (Noss et al. 2006, Turner 2010, Johnstone et al. 2016). However, the frequency,
 90 severity and extent of such disturbances have increased in recent decades due to
 91 anthropogenic activity (Seidl et al. 2017) and are predicted to further increase in the future
 92 (Schelhaas et al. 2003, Kurz et al. 2008, Pausas and Fernández-Muñoz 2012, Seidl et al.
 93 2017). As a result, it is crucial to identify and adopt management strategies that promote
 94 regeneration and maintain ecosystem functions of post-disturbance forests, whether through
 95 active intervention or passive management (Crouzeilles et al. 2017). A common
 96 post-disturbance management approach in many parts of the world is salvage logging, i.e.
 97 the widespread felling and removal of the affected trees (McIver and Starr 2000,
 98 Lindenmayer et al. 2008, Thorn et al. 2018). Salvage logging has been reported after
 99 wildfires (Lindenmayer et al. 2018), volcanic eruptions (Titus and Householder 2007),
 100 insect infestations (Thorn et al. 2016), windstorms (Waldron et al. 2014), and ice storms
 101 (Sun et al. 2012). It is frequent in disturbed production forests but also common in
 102 protected forests in some parts of the world (Schiermeier 2016, Leverkus et al. 2017,
 103 Müller et al. 2018). However, there is concern that the additional logging-related
 104 disturbance can imperil ecosystem recovery and affect biodiversity and ecosystem services
 105 (Karr et al. 2004, Beschta et al. 2004, Donato et al. 2006, Lindenmayer et al. 2008). Besides
 106 the mechanical disturbance, salvage logging affects ecosystems through the removal and
 107 modification of large amounts of biological legacies –i.e. the organisms, organic materials,
 108 and organically-generated environmental patterns that persist through a disturbance and
 109 constitute the baseline for post-disturbance recovery and regeneration (Franklin et al. 2000).

Bajado [1]: along with 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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Movido (inserción) [1]

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121 The most frequent motivation for salvage logging across the world is the recovery of
122 some part of the economic value of the forest (Müller et al. 2018). Tree-killing disturbances
123 trigger a set of processes that can rapidly reduce the timber value due to reductions in wood
124 quality (e.g. stain, decay, and the activity of insect borers) and to pulses in wood supply to
125 the market (Prestemon and Holmes 2010). Rapid post-disturbance harvest is a frequent
126 response to disturbance that aims to avoid further deterioration of the damaged wood
127 (Prestemon and Holmes 2010, Lewis and Thompson 2011). In some parts of the world,
128 such as regions of North America, large-scale wildfires and insect outbreaks have become
129 so frequent that salvage logging is no longer a hasty response to unexpected events but
130 rather constitutes an expected source of wood to fill market demands (Mansuy et al. 2015).
131 However, the logging of disturbed forests is not profitable in all cases (e.g. Leverkus et al.
132 2012), and it may also aim to fulfil other management objectives. Salvage logging can
133 target the reduction of the risk of subsequent disturbances, such as pest outbreaks and
134 wildfire, through the elimination of the substrate or fuel generated by the initial disturbance
135 (Schroeder and Lindelöw 2002, Collins et al. 2012). The simplification of post-disturbance
136 ecosystem structure through the removal of fallen trunks is intended to ease subsequent
137 active restoration activities such as reforestation (Leverkus et al. 2012, Man et al. 2013).
138 Finally, there is a general negative aesthetic perception of disturbed forests that may be
139 offset by removing the visual evidence of what is generally considered a “calamity” (Noss
140 and Lindenmayer 2006). However, these motivations are not always based on scientific
141 evidence, but rather on traditional practices, perceptions and deductions –as is often the
142 case in conservation-related decision-making (Pullin et al. 2004, Sutherland et al. 2004a).

143 The lack of scientific evidence on the effects of salvage logging was highlighted in
144 2000 (McIver and Starr 2000). In 2004, Lindenmayer and colleagues (Lindenmayer et al.
145 2004) called for a revision of post-disturbance management policies, arguing that salvage
146 logging can have long-lasting negative effects on biodiversity, undermine the –largely

6

147 unrecognised– ecological benefits of natural disturbances, and impair ecosystem recovery.
 148 Numerous studies were established in subsequent years to assess the ecological
 149 consequences of this practice, covering a wide array of disturbance types and severities,
 150 biomes, forest compositions, logging methods, and response variables (Thorn et al. 2018).
 151 As a result, the above-mentioned motivations for salvage logging have been challenged
 152 [e.g. wildfire risk (Donato et al. 2006) and economics (Leverkus et al. 2012)], and many
 153 other effects of this practice have been described (e.g. Lindenmayer et al. 2008, Beghin et
 154 al. 2010, Priewasser et al. 2013, Wagenbrenner et al. 2015, Hernández-Hernández et al.
 155 2017). Nonetheless, under some circumstances, salvage logging can meet both management
 156 and conservation objectives and address societal concerns. [For example, post-bark beetle](#)
 157 [salvage logging lodgepole pine forests in Colorado commonly reduces canopy fuels and](#)
 158 [regenerates new stands without negatively effecting native plant diversity or soil](#)
 159 [productivity](#) (Collins et al. 2011, 2012, Fornwalt et al. 2017, Rhoades et al. 2018). As a
 160 consequence, controversy surrounding salvage logging among managers,
 161 environmentalists, politicians and academics, remains lively (Schiermeier 2016, Leverkus
 162 et al. 2017, Lindenmayer et al. 2017, Müller et al. 2018).

164 The ecological impacts of salvage logging can broadly be categorised according to
 165 whether they affect,

- 166 a) The physical structure of ecosystems. [An immediate consequence of logging is](#)
 167 the reduction in parameters such as standing and downed woody debris, living
 168 canopy cover, and habitat structural complexity (Lee et al. 2008, Waldron et al.
 169 2013, Peterson et al. 2015).

Eliminado: (Lindenmayer and Noss 2006):

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).

176 | b) Particular elements of the biota and species assemblages. The removal of dead
 177 | wood can affect many species, particularly deadwood-dependent taxa (as
 178 | 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.

Eliminado: this

179 | c) Forest regeneration capacity. Salvage logging has the potential to alter residual
 180 | growing stock, soil seed bed, canopy and soil seed banks, and species
 181 | interactions such as competition, seed dispersal, seed predation, and herbivory
 182 | (Greene et al. 2006, Collins et al. 2010, Puerta-Piñero et al. 2010, Castro et al.
 183 | 2012, Castro 2013).

184 | d) Key ecosystem processes and services. Ecosystem services are the benefits that
 185 | people obtain from ecosystems; they are the link between particular elements of
 186 | the ecosystem or functions that they perform (i.e. the biophysical component),
 187 | the benefits that society obtains and, ultimately, the value placed on them (i.e.
 188 | the human well-being component; Fig 1; Haines-Young and Potschin 2010).
 189 | They are categorised into provisioning, cultural, regulating, and supporting
 190 | services (Millennium Ecosystem Assessment 2003). As outlined above, salvage
 191 | logging is most often conducted to recover the value of the affected wood. In
 192 | the case of timber and other provisioning services, the human well-being
 193 | component is often well defined and quantified. However, salvage logging also
 194 | may affect cultural, regulating and supporting ecosystem services throughout
 195 | the ecosystem services cascade. This implies that some of the effects outlined in
 196 | a), b) and c) can also be considered to fall into the category of ecosystem
 197 | services (Fig 1; Leverkus and Castro 2017). In the case of supporting and
 198 | regulating services, the biophysical component is usually better understood than
 199 | the human well-being component (Boerema et al. 2016), and this is likely also
 200 | the case regarding the responses to salvage logging (Leverkus and Castro
 201 | 2017).

Eliminado: before

Eliminado: (Fig 1; Leverkus and Castro 2017).

210 |
211 | Although ecosystem services have seldom been explicitly addressed in the scientific
212 | literature on salvage logging, they provide a common framework that allows balancing
213 | economic benefits from timber against the wide array of ecological variables that are also
214 | affected by post-disturbance management (Leverkus and Castro 2017). This framework
215 | represents an Ecosystem Approach (Secretariat of the Convention on Biological Diversity
216 | 2000), i.e. the consideration of multiple benefits provided by ecosystems –rather than only
217 | market values– to guide sustainable management decisions.

218 | Salvage logging can affect ecosystem services by altering processes such as soil
219 | erosion and hydrological regimes (Wagenbrenner et al. 2016), nutrient cycling (Kishchuk et
220 | al. 2015), carbon sequestration (Serrano-Ortiz et al. 2011b), seed dispersal (Castro et al.
221 | 2012), vegetation cover (Macdonald 2007), tree regeneration (Castro et al. 2011, Marzano
222 | et al. 2013, Boucher et al. 2014), resistance to invasive species (Holzmueller and Jose
223 | 2012), resilience to subsequent disturbances (Fraver et al. 2011), and many others (McIver
224 | and Starr 2000, Karr et al. 2004, Beschta et al. 2004, Lindenmayer and Noss 2006,
225 | Lindenmayer et al. 2008). Some authors argue that ecological responses to salvage logging
226 | may result in synergistic effects due to the two successive disturbance events (the natural
227 | disturbance and then logging) occurring close in time (Van Nieuwstadt et al. 2001,
228 | Wohlgemuth et al. 2002, Karr et al. 2004, Lindenmayer et al. 2004, DellaSala et al. 2006,
229 | Lindenmayer and Noss 2006). Others have found that environmental drivers other than
230 | salvage logging are more important in determining ecosystem regeneration (Kramer et al.
231 | 2014, Peterson and Dodson 2016, Royo et al. 2016, Rhoades et al. 2018). Further, studies
232 | often report contradictory results, and there is currently no comprehensive, global
233 | assessment of the studies that have addressed salvage logging effects on ecosystem
234 | 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.

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

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

266

267 **Materials and methods**

268 We followed the guidelines for systematic reviews in environmental management as
269 prescribed by the Collaboration for Environmental Evidence (CEBC 2010) and several
270 other texts (Sutherland et al. 2004b, Pullin and Stewart 2006, Koricheva et al. 2013, James

271 et al. 2016). The Methods described below are an expansion of those presented in our
272 protocol (Leverkus et al. 2015a).

273 Research question

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

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

278 This question implies the following key elements:

- 279 • *Population:* Forests affected by one of the following disturbances: windstorms, pest
280 insect outbreaks, or wildfire.
- 281 • *Intervention:* Salvage logging, i.e. the harvesting of trees from areas after disturbance
282 events.
- 283 • *Comparator:* Forests after disturbance where no salvage logging was conducted.
- 284 • *Outcome:* Variables that could be regarded as indicators of regulating or supporting
285 ecosystem services.

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

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

- 290 • type and severity of the disturbance?
- 291 • geographic region?
- 292 • intensity, method, or timing of salvage logging?

Eliminado: Objective of the systematic map

Eliminado: 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. - [1]

Eliminado: A

Eliminado: was established

Eliminado: answer

Eliminado: asked

- 311 • forest type?
- 312 • [type](#) of study design?

Eliminado: kind

313 **Literature searches**

314 The primary literature search was conducted in English in Web of Science (WoS) and
315 Scopus with the aim of answering the primary research question. The terms were searched
316 in titles, abstracts and keywords and were based on the Population and the Intervention.
317 The final search string (Table S1) was established after the scoping exercise described in
318 the protocol (Leverkus et al. 2015a). The search in WoS was initially made on 18 Aug 2015
319 and updated on 5 May 2017 to encompass all studies published until 31 Dec 2016. In WoS,
320 the search was restricted to the fields of Environmental Sciences and Ecology/ Forestry/
321 Biodiversity Conservation/ Zoology/ Plant Sciences/ Meteorology and Atmospheric
322 Sciences/ Entomology/ Water Resources, and in Scopus to Agricultural and Biological
323 Sciences/ Environmental Science/ Earth and Planetary Sciences/ Multidisciplinary.

324 We performed secondary searches to find other publications, including grey literature,
325 with simplified Population and Intervention terms. These searches were made in the
326 Directory of Open Access Journals (<https://doaj.org/>), the CABI database of forest science
327 (<http://www.cabi.org/forestsience/>), and websites of the Canadian Forest Service
328 (<http://cfs.nrcan.gc.ca/publications>) and the US Forest Service
329 (<http://www.treesearch.fs.fed.us/>). We also searched in Google Scholar. For complete
330 search terms, see Table S1.

332 As supplementary bibliographic searches, the reference lists of relevant articles (review
333 articles and books) were screened for additional articles to complement the list of articles
334 identified using the search terms. A list of the publications was sent to all the authors of this
335 systematic map, most of who have research experience on salvage logging. Authors were
336 asked to identify relevant articles that were omitted from the search, and these articles were
337 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.

338 **Study inclusion criteria**

339 To be considered for the review, studies had to be empirical and fulfil each of the
340 following inclusion criteria:

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

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

348 c) Relevant comparator: forest disturbed by the same disturbance event but not
349 subject to salvage logging. We did not consider areas of disturbed forest prior to logging as
350 a comparator [i.e. Before-After (BA) study designs], as post-disturbance ecosystems are
351 highly dynamic and the effects of salvage logging could be confounded with the effects of
352 the time elapsed since the disturbance. As comparators, we considered the disturbed but

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357 [unsalvaged areas of Control-Intervention \(CI\) and Before-After-Control-Intervention](#)
358 (BACI) designs.

Eliminado: were considered in

359 d) Relevant outcome: response variable that could broadly be regarded as a regulating
360 or supporting ecosystem service. As it was expected that ecosystem services would rarely
361 be directly addressed, we used variables considered to be indicators or proxies for
362 ecosystem services (e.g. the quality of stream water for water purification, the abundance of
363 seed dispersers for seed dispersal, plant biomass or cover for primary productivity, or the
364 abundance of invasive species for invasion resistance). We also included studies addressing
365 post-disturbance tree regeneration, such as seedling density, survival, and growth.

Eliminado: as such

366 Provisioning ecosystem services such as timber were excluded because they are tightly
367 linked to market conditions, which can vary considerably across locations and time. Rather
368 than neglecting the importance of such ecosystem services (which are a major driver of the
369 decision to salvage log disturbed forests), our intention was to complement the list of

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370 ecosystem services that can be affected by this practice. We also excluded cultural services
371 because we expected few studies on this topic. Also, any variables directly related to the
372 number of standing trees were excluded on the basis that the intervention directly aims at
373 their extraction and reductions are thus a logical outcome. [Finally, biodiversity was not](#)
374 [included in the systematic map because such responses were thoroughly reviewed in a](#)
375 [recent meta-analysis \(Thorn et al. 2018\).](#)

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

382 **Article screening**

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

385 1. Each title was read in the first step, and articles with irrelevant titles were
386 discarded. This step was completed in a conservative way to avoid discarding any
387 potentially relevant publications. Before screening all the titles, two members of the review
388 team (ABL and LG) screened 401 titles and the difference in outcomes was assessed
389 through a kappa test. As the results indicated heterogeneity of application of selection
390 criteria (see Results), the inclusion criteria were discussed again prior to screening all the
391 titles. After screening the titles, the word “salvage” was searched in the titles, keywords and
392 abstracts of all the papers that were recorded as irrelevant based on title. Their titles were
393 screened again under a more inclusive approach, and those considered potentially relevant
394 were re-included for the next step.

395 2. The abstracts of articles with relevant titles were read in the second step, and
396 articles with irrelevant abstracts were discarded. To be classified as relevant in this step, the
397 abstracts had to fulfil the inclusion criteria a), b), and c). In cases where there was doubt
398 about the relevance of a publication, it was kept for the next step. Three authors (ABL, JC,
399 and LG) initially revised 63 randomly-chosen abstracts and kappa tests were again used to
400 assess and improve homogeneity of application of inclusion criteria.

401 3. The articles with potentially relevant abstracts were read in full. At this stage,
402 articles failing to fulfil any one of the study inclusion criteria were discarded. To select

403 studies that fulfilled inclusion criterion d), the main objectives of the studies were assessed
 404 as well as the study-site descriptions (including tables and figures). Relevant articles were
 405 categorised according to the study quality assessment criteria defined below.

406 **Study quality and validity assessment**

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

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

416 1. Empirical studies with treatments applied at appropriate spatial scales and with
 417 true replication at the scale of management operations and with randomised allocation of
 418 treatments to spatial units. An appropriate scale was considered as one that would generally
 419 be used in post-disturbance management under local conditions, or that would reasonably
 420 allow the measured responses to appear.

421 2. Studies as in 1 above, but without randomisation in the allocation of treatments to
 422 spatial units. This is often the case, as the authors of the retrieved articles rarely had control
 423 over the salvage logging process. This quality aspect is relevant from the point of view of
 16

- Eliminado: could
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429 susceptibility to bias and it should be considered in subsequent systematic reviews.
430 Although we did not use this criterion to reject studies in this systematic map, we did
431 record whether the spatial units where the intervention and the comparator were established
432 were chosen by the researchers (see Systematic map database, below).

433 3. Empirical studies without true replication or at inappropriate spatial scales. Studies
434 with pseudo-replicated designs were placed in this category. One of the most frequent cases
435 was that of one disturbance event affecting a reserve (unsalvaged comparator) and adjacent,
436 unprotected forest (salvaged intervention area). Such designs are highly susceptible to
437 confounding factors related to the management history and objectives of the different
438 management (“treatment”) units and hence to bias, so we decided to exclude such studies
439 from the systematic map. As a matter of consistency, we also eliminated all other studies
440 that contained only one true replicate unit per treatment. It should be noted that in some
441 studies, the degree of true replication was very hard to assess from the study site
442 descriptions, and in other cases there was ambiguity in what could be considered true
443 replication. In such cases, other articles from the same sites were assessed and, where
444 necessary, authors were contacted to clarify their study designs.

445 **Systematic map database and data coding strategy**

446 We constructed a database with information relative to each publication, which
447 included bibliographic information and data [related](#) to the secondary research questions.
448 This encompassed data on stand, disturbance and salvage logging characteristics, study

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

452

453 Calculations and graphical output were produced in R version 3.3.1 (R Core Team
 454 2016).

455

456 **Results and discussion**

457 **Literature searches**

458 We retrieved 4341 publications from the primary searches (Fig 2). A total of 274
 459 publications was assessed at full-text length, and 90 were kept in this systematic map (Fig
 460 2; see Supplementary Table S2 for publications excluded at this stage and the reasons for
 461 exclusion). For detailed descriptions of the results of the literature searches and screening,
 462 see Appendix A2. The remainder of the systematic map is primarily grounded on the 90
 463 publications that were kept, which are included in the systematic map database
 464 (Supplementary Table S3).

465 The following results are presented at the level we considered most relevant for each
 466 addressed characteristic: some at the level of publications (n = 90), others at the level of
 467 studies (n = 49) (see Appendix A1), and others at the level of stand types within study sites
 468 or within publications (for example, in cases where more than one stand was addressed in a

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Eliminado: 739 of these had a potentially relevant title

Eliminado: These and an additional 58 publications retrieved in the secondary searches were screened at the abstract level.

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481 single study; $n > 49$). The level of each result is always indicated in the text, and the
 482 database allows assessing any data at any desired level.

483 **Origin and distribution of publications**

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

487 The 90 publications resulted from 49 studies, including studies with multiple study
 488 sites. Individual studies produced an average of 1.8 ± 1.2 publications (mean \pm SD; range:
 489 1-6), although it should be noted that not all publications from all studies are included in
 490 this systematic map [e.g. some papers from the Bavarian Forest National Park in Germany
 491 that dealt with salvage logging effects on biodiversity were excluded (Beudert et al. 2015,
 492 Thorn et al. 2015a, 2015b)]. Studies were generally established within one clearly defined
 493 study area, such as a publicly owned forest (e.g., National Forest) with adjacent private
 494 forestland, but eight studies (yielding 12 publications) either addressed two or more study
 495 sites that were located in different regions (separated by more than 100 km; e.g.
 496 Wagenbrenner et al., 2015) or had a sampling design of regional scale, with multiple sites
 497 (e.g. Priewasser et al., 2013) (Table 1).

498 The publications included in the database were overwhelmingly concentrated in North
 499 America and Europe, with only two publications from another continent and no
 500 representation from the tropics or the Southern Hemisphere (Fig 4; Table 1). Even within
 501 these two geographic clusters, the publications were not equally distributed. In North

Eliminado: (those found in Scopus were either repeated or excluded), 1 from the secondary searches (US Forest Service website), and 8 from the supplementary searches (article reference lists)

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Movido (inserción) [3]

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515 America, there were nearly twice as many publications from the U.S.A than from Canada,
516 and even publications from Canada were more abundant than those from all Europe (where
517 half of the publications came from Spain). One could predict that studies on
518 post-disturbance logging would occur more frequently in places where more natural
519 disturbance occurs, or where natural disturbance is more often followed by logging.
520 However, disturbances are common across forests globally (Seidl et al. 2017), and there is
521 no obvious reason to consider that the countries not included in the systematic map lack
522 salvage logging.

523 A possible explanation for the paucity of studies in the tropics lies in differences in
524 human-related causes and consequences of disturbances across regions. Disturbances like
525 wildfire in regions at the frontline of land-use change, such as many tropical regions, often
526 constitute an instrument for deforestation and land conversion rather than a natural process
527 followed by regeneration. In contrast, developed countries have generally reached more
528 stable land uses, so that disturbed forests will be expected to regrow, either for production
529 or for nature conservation. In this way, assessing the effects of salvage logging on
530 ecosystems makes more sense in cases where management or conservation objectives are to
531 maintain forest cover, as is more often the case in Europe and North America than in other
532 regions. Even in the few exceptions where salvage logging was addressed in tropical areas,
533 the research was conducted by foreign researchers (Van Nieuwstadt et al. 2001). Most of
534 the studies outside these two zones, including studies in Chile (Smith-Ramírez et al. 2014)
535 and Australia (Blair et al. 2016), failed to pass the inclusion criteria regarding the relevance
536 of response variables. Other non-mutually exclusive reasons for the predominance of

20

537 [European and North American studies, as highlighted in a systematic map on active](#)
538 [interventions for biodiversity conservation \(Bernes et al. 2015\), are: a\) the large extents of](#)
539 [forest, b\) the greater abundance of researchers and availability of funding, and c\) the large](#)
540 [emphasis on research in ecology and environmental management in Europe and North](#)
541 [America. Finally, an important factor could be the language selected for the literature](#)
542 [search –English–, which was originally aimed at identifying scientific studies from over the](#)
543 [world but was biased against studies from nations where English is either not the official](#)
544 [language or not spoken at a sufficient level of proficiency to facilitate publication in](#)
545 [indexed journals.](#)

546 **Disturbance characteristics**

547 [Wildfire was the most frequent disturbance type, with 51 publications \(27 studies\),](#)
548 [followed by wind \(26 publications, 12 studies\), and insect outbreaks \(13 publications, 11](#)
549 [studies\).](#) [McIver and Starr \(2000\) conducted a review that highlighted several mechanisms](#)
550 [through which burnt forests could be particularly vulnerable to subsequent logging](#)
551 [disturbance, including effects on burnt soil and vegetation. This review also noted a lack of](#)
552 [empirical evidence regarding the consequences of post-fire logging, which triggered](#)
553 [numerous research projects on logging after wildfire \[e.g., McIver and McNeil \(2006\),](#)
554 [Donato et al. \(2006\), Castro et al. \(2010\)\]. Wildfire produces some unique ecological](#)
555 [responses, such as significant reductions in small-diameter aboveground biomass, as well](#)
556 [as direct and indirect wildlife mortality. Wildfire also generates direct impacts on people](#)
557 [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).

Movido (inserción) [4]

566 likely generated more public and political demand for understanding the various
567 implications of wildfire as compared to windstorms or insect outbreaks, including impacts
568 related to subsequent salvage logging. However, logging after large storms (e.g., Kramer et
569 al. 2014), and after massive insect outbreaks (e.g., Collins et al. 2011), has recently
570 attracted increasing attention. The three kinds of disturbances addressed here have
571 increased –and will likely continue to increase– in frequency and extent due to climate
572 change and other factors related to ecosystem conversion and changes in land-use intensity
573 (Seidl et al. 2017). Addressing questions related to post-disturbance management is a
574 logical response to increasingly prevalent situations.

575 Many ecological responses to disturbances largely depend on disturbance severity,
576 which highlights the relevance of studying the response to disturbance, and to subsequent
577 logging, under different degrees of severity. The severity of natural disturbance among the
578 retrieved publications ranged between 10 and 100% (Fig 5A; note the limitations in these
579 data described in the *Systematic map database and coding strategy* section in Appendix
580 A1). We found that wildfire was generally described as having greater disturbance severity
581 than insect outbreaks or windstorms. Studies on logging after wildfire or insect outbreaks
582 were generally tightly clustered at high severity values, whereas disturbance severity by
583 wind was less severe and more variable. Most of the studies included in the systematic map
584 were performed within patches subject to disturbances of specific severity, thereby
585 controlling for this factor as much as possible. In only a few cases (8 out of 49) did the
586 studies directly address disturbance severity as an explanatory variable, either through the
587 selection of stands within different degrees of severity (e.g. Brewer et al., 2012) or by

22

588 [sampling severity gradients within plots \(e.g. Royo et al., 2016\). Although the selection of](#)
589 [plots of different disturbance severity is an appropriate way to increase the robustness of](#)
590 [the study design, it may come at the cost of lower replication. In contrast, measuring](#)
591 [disturbance severity at smaller scales as a covariate can help increase the explanatory power](#)
592 [of management variables without sacrificing replication. Of course, this is not always](#)
593 [possible, and it hinges on the spatial scale at which disturbance severity varies and the](#)
594 [spatial scale required to accurately assess the response variable of interest.](#)

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

609 Intervention characteristics

610 Ecological responses to salvage logging are often considered to vary with the time elapsed
611 between the disturbance and logging, particularly in the case of discrete disturbance events
612 like wildfire. For example, post-fire logging may have greater impact on soils if it is
613 conducted directly after wildfire because it may delay post-fire recovery (Wagenbrenner et
614 al. 2016). If logging occurs during or after the first growing season, natural regeneration
615 can be most severely affected due to the physical destruction of resprouting stems and
616 emerging seedlings (Martínez-Sánchez et al. 1999, Castro et al. 2011). The studies included
617 in the systematic map most often included information on when logging was conducted, yet
618 individual studies did not explicitly test the effect of different timing of salvage logging.

619 Salvage logging took place between immediately and 10.5 years following the disturbance,
620 with an average of 1.8 ± 2.0 (mean \pm 1SD) years across publications. Burnt stands were
621 generally those salvage logged most quickly (after 1.1 ± 0.8 years), followed by
622 wind-affected stands (1.7 ± 0.8 years; Fig 5B). In the case of disturbance by insects, salvage
623 logging often started several years after the beginning of the outbreak, and the variability in
624 the timing of salvage logging was much greater than for the other two disturbance types
625 (4.4 ± 3.7 years). Insect outbreaks most often take several years to develop, during which
626 each tree goes through several stages of decline (Sullivan et al. 2010), and logging can take
627 place at any stage from before the beginning of the outbreak –pre-emptive logging, not
628 addressed here– to logging after several years of infestation. Logging is sometimes
629 conducted in an attempt to prevent the infestation of particular stands or the expansion of
630 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).

635 decay or the accumulation of fuel once the stand has been affected. These are likely reasons
 636 for the greater variability in the timing of salvage logging related to insect outbreaks than
 637 after disturbance by fire or wind.

638 The intensity of salvage logging can be another crucial factor explaining salvage
 639 logging effects, as already identified more than six decades ago (Roy 1956). The studies in
 640 the systematic map included a wide range of salvage logging intensity for the three
 641 disturbance types considered, although intensity was mostly categorised in excess of 90%.

642 Salvage logging intensity ranged between 25 and 100%, and it averaged $80 \pm 24\%$

643 (including up to 4 values per publication). Average intensities were $79 \pm 24\%$ for wildfire,

644 $90 \pm 15\%$ for insect outbreaks, and $79 \pm 27\%$ for wind damage (Fig 5C; as with disturbance

645 severity, note the limitations in these data, described in Appendix A1). In some cases, the

646 effect of different logging intensity was assessed within individual studies; this often

647 included qualitative differences in logging practices such as the removal of slash or the

648 retention of standing dead trees. Notably, in one experimental study, stands under five

649 classes of logging intensity were established, ranging from 0 to 100% (Ritchie et al. 2013).

650 The authors further assessed the effect of amount of basal area retained, which explained

651 the variation in some of the response variables better than the categorical experimental

652 factor (Ritchie et al. 2013). Such studies can provide important insights into the responses

653 to salvage logging and can evaluate the effectiveness of Best Management Practices, as

654 logging –and other disturbances– may not necessarily produce generalizable effects but

655 rather effects that vary nonlinearly according to disturbance intensity or severity (Buma

656 2015, Foster et al. 2016, Leverkus et al. 2018). This has long been acknowledged in

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Eliminado: The intensity of s

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Eliminado: these values of logging intensity represent a broad approximation due to the various ways in which it was measured in the retrieved publications

666 [traditional green-tree silviculture, where the retention forestry approach was created under](#)
667 [the acknowledgement that the effects of commercial clearcutting can be greatly mitigated](#)
668 [by leaving behind structures that favour the continuity of the forest ecosystem \(Gustafsson](#)
669 [et al. 2012, Lindenmayer et al. 2012\).](#) The rapid deterioration of wood quality following
670 [disturbance-induced mortality reduces the profitability of salvage operations compared to](#)
671 [green-tree silviculture, and this could be a limitation for retention approaches. Nevertheless,](#)
672 [the potential benefits of the retention of biological legacies \(Franklin et al. 2000\) during](#)
673 [post-disturbance harvest operations should be more profoundly explored \(Lindenmayer et](#)
674 [al. 2018, Thorn et al. 2018\).](#)

675 [The methods employed in salvage logging operations can also modulate the effect of](#)
676 [the intervention. For example, mechanized harvesting equipment is more likely to compact](#)
677 [soils than manual cutting with chainsaws, but it may also produce novel, positive effects](#)
678 [like forming ruts that fill with water and create persistent aquatic habitat \(Ernst et al. 2016\).](#)

679 Logging operations were often not described well enough in publications included in the
680 [systematic map to identify logging methods, sometimes because the operations were not](#)
681 observed by the researchers. Harvesting with feller-bunchers was mentioned in 15 studies
682 (not publications), and manual cutting in 10 studies. Ground-based yarding was mentioned
683 in 20 studies, and by helicopter in two studies. [Extraction of wood by helicopter is well](#)
684 [known to reduce soil impacts compared to ground-based yarding. However, helicopter use](#)
685 [is extremely costly; this, combined with the low economic value of disturbance-affected](#)
686 [timber and depressed price that typically follow large disturbance events, are likely reasons](#)
687 [for the scant mentions of helicopters.](#)

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690 Stand characteristics

691 Of the 49 studies included in the systematic map, 11 were established in broadleaf forests
692 or included broadleaf stands, 33 were established in or included conifer stands, 10 included
693 mixed stands, and 3 included combinations of stand types without differentiation. In most
694 cases, the stands fell into the “mature” category. There were 37 tree species dominating or
695 co-dominating the stands addressed in the retrieved publications. For further details on the
696 characteristics of stands among the retrieved studies, see Appendix A3.

Eliminado: (stand age, leaf habit, and dominant tree species)

697 **Characteristics of study designs**

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

712 In 11 of the 49 studies, the selection of stands for management intervention was at least
 713 under partial control by the researchers and thus included randomisation in the allocation of
 714 treatments to spatial units. In the rest of the studies, researchers made use of areas that were
 715 either salvaged or left unsalvaged to achieve management objectives rather than to conduct
 716 research. Both approaches provided several advantages and disadvantages.
 717 Non-experimental studies have a risk of bias between intervention and comparator stands,
 718 for example due to the selection of more productive stands, or those nearest to roads, for
 719 salvage operations. Further, the choice not to salvage log particular stands is sometimes
 720 justified by reasons such as fiscal constraints and litigation; stream, hillside, and habitat
 721 protection; or inaccessibility (McGinnis et al. 2010), highlighting the potential for bias.
 722 Still, in non-experimental studies, care was generally taken to select salvaged and
 723 unsalvaged stands of similar pre-disturbance conditions to minimise such bias. In addition,
 724 some studies controlled for random spatial variation by implementing a BACI design –i.e.
 725 by measuring how the response variables changed over time from pre-logging to
 726 post-logging and in stands with and without the salvage logging intervention, thus
 727 providing a robust method for addressing bias. Such a BACI design was implemented in
 728 36% of the 11 studies where salvage logging was performed experimentally, and in 19% of
 729 the 37 non-experimental studies. One good example of experimental design is the one
 730 established after the Summit Fire in Oregon, which included randomisation, blocking,
 731 treatments applied at an appropriate spatial scale, replication, consideration of disturbance
 732 severity and salvage logging intensity, and a BACI sampling design (McIver and Ottmar
 733 2007). Such studies are extremely difficult to implement, as exemplified by one paper that

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Eliminado: , 36% (four studies) employed a Before-After Control-Intervention (BACI) design in at least some part of their sampling

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745 reports the conceptualisation of a randomised complete block design that, however, could
746 not be turned to practice due to legal constraints and which resulted in a pseudo-replicated
747 design comparing salvaged private forest vs unsalvaged public land (Slesak et al. 2015) –
748 hence leading to exclusion from our systematic map.

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

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

771 **Characteristics of the responses**

772 [Studies explicitly focusing on the response of ecosystem services to salvage logging were](#)
 773 [scant. Most publications addressed ecosystem elements and structures, fewer studied](#)
 774 [ecosystem functions, and very few addressed the human well-being component of](#)
 775 [ecosystem services directly \(Fig 1\). This is consistent with the findings of a global literature](#)
 776 [review on ecosystem service studies \(Boerema et al. 2016\), and it highlights the need to](#)
 777 [better address the human component of salvage logging effects to improve the](#)
 778 [transferability of results to management decisions \(Leverkus and Castro 2017\). It should](#)
 779 [also be noted that most of the publications \(79%\) included data on one or two](#)
 780 [measurements of the response variable undertaken at different times, and the maximum was](#)
 781 [20 measurements \(Fig 7, inset\). Four publications included continuous measurements taken](#)
 782 [over 3 or 6 years.](#)

783 The most frequent response variables examined were related to tree regeneration
 784 [\(addressed by 51% of the publications; Fig. 7\)](#). These included the density, basal area,
 785 growth, and survival of trees established after disturbance. This was no surprise, as
 786 establishment of trees is perhaps the most direct indicator of the recovery of the previous
 787 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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Distribution of studies

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808 monitor and rectify tree regeneration failure associated with management activities. In
 809 many situations, lack of appropriate regeneration means that trees would have to be planted,
 810 so that natural regeneration provides direct value for society (Fig 1). In fact, as early as in
 811 1956, a report (Roy 1956) already advised “When you find good reproduction, protect it.
 812 Try to save the high costs of artificial regeneration.”

813 Second in importance were the response variables related to ground cover [\(addressed](#)
 814 [by 42% of publications\)](#). Typically, this would include [vegetation cover](#), a useful measure
 815 of protection from soil erosion or primary productivity. Cover of pits and mounds, as well
 816 as cover of deadwood, may be used as indicators of the microclimatic and
 817 micro-topographic habitat availability and heterogeneity. Bare soil cover could be an
 818 indicator of available seedbed in measurements made right after the disturbance, or of
 819 ground disturbance and lack of regeneration in both early and subsequent measurements.

820 ~~Finally, skid trail cover would indicate soil disturbance and compaction.~~

821 [The third most frequent response variable type was related to the availability and](#)
 822 [characteristics](#) of deadwood [\(addressed by 41% of publications\)](#). This included snags,
 823 downed logs, branches and twigs, often separated by species, size and decay stage.
 824 Deadwood after disturbance is an important component associated with many
 825 post-disturbance specialists, including birds and beetles (Thorn et al. 2018). Standing trees
 826 can act as habitat for species that live in tree hollows (Lindenmayer and Possingham 1996)
 827 and as perches or visual cues for seed dispersers (Castro et al. 2012, Cavallero et al. 2013).
 828 Deadwood constitutes a pool of nutrients that is released to the soil in the mid- and

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833 long-term through decomposition (Marañón-Jiménez and Castro 2013, Molinas González et
834 al. 2017). It can also ameliorate microclimatic conditions to enhance tree regeneration
835 (Castro et al. 2011) and help reduce herbivory by large ungulates (Leverkus et al. 2015b).
836 However, there is also a risk that the wood left behind by disturbance constitutes the means
837 of propagation of a subsequent disturbance such as wildfire or insect outbreaks. As a result,
838 in many studies, the aim of deadwood characterisation was to assess the amount and
839 features of fuels, including the modelling of future fuel characteristics and of potential fire
840 behaviour (McIver and Ottmar 2007, Keyser et al. 2009, Donato et al. 2013, Hood et al.
841 2017). One publication with a chronosequence approach that was excluded from the map
842 for design-related reasons provides a thorough assessment of the time frames at which fuels
843 are enhanced or reduced by salvage logging (Peterson et al. 2015). In fact, risk reduction of
844 subsequent disturbance is one of the main justifications for salvage logging (Müller et al.
845 2018), including fire but also the risk of bark beetle outbreaks after windstorms (Leverkus
846 et al. 2017) and other linked disturbances (Buma 2015). Nevertheless, we identified only
847 two studies addressing resilience to subsequent wildfire as a response variable (Fraver et al.
848 2011, Buma and Wessman 2012). This is likely due to the complex concatenation of
849 disturbance events required to assess such a variable empirically: it requires both
850 intervention and comparator stands to be followed by the same subsequent disturbance and
851 compliance with the additional criteria established in our protocol. Fuel characterisation
852 and modelling of fire behaviour are thus logical ways to address such questions, and our
853 systematic map may have left out relevant studies in this regard. Conversely, the amount of
854 deadwood also can be used as an indicator of the size of the carbon pool in disturbed

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855 ecosystems. The trade-off between C retention and wildfire prevention can be solved by
856 assessing the C cycle directly (Serrano-Ortiz et al. 2011a) or by focusing independently on
857 recalcitrant C pools (large trees, snags, coarse wood, and soil) and labile fuels (understory
858 shrubs, fine wood, and duff) (Powers et al. 2013); the studies in the systematic map
859 generally allow this approach due to the explicit consideration of different size classes.

860 The fourth most frequent type of response variable was non-tree vegetation (beyond
861 mere percent cover values; addressed by 28% of publications). Although we avoided
862 including biodiversity responses in this map due to the existence of a recent review on the
863 topic (Thorn et al. 2018), we did include vegetation as an indicator of the recovery of
864 ecosystem structure, habitat, and soil retention.

865 Next, soil physical and chemical properties (addressed by 26% of publications)
866 included measurements related to soil fertility. The remaining response variable categories
867 were addressed by <15% of the publications (Fig 7). Both erosion control and the
868 abundance of exotic or invasive species were addressed in only six publications, which is
869 surprising given that they constitute some of the core concerns of managers after natural
870 disturbances. Negative results and the absence of invasive species could partially explain
871 the lack of published results on this topic (e.g., Leverkus et al. 2014). Next, non-deadwood
872 C pool was addressed in five studies. Biological indicators of nutrient cycling and riparian
873 ecosystem functioning were addressed in four publications. Again, the latter variable comes
874 as one of the main concerns regarding salvage logging yet with very little research (Karr et
875 al. 2004). This likely has to do with the spatial scale defined for inclusion in the systematic

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879 map (that of salvage logging intervention), which excluded several studies implemented at
 880 the scale of watersheds and with problems of replication. Only one study addressed seed
 881 dispersal and one addressed drinking water quality (perhaps the one publication most
 882 clearly focusing on the human well-being side of the ecosystem services cascade; Fig 1).
 883 Avalanche protection in steep hills is another important ecosystem service affected by
 884 salvage logging (Wohlgemuth et al. 2017), yet it was not included in the systematic map as
 885 a response because the one study addressing it (Schönenberger et al. 2005) lacked
 886 replication.

887 **Conclusions**

888 The systematic map presented here provides a rigorous account of the empirical studies
 889 addressing the effects of salvage logging on supporting and regulating ecosystem services
 890 that fulfil some qualitative requirements. It shows that substantial research has been
 891 conducted in the last two decades, particularly after the publication of an article in Science
 892 in 2004 calling for a careful revision of post-disturbance management practices
 893 (Lindenmayer et al. 2004). Our systematic map is based on a comprehensive and systematic
 894 screening of the scientific literature on post-disturbance logging written in English and
 895 considers a range of stand, disturbance and logging characteristics and of outcomes. It
 896 should help managers and policy makers identify the most relevant studies addressing the
 897 effects of salvage logging and thus spare them the work of searching from scratch. It is also
 898 relevant for scientists who aim to synthesize previous work and it identifies knowledge
 899 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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923 | all continents except Europe and North America. We also found that there has been only
924 | very limited research focusing on the link between ecosystem elements and processes and
925 | the benefits and values for human society, which ultimately define many management
926 | schemes. It should also be noted that very few of the retrieved studies specifically
927 | addressed the effects of deadwood retention. Whereas small-scale retention is nowadays a
928 | well-known practice in green-tree harvesting and much research has been conducted on the
929 | topic (Fedrowitz et al. 2014), the benefits of such practices in disturbed forests are not yet
930 | well known and require substantial additional research (Lindenmayer et al. 2018, Thorn et
931 | al. 2018). Finally, the systematic map identified some areas with substantial research where
932 | systematic review or meta-analysis can be performed:

- 933 | • The effect of salvage logging on recalcitrant vs. labile deadwood components (i.e. C
934 | pool vs. fuel loads) and how these vary over time.
- 935 | • The effect of salvage logging on tree regeneration.
- 936 | • The effect of the time between disturbance and subsequent logging on response
937 | variables.
- 938 | • The effect of disturbance type on the ecological effects of salvage logging.

939

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948 **References**

949 [Millennium Ecosystem Assessment], M. 2003. MA Conceptual Framework. *In*
950 Ecosystems and human well-being: A framework for assessment. Island Press. pp. 25–
951 36. doi:10.1079/PHN2003467.

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

956 Beghin, R., Lingua, E., Garbarino, M., Lonati, M., Bovio, G., Motta, R., and Marzano, R.
957 2010. *Pinus sylvestris* forest regeneration under different post-fire restoration practices
958 in the northwestern Italian Alps. *Ecol. Eng.* **36**(10): 1365–1372. Elsevier B.V.
959 doi:10.1016/j.ecoleng.2010.06.014.

960 Bernes, C., Jonsson, B.G., Junninen, K., Lõhmus, A., Macdonald, E., Müller, J., and
961 Sandström, J. 2015. What is the impact of active management on biodiversity in boreal
962 and temperate forests set aside for conservation or restoration? A systematic map.
963 *Environ. Evid.* **4**(1): 25. BioMed Central. doi:10.1186/s13750-015-0050-7.

- 964 Beschta, R.L., Rhodes, J.J., Kauffman, J.B., Gresswell, R.E., Minshall, G.W., Karr, J.R.,
965 Perry, D.A., Hauer, F.R., and Frissell, C.A. 2004. Postfire management on forested
966 public lands of the Western United States. *Conserv. Biol.* **18**(4): 957–967.
967 doi:10.1111/j.1523-1739.2004.00495.x.
- 968 Beudert, B., Bässler, C., Thorn, S., Noss, R., Schröder, B., Dieffenbach-Fries, H., Foullois,
969 N., and Müller, J. 2015. Bark beetles increase biodiversity while maintaining drinking
970 water quality. *Conserv. Lett.* **8**(4): 272–281. doi:10.1111/conl.12153.
- 971 Blair, D.P., McBurney, L.M., Blanchard, W., Banks, S.C., and Lindenmayer, D.B. 2016.
972 Disturbance gradient shows logging affects plant functional groups more than fire.
973 *Ecol. Appl.*: n/a-n/a. doi:10.1002/eap.1369.
- 974 Boerema, A., Rebelo, A.J., Bodi, M.B., Esler, K.J., and Meire, P. 2016. Are ecosystem
975 services adequately quantified? *J. Appl. Ecol.* **In press**: 10.1111/1365-2664.12696.
976 doi:10.1111/1365-2664.12696.
- 977 Boucher, D., Gauthier, S., Noël, J., Greene, D.F., and Bergeron, Y. 2014. Salvage logging
978 affects early post-fire tree composition in Canadian boreal forest. *For. Ecol. Manage.*
979 **325**: 118–127. Elsevier B.V. doi:10.1016/j.foreco.2014.04.002.
- 980 Brewer, J.S., Bertz, C.A., Cannon, J.B., Chesser, J.D., and Maynard, E.E. 2012. Do natural
981 disturbances or the forestry practices that follow them convert forests to
982 early-successional communities? *Ecol. Appl.* **22**(2): 442–458. doi:10.1890/11-0386.1.
- 983 Buma, B. 2015. Disturbance interactions: characterization, prediction, and the potential for
984 cascading effects. *Ecosphere* **6**(April): Art70. doi:10.1890/ES15-00058.1.

- 985 Buma, B., and Wessman, C.A. 2012. Differential species responses to compounded
986 perturbations and implications for landscape heterogeneity and resilience. *For. Ecol.*
987 *Manage.* **266**: 25–33. Elsevier B.V. doi:10.1016/j.foreco.2011.10.040.
- 988 Castro, J. 2013. Postfire Burnt-Wood Management Affects Plant Damage by Ungulate
989 Herbivores. *Int. J. For. Res.* **2013**: 1–6. doi:10.1155/2013/965461.
- 990 Castro, J., Allen, C.D., Molina-Morales, M., Marañón-Jiménez, S., Sánchez-Miranda, Á.,
991 and Zamora, R. 2011. Salvage logging versus the use of burnt wood as a nurse object
992 to promote post-fire tree seedling establishment. *Restor. Ecol.* **19**(4): 537–544.
993 doi:10.1111/j.1526-100X.2009.00619.x.
- 994 Castro, J., Moreno-Rueda, G., and Hódar, J.A. 2010. Experimental test of postfire
995 management in pine forests: Impact of salvage logging versus partial cutting and
996 nonintervention on bird-species assemblages. *Conserv. Biol.* **24**(3): 810–819.
997 doi:10.1111/j.1523-1739.2009.01382.x.
- 998 Castro, J., Puerta-Piñero, C., Leverkus, A.B., Moreno-Rueda, G., and Sánchez-Miranda, A.
999 2012. Post-fire salvage logging alters a key plant-animal interaction for forest
1000 regeneration. *Ecosphere* **3**(10): art90.
- 1001 Cavallero, L., Raffaele, E., and Aizen, M.A. 2013. Birds as mediators of passive restoration
1002 during early post-fire recovery. *Biol. Conserv.* **158**: 342–350.
1003 doi:10.1016/j.biocon.2012.10.004.
- 1004 CEBC. 2010. Guidelines for Systematic Reviews in Environmental Management Version 4.0.
1005 *In* Environmental Evidence. Bangor, UK.

- 1006 Collins, B.J., Rhoades, C.C., Battaglia, M.A., and Hubbard, R.M. 2012. The effects of bark
1007 beetle outbreaks on forest development, fuel loads and potential fire behavior in
1008 salvage logged and untreated lodgepole pine forests. *For. Ecol. Manage.* **284**: 260–
1009 268. Elsevier B.V. doi:10.1016/j.foreco.2012.07.027.
- 1010 Collins, B.J., Rhoades, C.C., Hubbard, R.M., and Battaglia, M.A. 2011. Tree regeneration
1011 and future stand development after bark beetle infestation and harvesting in Colorado
1012 lodgepole pine stands. *For. Ecol. Manage.* **261**(11): 2168–2175. Elsevier B.V.
1013 doi:10.1016/j.foreco.2011.03.016.
- 1014 Collins, B.J., Rhoades, C.C., Underhill, J., and Hubbard, R.M. 2010. Post-harvest seedling
1015 recruitment following mountain pine beetle infestation of Colorado lodgepole pine
1016 stands: a comparison using historic survey records. *Can. J. For. Res.* **40**(12): 2452–
1017 2456. doi:10.1139/X10-172.
- 1018 Crouzeilles, R., Ferreira, M.S., Chazdon, R.L., Lindenmayer, D.B., Sansevero, J.B.B.,
1019 Monteiro, L., Iribarrem, A., Latawiec, A.E., and Strassburg, B.B.N. 2017. Ecological
1020 restoration success is higher for natural regeneration than for active restoration in
1021 tropical forests. *Sci. Adv.* **3**: 1701345. doi:10.1126/sciadv.1701345.
- 1022 DellaSala, D.A., Karr, J.R., Schoennagel, T., Perry, D., Noss, R.F., Lindenmayer, D.,
1023 Beschta, R., Hutto, R.L., Swanson, M.E., and Evans, J. 2006. Post-fire logging debate
1024 ignores many issues. *Science (80-.)*. **314**(October): 51–52.
- 1025 Donato, D.C., Fontaine, J.B., Campbell, J.L., Robinson, W.D., Kauffman, J.B., and Law,
1026 B.E. 2006. Post-wildfire logging hinders regeneration and increases fire risk. *Science*

- 1027 (80-). **311**: 352. doi:10.1126/science.1127481.
- 1028 Donato, D.C., Simard, M., Romme, W.H., Harvey, B.J., and Turner, M.G. 2013. Evaluating
1029 post-outbreak management effects on future fuel profiles and stand structure in bark
1030 beetle-impacted forests of Greater Yellowstone. *For. Ecol. Manage.* **303**: 160–174.
1031 Elsevier B.V. doi:10.1016/j.foreco.2013.04.022.
- 1032 Ernst, R., Hölting, M., Rodney, K., Benn, V., Thomas-Caesar, R., and Wegmann, M. 2016.
1033 A frog's eye view: logging roads buffer against further diversity loss. *Front. Ecol.*
1034 *Environ.* **14**(7): 353–355.
- 1035 Fedrowitz, K., Koricheva, J., Baker, S.C., Lindenmayer, D.B., Palik, B., Rosenvald, R.,
1036 Beese, W., Franklin, J.F., Kouki, J., Macdonald, E., Messier, C., Sverdrup-Thygeson,
1037 A., and Gustafsson, L. 2014. Can retention forestry help conserve biodiversity? A
1038 meta-analysis. *J. Appl. Ecol.* **51**: 1669–1679. doi:10.1111/1365-2664.12289.
- 1039 Fornwalt, P.J., Rhoades, C.C., Hubbard, R.M., Harris, R.L., Faist, A.M., and Bowman,
1040 W.D. 2017. Short-term response of understory plant communities to salvage logging
1041 in beetle-affected lodgepole pine forests, Colorado, USA. *For. Ecol. Manage.* **409**(July
1042 2017): 84–93. Elsevier. doi:10.1016/j.foreco.2017.10.056.
- 1043 Foster, C.N., Sato, C.F., Lindenmayer, D.B., and Barton, P.S. 2016. Integrating theory into
1044 disturbance interaction experiments to better inform ecosystem management. *Glob.*
1045 *Chang. Biol.* **22**(4): 1325–1335. doi:10.1111/gcb.13155.
- 1046 Francos, M., Pereira, P., Alcañiz, M., and Úbeda, X. 2018. Post-wildfire management
1047 effects on short-term evolution of soil properties (Catalonia, Spain, SW-Europe). *Sci.*

- 1048 Total Environ. **633**: 285–292. Elsevier B.V. doi:10.1016/j.scitotenv.2018.03.195.
- 1049 Franklin, J.F., Lindenmayer, D., Macmahon, J.A., Mckee, A., Perry, D.A., Waide, R., and
1050 Foster, D. 2000. Threads of continuity. *Conserv. Pract.* **1**(1): 8–17.
- 1051 Fraver, S., Jain, T., Bradford, J.B., D’Amato, A.W., Kastendick, D., Palik, B., Shinneman,
1052 D., and Stanovick, J. 2011. The efficacy of salvage logging in reducing subsequent fire
1053 severity in conifer-dominated forests of Minnesota, USA. *Ecol. Appl.* **21**(May 2007):
1054 1895–1901.
- 1055 Greene, D.F., Gauthier, S., Noël, J., Rousseau, M., and Bergeron, Y. 2006. A field
1056 experiment to determine the effect of post-fire salvage on seedbeds and tree
1057 regeneration. *Front. Ecol. Environ.* **4**(2): 69–74.
1058 doi:10.1890/1540-9295(2006)004[0069:AFETDT]2.0.CO;2.
- 1059 Gustafsson, L., Baker, S.C., Bauhus, J., Beese, W.J., Brodie, A., Kouki, J., Lindenmayer,
1060 D.B., Löhmus, A., Martínez Pastur, G., Messier, C., Neyland, M., Palik, B.,
1061 Sverdrup-Thygeson, A., Volney, W.J.A., Wayne, A., and Franklin, J.F. 2012.
1062 Retention forestry to maintain multifunctional forests: A world perspective.
1063 *Bioscience* **62**(7): 633–645. doi:10.1525/bio.2012.62.7.6.
- 1064 Haines-Young, R., and Potschin, M. 2010. The links between biodiversity, ecosystem
1065 services and human well-being. *In Ecosystem Ecology: A new Synthesis. Edited by*
1066 *D.G. Raffaelli and C.L. Frid. Cambridge University Press. pp. 110–139.*
1067 doi:10.1017/CBO9780511750458.007.
- 1068 Hernández-Hernández, R., Castro, J., Del Arco Aguilar, M., Fernández-López, Á.B., and
41

- 1069 González-Mancebo, J.M. 2017. Post-fire salvage logging imposes a new disturbance
1070 that retards succession: The case of bryophyte communities in a Macaronesian laurel
1071 forest. *Forests* **8**(7): 252. doi:10.3390/f8070252.
- 1072 Holzmueller, E.J., and Jose, S. 2012. Response of the invasive grass *Imperata cylindrica* to
1073 disturbance in the southeastern forests, USA. *Forests* **3**(4): 853–863.
1074 doi:10.3390/f3040853.
- 1075 Hood, P.R., Nelson, K.N., Rhoades, C.C., and Tinker, D.B. 2017. The effect of salvage
1076 logging on surface fuel loads and fuel moisture in beetle-infested lodgepole pine
1077 forests. *For. Ecol. Manage.* **390**: 80–88. Elsevier B.V.
1078 doi:10.1016/j.foreco.2017.01.003.
- 1079 James, K.L., Randall, N.P., and Haddaway, N.R. 2016. A methodology for systematic
1080 mapping in environmental sciences. *Environ. Evid.* **5**(1): 7. BioMed Central.
1081 doi:10.1186/s13750-016-0059-6.
- 1082 Johnstone, J.F., Allen, C.D., Franklin, J.F., Frelich, L.E., Harvey, B.J., Higuera, P.E.,
1083 Mack, M.C., Meentemeyer, R.K., Metz, M.R., Perry, G.L.W., Schoennagel, T., and
1084 Turner, M.G. 2016. Changing disturbance regimes, ecological memory, and forest
1085 resilience. *Front. Ecol. Environ.* **14**(7): 369–378. doi:10.1002/fee.1311.
- 1086 Karr, J.R., Rhodes, J.J., Minshall, G.W., Hauer, F.R., Beschta, R.L., Frissell, C.A., and
1087 Perry, D.A. 2004a. The effects of postfire salvage logging on aquatic ecosystems in
1088 the American West. *Bioscience* **54**(11): 1029–1033. doi:10.1641/0006-3568.
- 1089 Karr, J.R., Rhodes, J.J., Minshall, G.W., Hauer, F.R., Beschta, R.L., Frissell, C. a., and
42

- 1090 Perry, D. a. 2004b. The effects of postfire salvage logging on aquatic ecosystems in
1091 the American West. *Bioscience* **54**(11): 1029.
1092 doi:10.1641/0006-3568(2004)054[1029:TEOPSL]2.0.CO;2.
- 1093 Keyser, T.L., Smith, F.W., and Shepperd, W.D. 2009. Short-term impact of post-fire
1094 salvage logging on regeneration, hazardous fuel accumulation, and understory
1095 development in ponderosa pine forests of the Black Hills, SD, USA. *Int. J. Wildl. Fire*
1096 **18**: 451–458. doi:10.1071/WF08004.
- 1097 Kishchuk, B.E., Thiffault, E., Lorente, M., Quideau, S., Keddy, T., and Sidders, D. 2015.
1098 Decadal soil and stand response to fire, harvest, and salvage-logging disturbances in
1099 the western boreal mixedwood forest of Alberta, Canada. *Can. J. For. Res.* **45**: 141–
1100 152.
- 1101 Koricheva, J., Gurevitch, J., and Mengersen, K. (*Editors*). 2013. *Handbook of*
1102 *Meta-analysis in Ecology and Evolution*. Princeton University Press, Princeton and
1103 Oxford.
- 1104 Kramer, K., Brang, P., Bachofen, H., Bugmann, H., and Wohlgemuth, T. 2014. Site factors
1105 are more important than salvage logging for tree regeneration after wind disturbance in
1106 Central European forests. *For. Ecol. Manage.* **331**: 116–128. Elsevier B.V.
1107 doi:10.1016/j.foreco.2014.08.002.
- 1108 Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata,
1109 T., and Safranyik, L. 2008. Mountain pine beetle and forest carbon feedback to climate
1110 change. *Nature* **452**(April): 987–990. doi:10.1038/nature06777.

- 1111 Lee, E.-J., Lee, W.-S., and Rhim, S.-J. 2008. Characteristics of small rodent populations in
1112 post-fire silvicultural management stands within pine forest. *For. Ecol. Manage.*
1113 **255**(5–6): 1418–1422. doi:10.1016/j.foreco.2007.10.055.
- 1114 Leverkus, A.B., and Castro, J. 2017. An ecosystem services approach to the ecological
1115 effects of salvage logging: valuation of seed dispersal. *Ecol. Appl.* **27**(4): 1057–1063.
1116 doi:10.1002/eap.1539.
- 1117 Leverkus, A.B., Gustafsson, L., Rey Benayas, J.M., and Castro, J. 2015a. Does
1118 post-disturbance salvage logging affect the provision of ecosystem services? A
1119 systematic review protocol. *Environ. Evid.* **4**: art16. BioMed Central.
1120 doi:10.1186/s13750-015-0042-7.
- 1121 Leverkus, A.B., Jaramillo-López, P.F., Brower, L.P., Lindenmayer, D.B., and Williams,
1122 E.H. 2017. Mexico's logging threatens butterflies. *Science* (80-.). **358**(6366): 1008.
- 1123 Leverkus, A.B., Lorite, J., Navarro, F.B., Sánchez-Cañete, E.P., and Castro, J. 2014.
1124 Post-fire salvage logging alters species composition and reduces cover, richness, and
1125 diversity in Mediterranean plant communities. *J. Environ. Manage.* **133**: 323–331.
1126 Elsevier Ltd. doi:10.1016/j.jenvman.2013.12.014.
- 1127 Leverkus, A.B., Puerta-Piñero, C., Guzmán-Álvarez, J.R., Navarro, J., and Castro, J. 2012.
1128 Post-fire salvage logging increases restoration costs in a Mediterranean mountain
1129 ecosystem. *New For.* **43**(5–6): 601–613. doi:10.1007/s11056-012-9327-7.
- 1130 Leverkus, A.B., Rey Benayas, J.M., and Castro, J. 2016. Shifting demographic conflicts
1131 across recruitment cohorts in a dynamic post-disturbance landscape. *Ecology* **97**(10):

- 1132 2628–2639.
- 1133 Leverkus, A.B., Rojo, M., and Castro, J. 2015b. Habitat complexity and individual acorn
1134 protectors enhance the post-fire restoration of oak forests via seed sowing. *Ecol. Eng.*
1135 **83**: 276–280. Elsevier B.V. doi:10.1016/j.ecoleng.2015.06.033.
- 1136 Leverkus, A.B., Thorn, S., Gustafsson, L., and Lindenmayer, D.B. 2018. Salvage logging in
1137 the world's forests: Interactions between natural disturbance and logging need
1138 recognition. Under Rev.
- 1139 Lewis, K., and Thompson, D. 2011. Degradation of wood in standing lodgepole pine killed
1140 by mountain pine beetle. *Wood Fiber Sci.* **43**(2): 130–142.
- 1141 Lindenmayer, D., Thorn, S., and Banks, S. 2017. Please do not disturb ecosystems further.
1142 *Nat. Ecol. Evol.* **1**(January): art31. Macmillan Publishers Limited.
1143 doi:10.1038/s41559-016-0031.
- 1144 Lindenmayer, D.B., Burton, P.J., and Franklin, J.F. 2008. Salvage logging and its
1145 ecological consequences. Island Press, Washington, D.C.
- 1146 Lindenmayer, D.B., Foster, D.R., Franklin, J.F., Hunter, M.L., Noss, R.F., Schmiegelow,
1147 F.A., and Perry, D. 2004. Salvage harvesting policies after natural disturbance.
1148 *Science* (80-). **303**(February): 1303.
- 1149 Lindenmayer, D.B., Franklin, J.F., Löhmus, a., Baker, S.C., Bauhus, J., Beese, W.,
1150 Brodie, a., Kiehl, B., Kouki, J., Pastur, G.M., Messier, C., Neyland, M., Palik, B.,
1151 Sverdrup-Thygeson, a., Volney, J., Wayne, a., and Gustafsson, L. 2012. A major
1152 shift to the retention approach for forestry can help resolve some global forest

- 1153 sustainability issues. *Conserv. Lett.* **5**(6): 421–431.
1154 doi:10.1111/j.1755-263X.2012.00257.x.
- 1155 Lindenmayer, D.B., McBurney, L., Blair, D., Wood, J., and Banks, S.C. 2018. From
1156 unburnt to salvage logged: quantifying bird responses to different levels of disturbance
1157 severity. *J. Appl. Ecol.* **In press**.
- 1158 Lindenmayer, D.B., and Noss, R.F. 2006. Salvage logging, ecosystem processes, and
1159 biodiversity conservation. *Conserv. Biol.* **20**(4): 949–958.
1160 doi:10.1111/j.1523-1739.2006.00497.x.
- 1161 Lindenmayer, D.B., and Possingham, H.P. 1996. Ranking Conservation and Timber
1162 Management Options for Leadbeater ' s Possum in Southeastern Australia Using
1163 Population Viability Analysis. *Conserv. Biol.* **10**(1): 235–251.
- 1164 Macdonald, S.E. 2007. Effects of partial post-fire salvage harvesting on vegetation
1165 communities in the boreal mixedwood forest region of northeastern Alberta, Canada.
1166 *For. Ecol. Manage.* **239**(1–3): 21–31. doi:10.1016/j.foreco.2006.11.006.
- 1167 Man, R., Chen, H.Y.H., and Schafer, A. 2013. Salvage logging and forest renewal affect
1168 early aspen stand structure after catastrophic wind. *For. Ecol. Manage.* **308**: 1–8.
1169 Elsevier B.V. doi:10.1016/j.foreco.2013.07.039.
- 1170 Mansuy, N., Thiffault, E., Lemieux, S., Manka, F., Paré, D., and Lebel, L. 2015.
1171 Sustainable biomass supply chains from salvage logging of fire-killed stands: a case
1172 study for wood pellet production in eastern Canada. *Appl. Energy* **154**: 62–73.
1173 Elsevier Ltd, Oxford. doi:10.1016/j.apenergy.2015.04.048.

- 1174 Marañón-Jiménez, S., and Castro, J. 2013. Effect of decomposing post-fire coarse woody
1175 debris on soil fertility and nutrient availability in a Mediterranean ecosystem.
1176 *Biogeochemistry* **112**(1–3): 519–535. doi:10.1007/s10533-012-9744-x.
- 1177 Martín-López, B., Gómez-Baggethun, E., García-Llorente, M., and Montes, C. 2014.
1178 Trade-offs across value-domains in ecosystem services assessment. *Ecol. Indic.*
1179 **37**(PART A): 220–228. Elsevier Ltd. doi:10.1016/j.ecolind.2013.03.003.
- 1180 Martínez-Sánchez, J.J., Ferrandis, P., De las Heras, J., and Herranz, J.M. 1999. Effect of
1181 burnt wood removal on the natural regeneration of *Pinus halepensis* after fire in a pine
1182 forest in Tus valley (SE Spain). *For. Ecol. Manage.* **123**: 1–10.
- 1183 Marzano, R., Garbarino, M., Marcolin, E., Pividori, M., and Lingua, E. 2013. Deadwood
1184 anisotropic facilitation on seedling establishment after a stand-replacing wildfire in
1185 Aosta Valley (NW Italy). *Ecol. Eng.* **51**: 117–122. Elsevier B.V.
1186 doi:10.1016/j.ecoleng.2012.12.030.
- 1187 McGinnis, T.W., Keeley, J.E., Stephens, S.L., and Roller, G.B. 2010. Fuel buildup and
1188 potential fire behavior after stand-replacing fires, logging fire-killed trees and
1189 herbicide shrub removal in Sierra Nevada forests. *For. Ecol. Manage.* **260**(1): 22–35.
1190 Elsevier B.V. doi:10.1016/j.foreco.2010.03.026.
- 1191 McIver, J.D., and McNeil, R. 2006. Soil disturbance and hill-slope sediment transport after
1192 logging of a severely burned site in Northeastern Oregon. *West. J. Appl. For.* **21**: 123–
1193 133.
- 1194 McIver, J.D., and Ottmar, R. 2007. Fuel mass and stand structure after post-fire logging of
47

- 1195 a severely burned ponderosa pine forest in northeastern Oregon. *For. Ecol. Manage.*
1196 **238**(1–3): 268–279. doi:10.1016/j.foreco.2006.10.021.
- 1197 McIver, J.D., and Starr, L. 2000. Environmental effects of postfire logging: Literature
1198 review and annotated bibliography. Gen. Tech. Rep. PNW-GTR-486. Portland, OR:
1199 U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.
- 1200 Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., and The PRISMA Group. 2009.
1201 Preferred reporting items for systematic reviews and meta-analyses: The PRISMA
1202 statement. *PLoS Med.* **6**(7). doi:10.1371/journal.pmed.1000097.
- 1203 Molinas-González, C.R., Leverkus, A.B., Marañón-Jiménez, S., and Castro, J. 2017. Fall
1204 rate of burnt pines across an elevational gradient in a mediterranean mountain. *Eur. J.*
1205 *For. Res.* **136**(3): 401–409. doi:10.1007/s10342-017-1040-9.
- 1206 Molinas González, C., Castro, J., and Leverkus, A.B. 2017. Deadwood decay in a burnt
1207 Mediterranean pine reforestation. *Forests* **8**: art158.
- 1208 Müller, J., Noss, R., Thorn, S., Bässler, C., Leverkus, A.B., and Lindenmayer, D. 2018.
1209 Increasing disturbance demands new policies to conserve intact forest. *Conserv. Lett.*:
1210 e12449. doi:10.1111/conl.12449.
- 1211 Ne'eman, G., Perevolotsky, A., and Schiller, G. 1997. The management implications of the
1212 Mt. Carmel research project. *Int. J. Wildl. Fire* **7**(4): 343–350.
1213 doi:10.1071/WF9970343.
- 1214 Van Nieuwstadt, M.G.. L., Sheil, D., and Kartawinata, K. 2001. The Ecological
1215 Consequences of Logging in the Burned Forests of East Kalimantan, Indonesia.

- 1216 Conserv. Biol. **15**(4): 1183–1186. doi:10.1046/j.1523-1739.2001.0150041183.x.
- 1217 Noss, R.F., Franklin, J.F., Baker, W.L., Schoennagel, T., and Moyle, P.B. 2006. Managing
1218 fire-prone forests in the western United States. *Front. Ecol. Environ.* **4**: 481–487.
- 1219 Noss, R.F., and Lindenmayer, D.B. 2006. The ecological effects of salvage logging after
1220 natural disturbance. *Conserv. Biol.* **20**(4): 946–948.
1221 doi:10.1111/j.1523-1739.2006.00498.x.
- 1222 Pausas, J.G., and Fernández-Muñoz, S. 2012. Fire regime changes in the Western
1223 Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Clim. Change*
1224 **110**(1–2): 215–226.
- 1225 Peterson, D.W., and Dodson, E.K. 2016. Post-fire logging produces minimal persistent
1226 impacts on understory vegetation in northeastern Oregon, USA. *For. Ecol. Manage.*
1227 **370**: 56–64. Elsevier B.V. doi:10.1016/j.foreco.2016.04.004.
- 1228 Peterson, D.W., Dodson, E.K., and Harrod, R.J. 2015. Post-fire logging reduces surface
1229 woody fuels up to four decades following wildfire. *For. Ecol. Manage.* **338**: 84–91.
1230 Elsevier B.V. doi:10.1016/j.foreco.2014.11.016.
- 1231 Powers, E.M., Marshall, J.D., Zhang, J., and Wei, L. 2013. Post-fire management regimes
1232 affect carbon sequestration and storage in a Sierra Nevada mixed conifer forest. *For.*
1233 *Ecol. Manage.* **291**: 268–277. doi:10.1016/j.foreco.2012.07.038.
- 1234 Prestemon, J.P., and Holmes, T.P. 2010. Economic impacts of hurricanes on forest owners.
1235 *In* U S Forest Service Pacific Northwest Research Station General Technical Report
1236 PNW-GTR 802, Part 1. pp. 207–221.

- 1237 Priewasser, K., Brang, P., Bachofen, H., Bugmann, H., and Wohlgemuth, T. 2013. Impacts
1238 of salvage-logging on the status of deadwood after windthrow in Swiss forests. *Eur. J.*
1239 *For. Res.* **132**(2): 231–240. doi:10.1007/s10342-012-0670-1.
- 1240 Puerta-Piñero, C., Sánchez-Miranda, A., Leverkus, A., and Castro, J. 2010. Management of
1241 burnt wood after fire affects post-dispersal acorn predation. *For. Ecol. Manage.*
1242 **260**(3): 345–352. ELSEVIER SCIENCE BV. doi:10.1016/j.foreco.2010.04.023.
- 1243 Pullin, A.S., Knight, T.M., Stone, D.A., and Charman, K. 2004. Do conservation managers
1244 use scientific evidence to support their decision-making? *Biol. Conserv.* **119**(2): 245–
1245 252. doi:10.1016/j.biocon.2003.11.007.
- 1246 Pullin, A.S., and Stewart, G.B. 2006. Guidelines for systematic review in conservation and
1247 environmental management. *Conserv. Biol.* **20**(6): 1647–1656.
1248 doi:10.1111/j.1523-1739.2006.00485.x.
- 1249 R Core Team. 2016. R: A language and environment for statistical computing. R
1250 Foundation for Statistical Computing, Vienna, Austria, R Foundation for Statistical
1251 Computing, Vienna, Austria.
- 1252 Rhoades, C.C., Pelz, K.A., Fornwalt, P.J., Wolk, B.H., and Cheng, A.S. 2018.
1253 Overlapping bark beetle outbreaks, salvage logging and wildfire restructure a
1254 lodgepole pine ecosystem. *Forests* **In press**.
- 1255 Ritchie, M.W., Knapp, E.E., and Skinner, C.N. 2013. Snag longevity and surface fuel
1256 accumulation following post-fire logging in a ponderosa pine dominated forest. *For.*
1257 *Ecol. Manage.* **287**: 113–122. Elsevier B.V. doi:10.1016/j.foreco.2012.09.001.

- 1258 Roy, D.F. 1956. Salvage logging may destroy Douglas-fir reproduction. USDA For. Serv.
1259 Calif. For. Range Exp. Station. For. Res. Notes No. 107: 5.
- 1260 Royo, A.A., Peterson, C.J., Stanovick, J.S., and Carson, W.P. 2016. Evaluating the
1261 ecological impacts of salvage logging: Can natural and anthropogenic disturbances
1262 promote coexistence? *Ecology* **97**(6): 1566–1582. doi:10.1890/15-1093.1.
- 1263 Schelhaas, M.J., Nabuurs, G.J., and Schuck, A. 2003. Natural disturbances in the European
1264 forests in the 19th and 20th centuries. *Glob. Chang. Biol.* **9**: 1620–1633.
1265 doi:10.1046/j.1365-2486.2003.00684.x.
- 1266 Schiermeier, Q. 2016. Pristine forest at risk. *Nature* **530**: 393. doi:10.1038/530394a.
- 1267 Schönenberger, W., Noack, A., and Thee, P. 2005. Effect of timber removal from
1268 windthrow slopes on the risk of snow avalanches and rockfall. *For. Ecol. Manage.*
1269 **213**(1–3): 197–208. doi:10.1016/j.foreco.2005.03.062.
- 1270 Schroeder, L.M., and Lindelöw, A. 2002. Attacks on living spruce trees by the bark beetle
1271 *Ips typographus* (Col . Scolytidae) following a storm-felling: a comparison between
1272 stands with and without removal of wind-felled trees. *Agric.* **4**: 47–56.
- 1273 Secretariat of the Convention on Biological Diversity. 2000. Sustaining life on Earth: How
1274 the Convention on Biological Diversity promotes nature and human well-being. *Secr.*
1275 *Conv. Biol. Divers.*: 14.
- 1276 Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J.,
1277 Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda,
1278 M., Fabrika, M., Nagel, T.A., and Reyser, C.P.O. 2017. Forest disturbances under

- 1279 climate change. *Nat. Clim. Chang.* **7**(6): 395–402. Nature Publishing Group.
1280 doi:10.1038/nclimate3303.
- 1281 Serrano-Ortiz, P., Marañón-Jiménez, S., Reverter, B.R., Sánchez-Cañete, E.P., Castro, J.,
1282 Zamora, R., and Kowalski, A.S. 2011a. Post-fire salvage logging reduces carbon
1283 sequestration in Mediterranean coniferous forest. *For. Ecol. Manage.* **262**(12): 2287–
1284 2296. Elsevier B.V. doi:10.1016/j.foreco.2011.08.023.
- 1285 Serrano-Ortiz, P., Marañón-Jiménez, S., Reverter, B.R., Sánchez-Cañete, E.P., Castro, J.,
1286 Zamora, R., and Kowalski, A.S. 2011b. Post-fire salvage logging reduces carbon
1287 sequestration in Mediterranean coniferous forest. *For. Ecol. Manage.* **262**(12): 2287–
1288 2296. doi:10.1016/j.foreco.2011.08.023.
- 1289 Slesak, R.A., Schoenholtz, S.H., and Evans, D. 2015. Hillslope erosion two and three years
1290 after wildfire, skyline salvage logging, and site preparation in southern Oregon, USA.
1291 *For. Ecol. Manage.* **342**: 1–7. Elsevier B.V. doi:10.1016/j.foreco.2015.01.007.
- 1292 Smith-Ramírez, C., Maturana, V., Gaxiola, A., and Carmona, M. 2014. Salvage logging by
1293 indigenous people in a Chilean conifer forest. *For. Sci.* **60**(6): 1100–1106.
- 1294 Sullivan, T.P., Sullivan, D.S., Lindgren, P.M.F., and Ransome, D.B. 2010. Green-tree
1295 retention and life after the beetle: Stand structure and small mammals 30 years after
1296 salvage harvesting. *Silva Fenn.* **44**(5): 749–774.
- 1297 Sun, Y., Gu, L., Dickinson, R.E., and Zhou, B. 2012. Forest greenness after the massive
1298 2008 Chinese ice storm: integrated effects of natural processes and human
1299 intervention. *Environ. Res. Lett.* **7**(3): 35702. doi:10.1088/1748-9326/7/3/035702.

- 1300 Sutherland, W.J., Pullin, A.S., Dolman, P.M., and Knight, T.M. 2004a. The need for
1301 evidence-based conservation. *Trends Ecol. Evol.* **19**(6): 305–308.
1302 doi:10.1016/j.tree.2004.03.018.
- 1303 Sutherland, W.J., Pullin, A.S., Dolman, P.M., and Knight, T.M. 2004b. The need for
1304 evidence-based conservation. *Trends Ecol. Evol.* **19**(6): 305–8.
1305 doi:10.1016/j.tree.2004.03.018.
- 1306 Thorn, S., Bässler, C., Bernhardt-Römermann, M., Cadotte, M., Heibl, C., Schäfer, H.,
1307 Seibold, S., and Müller, J. 2015a. Changes in the dominant assembly mechanism
1308 drives species loss caused by declining resources. *Ecol. Lett.* **19**(2): 109–215.
1309 doi:10.1111/ele.12548.
- 1310 Thorn, S., Bässler, C., Brandl, R., Burton, P., Cahall, R., Campbell, J.L., Castro, J., Choi,
1311 C.-Y., Cobb, T., Donato, D., Durska, E., Fontaine, J., Gauthier, S., Hebert, C.,
1312 Hothorn, T., Hutto, R., Lee, E.-J., Leverkus, A., Lindenmayer, D., Obrist, M., Rost, J.,
1313 Seibold, S., Seidl, R., Thom, D., Waldron, K., Wermelinger, B., Winter, M.-B.,
1314 Zmihorski, M., and Müller, J. 2018. Impacts of salvage logging on biodiversity – a
1315 meta-analysis. *J. Appl. Ecol.* **55**: 279–289. doi:10.1111/1365-2664.12945.
- 1316 Thorn, S., Bässler, C., Svoboda, M., and Müller, J. 2016. Effects of natural disturbances
1317 and salvage logging on biodiversity – Lessons from the Bohemian Forest. *For. Ecol.*
1318 *Manage.* Elsevier B.V. doi:10.1016/j.foreco.2016.06.006.
- 1319 Thorn, S., Hacker, H.H., Seibold, S., Jehl, H., Bässler, C., and Müller, J. 2015b.
1320 Guild-specific responses of forest Lepidoptera highlight conservation-oriented forest

- 1321 management – Implications from conifer-dominated forests. *For. Ecol. Manage.* **337**:
1322 41–47. Elsevier B.V. doi:10.1016/j.foreco.2014.10.031.
- 1323 Titus, J.H., and Householder, E. 2007. Salvage logging and replanting reduce understory
1324 cover and richness compared to unsalvaged-unplanted sites at Mount St. Helens,
1325 Washington. *West. North Am. Nat.* **67**(2): 219–231.
1326 doi:10.3398/1527-0904(2007)67[219:SLARRU]2.0.CO;2.
- 1327 Turner, M.G. 2010. Disturbance and landscape dynamics in a changing world. *Ecology*
1328 **91**(10): 2833–2849. doi:10.1890/10-0097.1.
- 1329 Wagenbrenner, J.W., MacDonald, L.H., Coats, R.N., Robichaud, P.R., and Brown, R.E.
1330 2015. Effects of post-fire salvage logging and a skid trail treatment on ground cover,
1331 soils, and sediment production in the interior western United States. *For. Ecol.*
1332 *Manage.* **335**: 176–193. Elsevier B.V. doi:10.1016/j.foreco.2014.09.016.
- 1333 Wagenbrenner, J.W., Robichaud, P.R., and Brown, R.E. 2016. Rill erosion in burned and
1334 salvage logged western montane forests: Effects of logging equipment type, traffic
1335 level, and slash treatment. *J. Hydrol.* **541**(Part B): 889–901. Elsevier B.V.
1336 doi:10.1016/j.jhydrol.2016.07.049.
- 1337 Waldron, K., Ruel, J.C., and Gauthier, S. 2013. Forest structural attributes after windthrow
1338 and consequences of salvage logging. *For. Ecol. Manage.* **289**: 28–37. Elsevier B.V.
1339 doi:10.1016/j.foreco.2012.10.006.
- 1340 Waldron, K., Ruel, J.C., Gauthier, S., De Grandpré, L., and Peterson, C.J. 2014. Effects of
1341 post-windthrow salvage logging on microsites, plant composition and regeneration.

- 1342 Appl. Veg. Sci. **17**(2): 323–337. doi:10.1111/avsc.12061.
- 1343 Wohlgemuth, T., Kull, P., and Wüthrich, H. 2002. Disturbance of microsites and early tree
1344 regeneration after windthrow in Swiss mountain forests due to the winter storm Vivian
1345 1990. For. Snow Landsc. Res. **77**(1/2): 17–47.
- 1346 Wohlgemuth, T., Schwitter, R., Bebi, P., Sutter, F., and Brang, P. 2017. Post-windthrow
1347 management in protection forests of the Swiss Alps. Eur. J. For. Res. **136**: 1029–1040.
1348 Springer Berlin Heidelberg. doi:10.1007/s10342-017-1031-x.
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1351 **Tables**

1352

1353 **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

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1356 **Figure captions**

1357 **Figure 1. Ecosystem services cascade illustrated for the case of seed dispersal by**
1358 **European jays (*Garrulus glandarius* L.) within a post-fire management**
1359 **experimental setting.** The diagram shows the link between the biophysical and the
1360 human well-being components of ecosystem services. Particular elements of the
1361 ecosystem perform functions that produce benefits for society via an ecosystem
1362 service. Society places a value on these benefits, whether economic or not. The
1363 resulting value feeds back to affect the ecosystem elements through management
1364 decisions. In the example (shown in the dashed boxes below each component of the
1365 conceptual diagram), burnt snags represent a supporting element for the seed caching
1366 activity of a major seed disperser, whose activity yields natural colonisation of the
1367 burnt area and reduces the economic cost of reforestation. Appreciation of this value
1368 can enhance the likelihood that snags be retained in post-fire management. Figure
1369 adapted from Haines-Young and Potschin (2010), Martín-López et al. (2014), and
1370 Leverkus and Castro (2017). References in the diagram: (1) = Molinas-González et al.
1371 (2017); (2) = Castro et al. (2012); (3) = Leverkus et al. (2016); (4) = Leverkus and
1372 Castro (2017).

1373
1374 **Figure 2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses**
1375 **(PRISMA) diagram.** Shown are the numbers of publications retrieved in the literature
1376 searches and the number excluded in each step. Diagram adapted from Moher et al.
1377 (2009).

1378
1379 **Figure 3. Cumulative number of publications per disturbance type included in**
1380 **this systematic map.**

1381 **Figure 4. Location of the individual studies included in the systematic map.**
1382 Number codes are indicated for reference (column Site_ref in the systematic map
1383 database, Table S3). Inset: Korean Peninsula.

1384

1385 **Figure 5. Disturbance and salvage logging characteristics.** A) Disturbance severity
1386 considered in the analysed publications. This includes 1-3 points per publication,
1387 according to whether one general disturbance severity was reported or the publication
1388 explicitly included sampling areas of different severity levels. B) Time elapsed
1389 between the disturbance and subsequent salvage logging. Each data point represents
1390 one publication. C) Logging intensity in the analysed publications. This includes 1-4
1391 points per publication. Note that this applies to the Intervention only, as each
1392 publication also included a Comparator with 0% logging intensity. In all plots, the
1393 thick horizontal lines are medians, and the boxes indicate the first and third quartiles of
1394 the values. Whiskers are either the minimum/maximum values or 1.5 times the
1395 interquartile range of the data, in which case outliers are shown as points. The values of
1396 disturbance severity and logging intensity are broad approximations. Sample sizes for
1397 the graphics are: for fire 53, 51 and 69 (panels A, B and C, respectively); for insect
1398 outbreaks 15, 13 and 15; and for wind 31, 26 and 21 for wind.

1399

1400 **Figure 6. The number of spatially independent salvage logging replicate units**
1401 **used in the 90 publications, classified by disturbance type.**

1402

1403 **Figure 7. Number of publications that reported different measured response**
1404 **variables, for each disturbance type.** Nutrient= biological indicators of nutrient
1405 cycling; Carbon= non-wood carbon pool; Water= drinking water quality; Erosion= soil

1406 erosion by wind or water; Invasives= Invasive and/or exotic species; Cover= ground
1407 cover, including cover of vegetation; Resilience= capacity to regenerate after
1408 subsequent wildfire (i.e. wildfire after salvage logging); Riparian= riparian ecosystem
1409 functioning; Dispersal= seed dispersal; Soil chem.= soil chemical properties; Soil
1410 phys.= soil physical properties; Deadwood= stand structure and deadwood amount and
1411 characteristics; Temp.= air, water or soil temperature; Regen.= tree regeneration;
1412 Vegetation= Vegetation composition. [Note that biodiversity responses were excluded](#)
1413 [from the systematic map](#). Inset: distribution of publications according to the number of
1414 individual measurements taken for the response variables. Both y axes have the same
1415 meaning.

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1419 **Supporting Information**

1420 Appendix A1. **Systematic map database and data coding strategy**

1421 Appendix A2. **Literature searches and screening –Results**

1422 Appendix A3. **Stand characteristics –Results and Discussion**

1423 Table S1. **Search strings used in the systematic map.**

1424 Table S2. **Publications excluded at full-text screening and reasons for exclusion.**

1425 Table S3. **Systematic Map Database.** For details on coding and variable names, see

1426 Appendix A1.

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Página 11: [1] Eliminado	Alex	30/04/18 16:50
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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?

Página 18: [2] Eliminado	Alex	01/05/18 23:03
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Characteristics of included publications

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

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).

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

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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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.

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

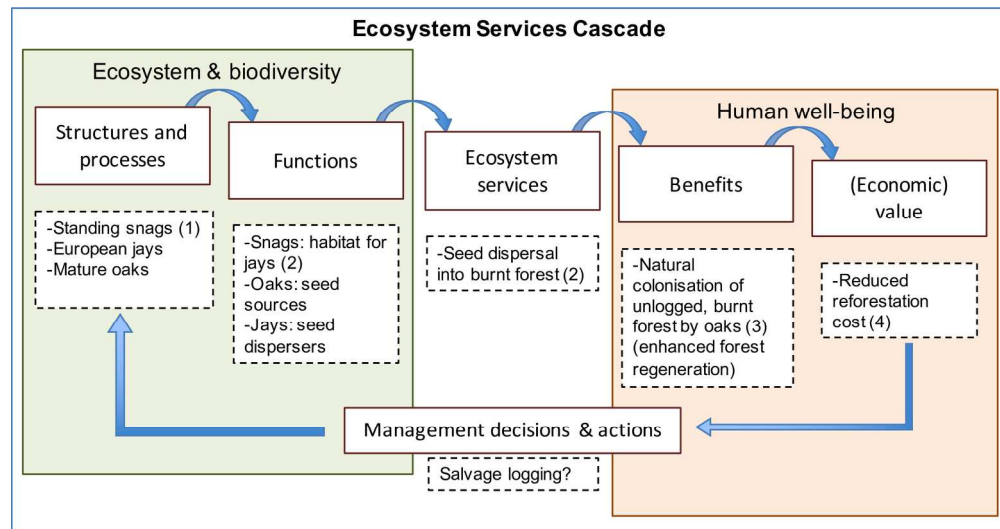
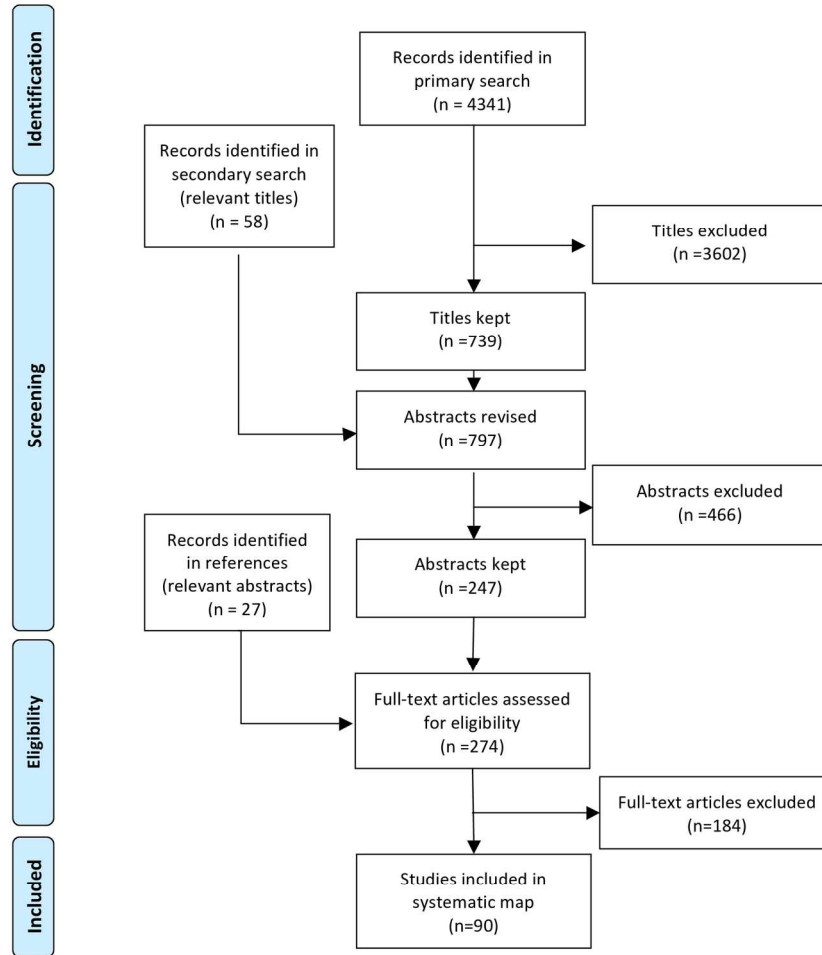


Figure 1. Ecosystem services cascade illustrated for the case of seed dispersal by European jays within a post-fire management experimental setting. The diagram shows the link between the biophysical and the human well-being components of ecosystem services. Particular elements of the ecosystem perform 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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PRISMA 2009 Flow Diagram

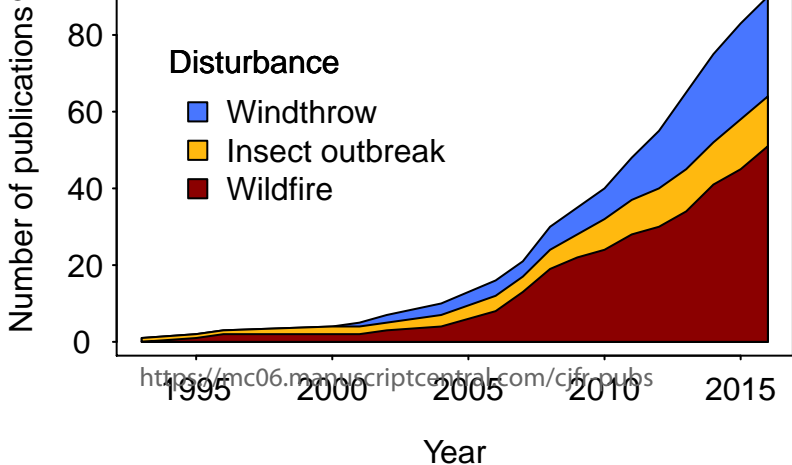


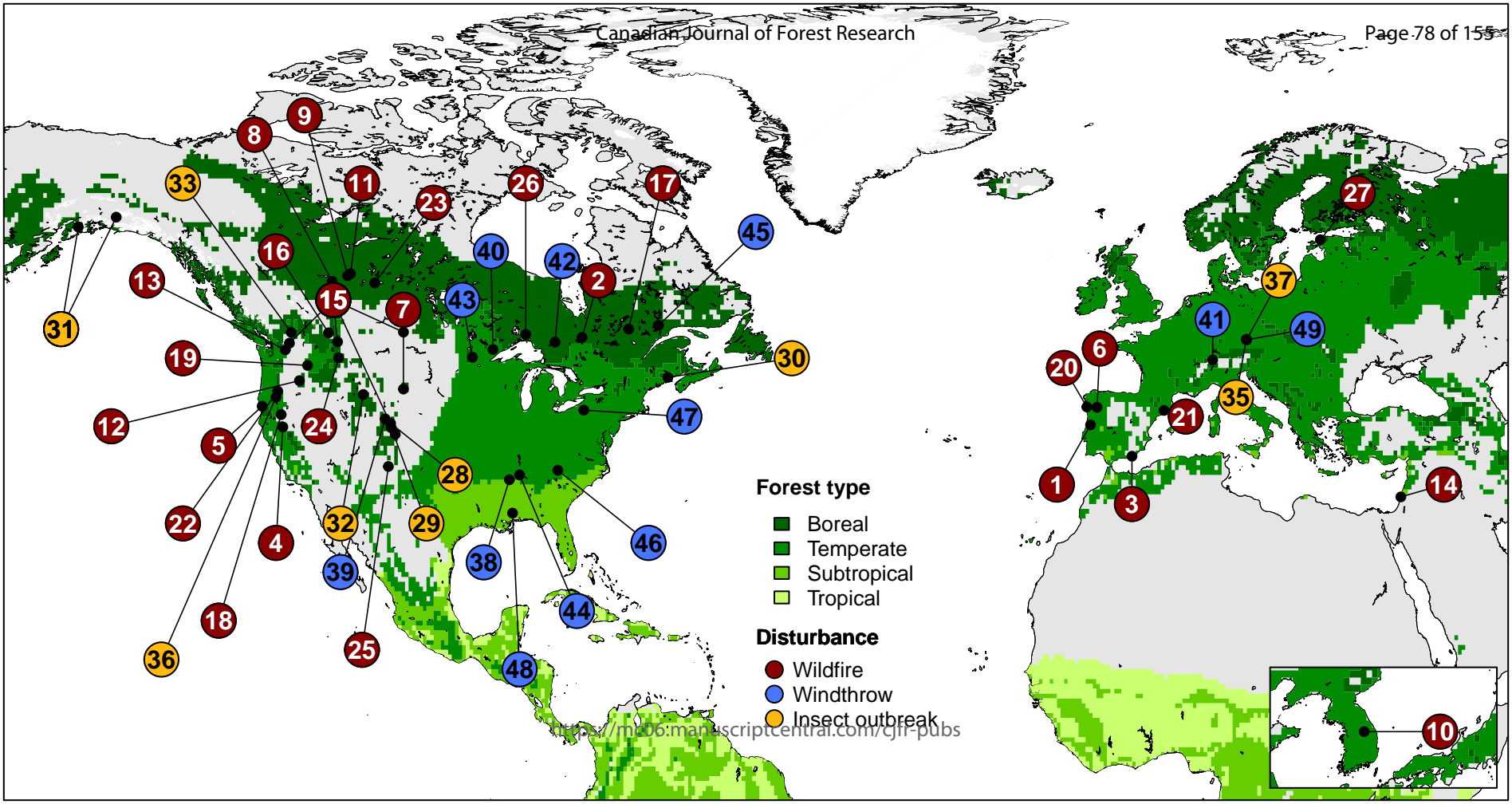
Adapted From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(6): e1000097. doi:10.1371/journal.pmed1000097

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

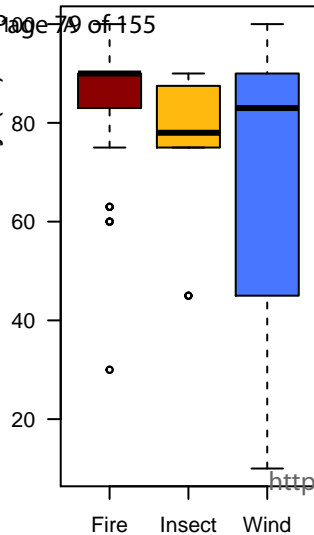
Figure 2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram. Shown are the numbers of publications retrieved in the literature searches and the number excluded in each step. Diagram adapted from Moher et al. (2009).

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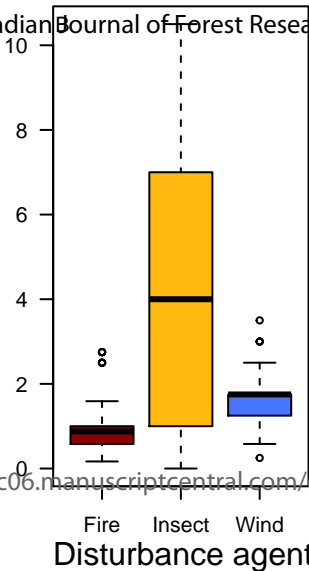




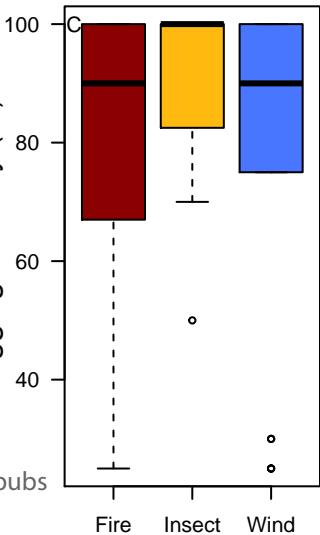
Disturbance severity (%)



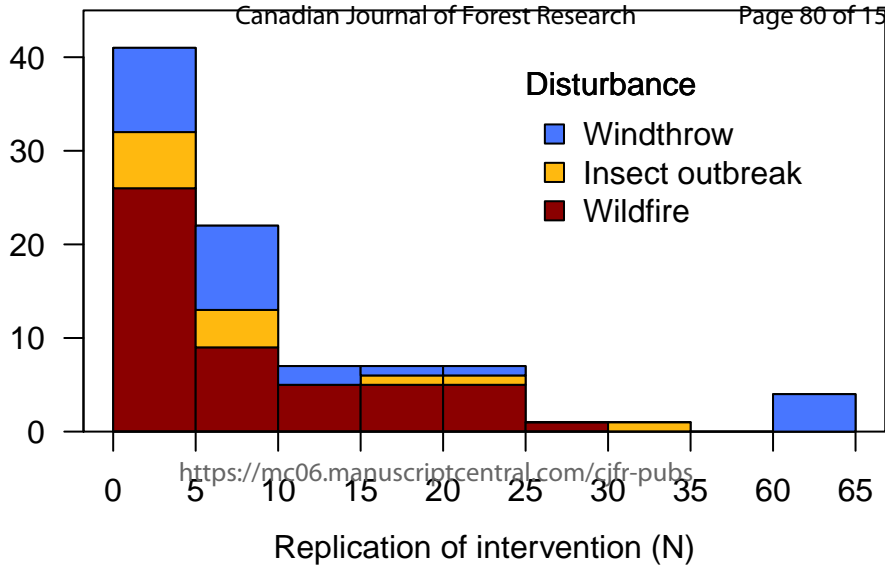
Time disturbance – logging (years)

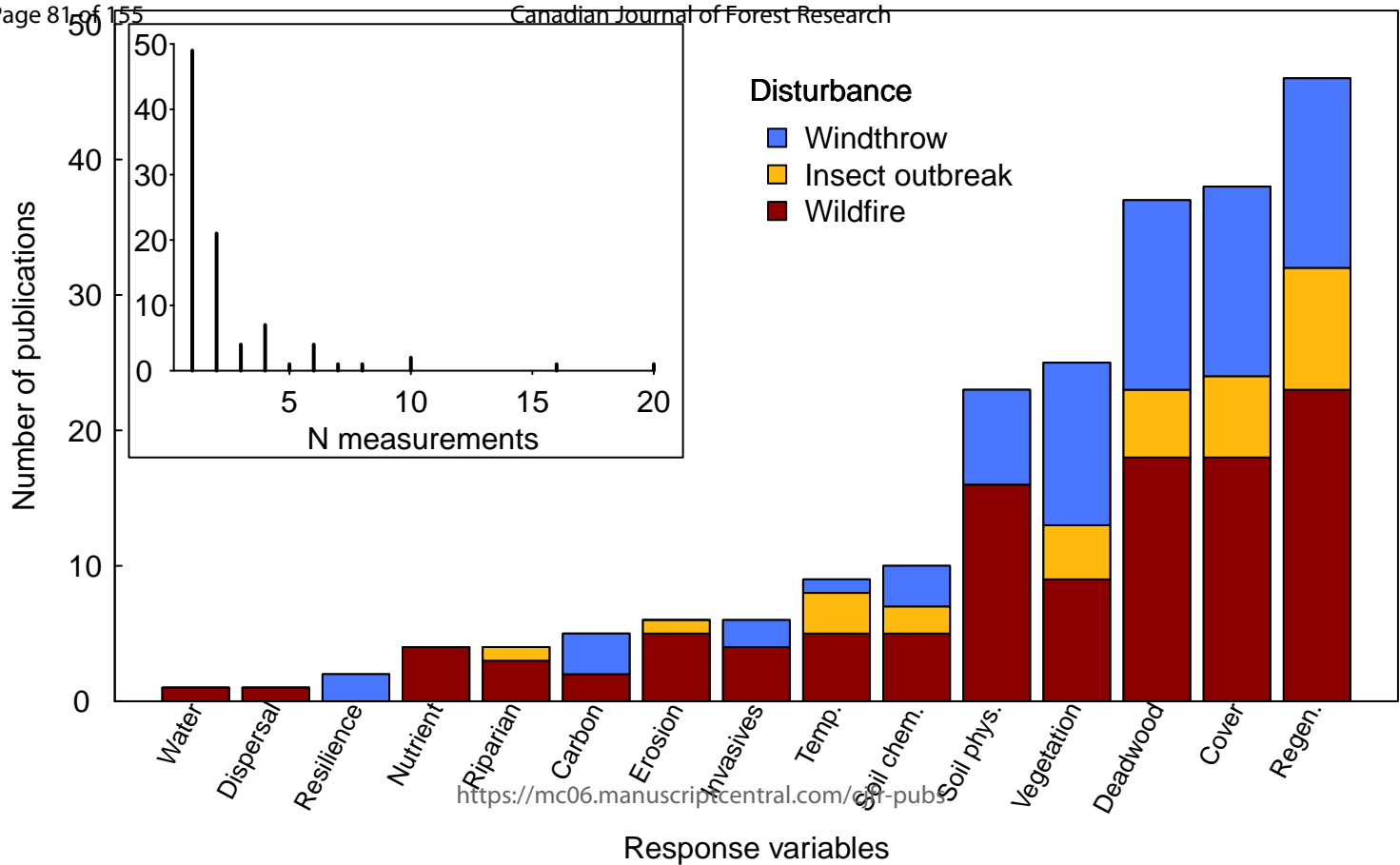


Logging intensity (%)



Number of publications





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.

References

- Castro, J., Puerta-Piñero, C., Leverkus, A.B., Moreno-Rueda, G., and Sánchez-Miranda, A. 2012. Post-fire salvage logging alters a key plant-animal interaction for forest regeneration. *Ecosphere* **3**(10): art90.
- James, K.L., Randall, N.P., and Haddaway, N.R. 2016. A methodology for systematic mapping in environmental sciences. *Environ. Evid.* **5**(1): 7. BioMed Central. doi:10.1186/s13750-016-0059-6.
- Leverkus, A.B., Lorite, J., Navarro, F.B., Sánchez-Cañete, E.P., and Castro, J. 2014. Post-fire salvage logging alters species composition and reduces cover, richness, and diversity in Mediterranean plant communities. *J. Environ. Manage.* **133**: 323–331. Elsevier Ltd. doi:10.1016/j.jenvman.2013.12.014.

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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 $\kappa = 0.47$, indicating only “moderate” agreement among reviewers and thus heterogeneity in the application of inclusion criteria (Landis and Koch 1977). After revising the 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 $\kappa = 0.68$ (ABL & LG), $\kappa = 0.43$ (LG & JC) and $\kappa = 0.43$ (JC & ABL). After discussing the criteria again and reassessing abstract inclusion, the obtained 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.

References

- Landis, J.R., and Koch, G.G. 1977. The measurement of observer agreement for categorical data. *Biometrics* **33**(1): 159–174. doi:10.2307/2529310.
- Thorn, S., Bässler, C., Brandl, R., Burton, P., Cahall, R., Campbell, J.L., Castro, J., Choi, C.-Y., Cobb, T., Donato, D., Durska, E., Fontaine, J., Gauthier, S., Hebert, C., Hothorn, T., Hutto, R., Lee, E.-J., Leverkus, A., Lindenmayer, D., Obrist, M., Rost, J., Seibold, S., Seidl, R., Thom, D., Waldron, K, Wermelinger, B., Winter, M.-B., Zmihorski, M., and Müller, J. 2018. Impacts of salvage logging on biodiversity – a meta-analysis. *J. Appl. Ecol.* **55**: 279–289. doi:10.1111/1365-2664.12945.

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).

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Table A2. Number of studies containing stands of each stand type and age combination

Stand age	Stand type (number of studies)			
	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

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

Dominant tree species	Disturbance type (N of publications)			
	Wildfire	Insect outbreak	Windthrow	Total
<u>Broadleaves</u>				
<i>Acer rubrum</i>	0	0	1	1
<i>Acer saccharum</i>	0	0	1	1
<i>Betula papyrifera</i>	0	1	1	2
<i>Carya</i> spp.	0	0	2	2
<i>Eucalyptus globulus</i>	2	0	0	2
<i>Fagus grandifolia</i>	0	0	1	1
<i>Fagus sylvatica</i>	0	1	4	5
<i>Populus balsamifera</i>	5	1	0	6
<i>Populus</i> spp.	0	0	1	1
<i>Populus tremuloides</i>	12	1	4	17
<i>Prunus serotina</i>	0	0	1	1
<i>Quercus ilex</i>	1	0	0	1
<i>Quercus</i> spp.	0	0	2	2
N species†	4	4	10	13
<u>Conifers</u>				
<i>Abies alba</i>	0	1	3	4
<i>Abies balsamea</i>	0	1	2	3
<i>Abies grandis</i>	1	0	0	1
<i>Abies lasiocarpa</i>	4	0	2	6
<i>Larix occidentalis</i>	1	0	0	1
<i>Picea abies</i>	0	3	4	7
<i>Picea engelmannii</i>	4	0	2	6
<i>Picea glauca</i>	7	1	0	8
<i>Picea mariana</i>	6	1	2	9
<i>Picea</i> spp.	0	1	0	1
<i>Picea x lutzii</i>	0	1	0	1
<i>Pinus banksiana</i>	5	0	4	8
<i>Pinus contorta</i>	7	6	3	16
<i>Pinus densiflora</i>	1	0	0	1
<i>Pinus elliotii</i>	0	0	1	1
<i>Pinus halepensis</i>	2	0	0	2
<i>Pinus nigra</i>	6	0	0	6
<i>Pinus pinaster</i>	11	0	0	11
<i>Pinus ponderosa</i>	12	2	0	14
<i>Pinus</i> spp.	0	1	0	1

<i>Pinus sylvestris</i>	4	0	0	4
<i>Pinus taeda</i>	0	0	2	2
<i>Pseudotsuga menziesii</i>	6	0	0	6
<i>Tsuga mertensiana</i>	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

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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).

References

- Kuuluvainen, T., and Ankala, T. 2011. Natural forest dynamics in boreal Fennoscandia: a review and classification. *Silva Fenn.* **45**(5): 823–841. doi:10.14214/sf.73.
- Leverkus, A.B., Thorn, S., Gustafsson, L., and Lindenmayer, D.B. 2018. Salvage logging in the world's forests: Interactions between natural disturbance and logging need recognition. Under Rev.
- Mayer, P., Brang, P., Dobbertin, M., Hallenbarter, D., Renaud, J.-P., Walthert, L., and Zimmermann, S. 2005. Forest storm damage is more frequent on acidic soils. *Ann. For. Sci.* **62**: 303–311. doi:10.1051/forest.
- Mutch, R.W. 1970. Wildland fires and ecosystems—A hypothesis. *Ecology* **51**(6): 1046–1051.

1 Salvage logging effects on regulating and supporting
2 ecosystem services – A systematic map
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5 Alexandro B. Leverkus^{1*}, José María Rey Benayas¹, Jorge Castro², Dominique Boucher³,
6 Stephen Brewer⁴, Brandon M. Collins⁵, Daniel Donato⁶, Shawn Fraver⁷, Barbara E.
7 Kishchuk⁸, Eun-Jae Lee⁹, David B. Lindenmayer¹⁰, Emanuele Lingua¹¹, Ellen Macdonald¹²,
8 Raffaella Marzano¹³, Charles C. Rhoades¹⁴, Alejandro Royo¹⁵, Simon Thorn¹⁶, Joseph W.
9 Wagenbrenner¹⁷, Kaysandra Waldron¹⁸, Thomas Wohlgemuth¹⁹, Lena Gustafsson²⁰

10 ¹ Departamento de Ciencias de la Vida, UD Ecología, Edificio de Ciencias, Universidad de
11 Alcalá, Alcalá de Henares, Spain. josem.rey@uah.es

12 ² Departamento de Ecología, Facultad de Ciencias, Universidad de Granada, Granada,
13 Spain. jorge@ugr.es

14 ³ Centre de foresterie des Laurentides, Service Canadien des Forêts, Ressources Naturelles
15 Canada, Québec, Québec, Canada. dominique.boucher@canada.ca

16 ⁴ Department of Biology, University of Mississippi, Mississippi, USA.
17 jbrewer@olemiss.edu

18 ⁵ Center for Fire Research and Outreach, University of California Berkeley, California,
19 USA. bcollins@berkeley.edu

20 ⁶ School of Environmental and Forest Sciences, University of Washington, Seattle, WA,
21 USA. daniel.donato@dnr.wa.gov

- 22 ⁷ School of Forest Resources, University of Maine, Orono, Maine, USA.
23 shawn.fraver@maine.edu
- 24 ⁸ Science Policy Integration Branch, Canadian Forest Service, Natural Resources Canada,
25 Ottawa, Ontario, Canada. barbara.kishchuk@canada.ca
- 26 ⁹ Urban Planning Research Group, Daejeon Sejong Research Institute, Jung-gu, Daejeon,
27 Korea. 2lejae@hanmail.net
- 28 ¹⁰ Fenner School of Environment and Society, The Australian National University,
29 Canberra, Australia. David.Lindenmayer@anu.edu.au
- 30 ¹¹ Department TESAF, University of Padova, Legnaro (PD), Italy.
31 emanuele.lingua@unipd.it
- 32 ¹² Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada.
33 emacдона@ualberta.ca
- 34 ¹³ Department DISAFA, University of Torino, Grugliasco (TO), Italy.
35 raffaella.marzano@unito.it
- 36 ¹⁴ Rocky Mountain Research Station, USDA Forest Service, Fort Collins, Colorado, USA.
37 crhoades@fs.fed.us
- 38 ¹⁵ Northern Research Station, USDA Forest Service, Irvine, PA, USA. aroyo@fs.fed.us
- 39 ¹⁶ Field Station Fabrikschleichach, Department of Animal Ecology and Tropical Biology
40 (Zoology III), Julius-Maximilians-University Würzburg, Rauhenebrach, Bavaria,
41 Germany. simon@thornonline.de
- 42 ¹⁷ Pacific Southwest Research Station, USDA Forest Service, Arcata, California, USA.
43 jwagbrenner@fs.fed.us

44 ¹⁸ Department of Wood and Forest Sciences, Université Laval, Québec, QC, Canada.

45 kaysandra.waldron.1@ulaval.ca

46 ¹⁹ Research Unit Forest Dynamics, Swiss Federal Institute for Forest, Snow and Landscape

47 Research WSL, Zuercherstrasse 111, CH-8903 Birmensdorf, Switzerland.

48 thomas.wohlgemuth@wsl.ch

49 ²⁰ Department of Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden.

50 Lena.Gustafsson@slu.se

51

52 * Corresponding author: ABL. Departamento de Ciencias de la Vida, UD Ecología,

53 Edificio de Ciencias, Universidad de Alcalá, Alcalá de Henares, Spain. Tel. +34

54 622689928. E-mail: alexandro.leverkus@uah.es (ABL)

55

56

57 **Abstract**

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

74

75

76 **Introduction**

77 Large, episodic, severe forest disturbances such as those caused by wildfires, insect
78 outbreaks, and windstorms are part of the natural dynamics of forest ecosystems across the
79 world (Noss et al. 2006, Turner 2010, Johnstone et al. 2016). However, the frequency,
80 severity and extent of such disturbances have increased in recent decades due to
81 anthropogenic activity (Seidl et al. 2017) and are predicted to further increase in the future
82 (Schelhaas et al. 2003, Kurz et al. 2008, Pausas and Fernández-Muñoz 2012, Seidl et al.
83 2017). As a result, it is crucial to identify and adopt management strategies that promote
84 regeneration and maintain ecosystem functions of post-disturbance forests, whether through
85 active intervention or passive management (Crouzeilles et al. 2017). A common
86 post-disturbance management approach in many parts of the world is salvage logging, i.e. the
87 widespread felling and removal of the affected trees (McIver and Starr 2000, Lindenmayer et
88 al. 2008, Thorn et al. 2018). Salvage logging has been reported after wildfires (Lindenmayer
89 et al. 2018), volcanic eruptions (Titus and Householder 2007), insect infestations (Thorn et
90 al. 2016), windstorms (Waldron et al. 2014), and ice storms (Sun et al. 2012). It is frequent in
91 disturbed production forests but also common in protected forests in some parts of the world
92 (Schiermeier 2016, Leverkus et al. 2017, Müller et al. 2018). However, there is concern that
93 the additional logging-related disturbance can imperil ecosystem recovery and affect
94 biodiversity and ecosystem services (Karr et al. 2004, Beschta et al. 2004, Donato et al. 2006,
95 Lindenmayer et al. 2008). Besides the mechanical disturbance, salvage logging affects
96 ecosystems through the removal and modification of large amounts of biological legacies –
97 i.e. the organisms, organic materials, and organically-generated environmental patterns that
98 persist through a disturbance and constitute the baseline for post-disturbance recovery and
99 regeneration (Franklin et al. 2000).

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

122 The lack of scientific evidence on the effects of salvage logging was highlighted in 2000
123 (McIver and Starr 2000). In 2004, Lindenmayer and colleagues (Lindenmayer et al. 2004)
124 called for a revision of post-disturbance management policies, arguing that salvage logging
125 can have long-lasting negative effects on biodiversity, undermine the –largely unrecognised–

126 ecological benefits of natural disturbances, and impair ecosystem recovery. Numerous
127 studies were established in subsequent years to assess the ecological consequences of this
128 practice, covering a wide array of disturbance types and severities, biomes, forest
129 compositions, logging methods, and response variables (Thorn et al. 2018). As a result, the
130 above-mentioned motivations for salvage logging have been challenged [e.g. wildfire risk
131 (Donato et al. 2006) and economics (Leverkus et al. 2012)], and many other effects of this
132 practice have been described (e.g. Lindenmayer et al. 2008, Beghin et al. 2010, Priewasser et
133 al. 2013, Wagenbrenner et al. 2015, Hernández-Hernández et al. 2017). Nonetheless, under
134 some circumstances, salvage logging can meet both management and conservation
135 objectives and address societal concerns. For example, post-bark beetle salvage logging
136 lodgepole pine forests in Colorado commonly reduces canopy fuels and regenerates new
137 stands without negatively effecting native plant diversity or soil productivity (Collins et al.
138 2011, 2012, Fornwalt et al. 2017, Rhoades et al. 2018). As a consequence, controversy
139 surrounding salvage logging among managers, environmentalists, politicians and academics,
140 remains lively (Schiermeier 2016, Leverkus et al. 2017, Lindenmayer et al. 2017, Müller et
141 al. 2018).

142

143 The ecological impacts of salvage logging can broadly be categorised according to
144 whether they affect:

- 145 a) The physical structure of ecosystems. An immediate consequence of logging is
146 the reduction in parameters such as standing and downed woody debris, living
147 canopy cover, and habitat structural complexity (Lee et al. 2008, Waldron et al.
148 2013, Peterson et al. 2015).

- 149 b) Particular elements of the biota and species assemblages. The removal of dead
150 wood can affect many species, particularly deadwood-dependent taxa (as
151 concluded in a recent global review on this topic; Thorn et al. 2018).
- 152 c) Forest regeneration capacity. Salvage logging has the potential to alter residual
153 growing stock, soil seed bed, canopy and soil seed banks, and species
154 interactions such as competition, seed dispersal, seed predation, and herbivory
155 (Greene et al. 2006, Collins et al. 2010, Puerta-Piñero et al. 2010, Castro et al.
156 2012, Castro 2013).
- 157 d) Key ecosystem processes and services. Ecosystem services are the benefits that
158 people obtain from ecosystems; they are the link between particular elements of
159 the ecosystem or functions that they perform (i.e. the biophysical component),
160 the benefits that society obtains and, ultimately, the value placed on them (i.e. the
161 human well-being component; Fig 1; Haines-Young and Potschin 2010). They
162 are categorised into provisioning, cultural, regulating, and supporting services
163 (Millennium Ecosystem Assessment 2003). As outlined above, salvage logging
164 is most often conducted to recover the value of the affected wood. In the case of
165 timber and other provisioning services, the human well-being component is often
166 well defined and quantified. However, salvage logging also may affect cultural,
167 regulating and supporting ecosystem services throughout the ecosystem services
168 cascade. This implies that some of the effects outlined in a), b) and c) can also be
169 considered to fall into the category of ecosystem services (Fig 1; Leverkus and
170 Castro 2017). In the case of supporting and regulating services, the biophysical
171 component is usually better understood than the human well-being component
172 (Boerema et al. 2016), and this is likely also the case regarding the responses to
173 salvage logging (Leverkus and Castro 2017).

174

175 Although ecosystem services have seldom been explicitly addressed in the scientific
176 literature on salvage logging, they provide a common framework that allows balancing
177 economic benefits from timber against the wide array of ecological variables that are also
178 affected by post-disturbance management (Leverkus and Castro 2017). This framework
179 represents an Ecosystem Approach (Secretariat of the Convention on Biological Diversity
180 2000), i.e. the consideration of multiple benefits provided by ecosystems –rather than only
181 market values– to guide sustainable management decisions.

182 Salvage logging can affect ecosystem services by altering processes such as soil erosion
183 and hydrological regimes (Wagenbrenner et al. 2016), nutrient cycling (Kishchuk et al.
184 2015), carbon sequestration (Serrano-Ortiz et al. 2011b), seed dispersal (Castro et al. 2012),
185 vegetation cover (Macdonald 2007), tree regeneration (Castro et al. 2011, Marzano et al.
186 2013, Boucher et al. 2014), resistance to invasive species (Holzmueller and Jose 2012),
187 resilience to subsequent disturbances (Fraver et al. 2011), and many others (McIver and Starr
188 2000, Karr et al. 2004, Beschta et al. 2004, Lindenmayer and Noss 2006, Lindenmayer et al.
189 2008). Some authors argue that ecological responses to salvage logging may result in
190 synergistic effects due to the two successive disturbance events (the natural disturbance and
191 then logging) occurring close in time (Van Nieuwstadt et al. 2001, Wohlgemuth et al. 2002,
192 Karr et al. 2004, Lindenmayer et al. 2004, DellaSala et al. 2006, Lindenmayer and Noss
193 2006). Others have found that environmental drivers other than salvage logging are more
194 important in determining ecosystem regeneration (Kramer et al. 2014, Peterson and Dodson
195 2016, Royo et al. 2016, Rhoades et al. 2018). Further, studies often report contradictory
196 results, and there is currently no comprehensive, global assessment of the studies that have
197 addressed salvage logging effects on ecosystem processes.

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

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

217

218 **Materials and methods**

219 We followed the guidelines for systematic reviews in environmental management as
220 prescribed by the Collaboration for Environmental Evidence (CEBC 2010) and several other
221 texts (Sutherland et al. 2004b, Pullin and Stewart 2006, Koricheva et al. 2013, James et al.

222 2016). The Methods described below are an expansion of those presented in our protocol
223 (Leverkus et al. 2015a).

224 **Research question**

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

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

228 This question implies the following key elements:

- 229 • *Population*: Forests affected by one of the following disturbances: windstorms, pest
230 insect outbreaks, or wildfire.
- 231 • *Intervention*: Salvage logging, i.e. the harvesting of trees from areas after disturbance
232 events.
- 233 • *Comparator*: Forests after disturbance where no salvage logging was conducted.
- 234 • *Outcome*: Variables that could be regarded as indicators of regulating or supporting
235 ecosystem services.

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

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

- 240 • type and severity of the disturbance?
- 241 • geographic region?
- 242 • intensity, method, or timing of salvage logging?
- 243 • forest type?

- 244 • type of study design?

245 **Literature searches**

246 The primary literature search was conducted in English in Web of Science (WoS) and
247 Scopus with the aim of answering the primary research question. The terms were searched in
248 titles, abstracts and keywords and were based on the Population and the Intervention. The
249 final search string (Table S1) was established after the scoping exercise described in the
250 protocol (Leverkus et al. 2015a). The search in WoS was initially made on 18 Aug 2015 and
251 updated on 5 May 2017 to encompass all studies published until 31 Dec 2016. In WoS, the
252 search was restricted to the fields of Environmental Sciences and Ecology/ Forestry/
253 Biodiversity Conservation/ Zoology/ Plant Sciences/ Meteorology and Atmospheric
254 Sciences/ Entomology/ Water Resources, and in Scopus to Agricultural and Biological
255 Sciences/ Environmental Science/ Earth and Planetary Sciences/ Multidisciplinary.

256 We performed secondary searches to find other publications, including grey literature,
257 with simplified Population and Intervention terms. These searches were made in the
258 Directory of Open Access Journals (<https://doaj.org/>), the CABI database of forest science
259 (<http://www.cabi.org/forestsience/>), and websites of the Canadian Forest Service
260 (<http://cfs.nrcan.gc.ca/publications>) and the US Forest Service
261 (<http://www.treearch.fs.fed.us/>). We also searched in Google Scholar. For complete search
262 terms, see Table S1.

263 As supplementary bibliographic searches, the reference lists of relevant articles (review
264 articles and books) were screened for additional articles to complement the list of articles

265 identified using the search terms. A list of the publications was sent to all the authors of this
266 systematic map, most of who have research experience on salvage logging. Authors were
267 asked to identify relevant articles that were omitted from the search, and these articles were
268 then assessed against the study inclusion criteria, as described next.

269 **Study inclusion criteria**

270 To be considered for the review, studies had to be empirical and fulfil each of the
271 following inclusion criteria:

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

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

279 c) Relevant comparator: forest disturbed by the same disturbance event but not subject
280 to salvage logging. We did not consider areas of disturbed forest prior to logging as a
281 comparator [i.e. Before-After (BA) study designs], as post-disturbance ecosystems are
282 highly dynamic and the effects of salvage logging could be confounded with the effects of the
283 time elapsed since the disturbance. As comparators, we considered the disturbed but
284 unsalvaged areas of Control-Intervention (CI) and Before-After-Control-Intervention
285 (BACI) designs.

286 d) Relevant outcome: response variable that could broadly be regarded as a regulating
287 or supporting ecosystem service. As it was expected that ecosystem services would rarely be
288 directly addressed, we used variables considered to be indicators or proxies for ecosystem
289 services (e.g. the quality of stream water for water purification, the abundance of seed
290 dispersers for seed dispersal, plant biomass or cover for primary productivity, or the
291 abundance of invasive species for invasion resistance). We also included studies addressing
292 post-disturbance tree regeneration, such as seedling density, survival, and growth.
293 Provisioning ecosystem services such as timber were excluded because they are tightly
294 linked to market conditions, which can vary considerably across locations and time. Rather
295 than neglecting the importance of such ecosystem services (which are a major driver of the
296 decision to salvage log disturbed forests), our intention was to complement the list of
297 ecosystem services that can be affected by this practice. We also excluded cultural services
298 because we expected few studies on this topic. Also, any variables directly related to the
299 number of standing trees were excluded on the basis that the intervention directly aims at
300 their extraction and reductions are thus a logical outcome. Finally, biodiversity was not
301 included in the systematic map because such responses were thoroughly reviewed in a recent
302 meta-analysis (Thorn et al. 2018).

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

305 **Article screening**

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

308 1. Each title was read in the first step, and articles with irrelevant titles were discarded.
309 This step was completed in a conservative way to avoid discarding any potentially relevant
310 publications. Before screening all the titles, two members of the review team (ABL and LG)
311 screened 401 titles and the difference in outcomes was assessed through a kappa test. As the
312 results indicated heterogeneity of application of selection criteria (see Results), the inclusion
313 criteria were discussed again prior to screening all the titles. After screening the titles, the
314 word “salvage” was searched in the titles, keywords and abstracts of all the papers that were
315 recorded as irrelevant based on title. Their titles were screened again under a more inclusive
316 approach, and those considered potentially relevant were re-included for the next step.

317 2. The abstracts of articles with relevant titles were read in the second step, and articles
318 with irrelevant abstracts were discarded. To be classified as relevant in this step, the abstracts
319 had to fulfil the inclusion criteria a), b), and c). In cases where there was doubt about the
320 relevance of a publication, it was kept for the next step. Three authors (ABL, JC, and LG)
321 initially revised 63 randomly-chosen abstracts and kappa tests were again used to assess and
322 improve homogeneity of application of inclusion criteria.

323 3. The articles with potentially relevant abstracts were read in full. At this stage,
324 articles failing to fulfil any one of the study inclusion criteria were discarded. To select
325 studies that fulfilled inclusion criterion d), the main objectives of the studies were assessed as

326 well as the study-site descriptions (including tables and figures). Relevant articles were
327 categorised according to the study quality assessment criteria defined below.

328 **Study quality and validity assessment**

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

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

338 1. Empirical studies with treatments applied at appropriate spatial scales and with true
339 replication at the scale of management operations and with randomised allocation of
340 treatments to spatial units. An appropriate scale was considered as one that would generally
341 be used in post-disturbance management under local conditions, or that would reasonably
342 allow the measured responses to appear.

343 2. Studies as in 1 above, but without randomisation in the allocation of treatments to
344 spatial units. This is often the case, as the authors of the retrieved articles rarely had control
345 over the salvage logging process. This quality aspect is relevant from the point of view of
346 susceptibility to bias and it should be considered in subsequent systematic reviews. Although

347 we did not use this criterion to reject studies in this systematic map, we did record whether
348 the spatial units where the intervention and the comparator were established were chosen by
349 the researchers (see Systematic map database, below).

350 3. Empirical studies without true replication or at inappropriate spatial scales. Studies
351 with pseudo-replicated designs were placed in this category. One of the most frequent cases
352 was that of one disturbance event affecting a reserve (unsalvaged comparator) and adjacent,
353 unprotected forest (salvaged intervention area). Such designs are highly susceptible to
354 confounding factors related to the management history and objectives of the different
355 management (“treatment”) units and hence to bias, so we decided to exclude such studies
356 from the systematic map. As a matter of consistency, we also eliminated all other studies that
357 contained only one true replicate unit per treatment. It should be noted that in some studies,
358 the degree of true replication was very hard to assess from the study site descriptions, and in
359 other cases there was ambiguity in what could be considered true replication. In such cases,
360 other articles from the same sites were assessed and, where necessary, authors were
361 contacted to clarify their study designs.

362 **Systematic map database and data coding strategy**

363 We constructed a database with information relative to each publication, which included
364 bibliographic information and data related to the secondary research questions. This
365 encompassed data on stand, disturbance and salvage logging characteristics, study designs,
366 and the response variables that were measured. For a detailed description of the data included
367 in the systematic map database, see Appendix A1.

368

369 Calculations and graphical output were produced in R version 3.3.1 (R Core Team
370 2016).

371

372 **Results and discussion**

373 **Literature searches**

374 We retrieved 4341 publications from the primary searches (Fig 2). A total of 274
375 publications was assessed at full-text length, and 90 were kept in this systematic map (Fig 2;
376 see Supplementary Table S2 for publications excluded at this stage and the reasons for
377 exclusion). For detailed descriptions of the results of the literature searches and screening,
378 see Appendix A2. The remainder of the systematic map is primarily grounded on the 90
379 publications that were kept, which are included in the systematic map database
380 (Supplementary Table S3).

381 The following results are presented at the level we considered most relevant for each
382 addressed characteristic: some at the level of publications ($n = 90$), others at the level of
383 studies ($n = 49$) (see Appendix A1), and others at the level of stand types within study sites or
384 within publications (for example, in cases where more than one stand was addressed in a
385 single study; $n > 49$). The level of each result is always indicated in the text, and the database
386 allows assessing any data at any desired level.

387 **Origin and distribution of publications**

18

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

391 The 90 publications resulted from 49 studies, including studies with multiple study sites.
392 Individual studies produced an average of 1.8 ± 1.2 publications (mean \pm SD; range: 1-6),
393 although it should be noted that not all publications from all studies are included in this
394 systematic map [e.g. some papers from the Bavarian Forest National Park in Germany that
395 dealt with salvage logging effects on biodiversity were excluded (Beudert et al. 2015, Thorn
396 et al. 2015a, 2015b)]. Studies were generally established within one clearly defined study
397 area, such as a publicly owned forest (e.g., National Forest) with adjacent private forestland,
398 but eight studies (yielding 12 publications) either addressed two or more study sites that were
399 located in different regions (separated by more than 100 km; e.g. Wagenbrenner et al. 2015)
400 or had a sampling design of regional scale, with multiple sites (e.g. Priewasser et al. 2013)
401 (Table 1).

402 The publications included in the database were overwhelmingly concentrated in North
403 America and Europe, with only two publications from another continent and no
404 representation from the tropics or the Southern Hemisphere (Fig 4; Table 1). Even within
405 these two geographic clusters, the publications were not equally distributed. In North
406 America, there were nearly twice as many publications from the U.S.A than from Canada,
407 and even publications from Canada were more abundant than those from all Europe (where
408 half of the publications came from Spain). One could predict that studies on post-disturbance

409 logging would occur more frequently in places where more natural disturbance occurs, or
410 where natural disturbance is more often followed by logging. However, disturbances are
411 common across forests globally (Seidl et al. 2017), and there is no obvious reason to consider
412 that the countries not included in the systematic map lack salvage logging.

413 A possible explanation for the paucity of studies in the tropics lies in differences in
414 human-related causes and consequences of disturbances across regions. Disturbances like
415 wildfire in regions at the frontline of land-use change, such as many tropical regions, often
416 constitute an instrument for deforestation and land conversion rather than a natural process
417 followed by regeneration. In contrast, developed countries have generally reached more
418 stable land uses, so that disturbed forests will be expected to regrow, either for production or
419 for nature conservation. In this way, assessing the effects of salvage logging on ecosystems
420 makes more sense in cases where management or conservation objectives are to maintain
421 forest cover, as is more often the case in Europe and North America than in other regions.
422 Even in the few exceptions where salvage logging was addressed in tropical areas, the
423 research was conducted by foreign researchers (Van Nieuwstadt et al. 2001). Most of the
424 studies outside these two zones, including studies in Chile (Smith-Ramírez et al. 2014) and
425 Australia (Blair et al. 2016), failed to pass the inclusion criteria regarding the relevance of
426 response variables. Other non-mutually exclusive reasons for the predominance of European
427 and North American studies, as highlighted in a systematic map on active interventions for
428 biodiversity conservation (Bernes et al. 2015), are: a) the large extents of forest, b) the greater
429 abundance of researchers and availability of funding, and c) the large emphasis on research in
430 ecology and environmental management in Europe and North America. Finally, an important

431 factor could be the language selected for the literature search –English–, which was
432 originally aimed at identifying scientific studies from over the world but was biased against
433 studies from nations where English is either not the official language or not spoken at a
434 sufficient level of proficiency to facilitate publication in indexed journals.

435 **Disturbance characteristics**

436 Wildfire was the most frequent disturbance type, with 51 publications (27 studies), followed
437 by wind (26 publications, 12 studies), and insect outbreaks (13 publications, 11 studies).
438 McIver and Starr (2000) conducted a review that highlighted several mechanisms through
439 which burnt forests could be particularly vulnerable to subsequent logging disturbance,
440 including effects on burnt soil and vegetation. This review also noted a lack of empirical
441 evidence regarding the consequences of post-fire logging, which triggered numerous
442 research projects on logging after wildfire [e.g., McIver and McNeil (2006), Donato et al.
443 (2006), Castro et al. (2010)]. Wildfire produces some unique ecological responses, such as
444 significant reductions in small-diameter aboveground biomass, as well as direct and indirect
445 wildlife mortality. Wildfire also generates direct impacts on people living in or near
446 fire-prone forests and spectacular images in the media. These factors have likely generated
447 more public and political demand for understanding the various implications of wildfire as
448 compared to windstorms or insect outbreaks, including impacts related to subsequent salvage
449 logging. However, logging after large storms (e.g., Kramer et al. 2014), and after massive
450 insect outbreaks (e.g., Collins et al. 2011), has recently attracted increasing attention. The
451 three kinds of disturbances addressed here have increased –and will likely continue to

452 increase– in frequency and extent due to climate change and other factors related to
453 ecosystem conversion and changes in land-use intensity (Seidl et al. 2017). Addressing
454 questions related to post-disturbance management is a logical response to increasingly
455 prevalent situations.

456 Many ecological responses to disturbances largely depend on disturbance severity,
457 which highlights the relevance of studying the response to disturbance, and to subsequent
458 logging, under different degrees of severity. The severity of natural disturbance among the
459 retrieved publications ranged between 10 and 100% (Fig 5A; note the limitations in these
460 data described in the *Systematic map database and coding strategy* section in Appendix A1).
461 We found that wildfire was generally described as having greater disturbance severity than
462 insect outbreaks or windstorms. Studies on logging after wildfire or insect outbreaks were
463 generally tightly clustered at high severity values, whereas disturbance severity by wind was
464 less severe and more variable. Most of the studies included in the systematic map were
465 performed within patches subject to disturbances of specific severity, thereby controlling for
466 this factor as much as possible. In only a few cases (8 out of 49) did the studies directly
467 address disturbance severity as an explanatory variable, either through the selection of stands
468 within different degrees of severity (e.g. Brewer et al., 2012) or by sampling severity
469 gradients within plots (e.g. Royo et al., 2016). Although the selection of plots of different
470 disturbance severity is an appropriate way to increase the robustness of the study design, it
471 may come at the cost of lower replication. In contrast, measuring disturbance severity at
472 smaller scales as a covariate can help increase the explanatory power of management
473 variables without sacrificing replication. Of course, this is not always possible, and it hinges

474 on the spatial scale at which disturbance severity varies and the spatial scale required to
475 accurately assess the response variable of interest.

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

489 **Intervention characteristics**

490 Ecological responses to salvage logging are often considered to vary with the time elapsed
491 between the disturbance and logging, particularly in the case of discrete disturbance events
492 like wildfire. For example, post-fire logging may have greater impact on soils if it is
493 conducted directly after wildfire because it may delay post-fire recovery (Wagenbrenner et
494 al. 2016). If logging occurs during or after the first growing season, natural regeneration can

495 be most severely affected due to the physical destruction of resprouting stems and emerging
496 seedlings (Martínez-Sánchez et al. 1999, Castro et al. 2011). The studies included in the
497 systematic map most often included information on when logging was conducted, yet
498 individual studies did not explicitly test the effect of different timing of salvage logging.
499 Salvage logging took place between immediately and 10.5 years following the disturbance,
500 with an average of 1.8 ± 2.0 (mean \pm 1SD) years across publications. Burnt stands were
501 generally those salvage logged most quickly (after 1.1 ± 0.8 years), followed by
502 wind-affected stands (1.7 ± 0.8 years; Fig 5B). In the case of disturbance by insects, salvage
503 logging often started several years after the beginning of the outbreak, and the variability in
504 the timing of salvage logging was much greater than for the other two disturbance types (4.4
505 ± 3.7 years). Insect outbreaks most often take several years to develop, during which each
506 tree goes through several stages of decline (Sullivan et al. 2010), and logging can take place
507 at any stage from before the beginning of the outbreak –pre-emptive logging, not addressed
508 here– to logging after several years of infestation. Logging is sometimes conducted in an
509 attempt to prevent the infestation of particular stands or the expansion of insect populations
510 (Müller et al. 2018), and in other cases it is performed to avoid wood decay or the
511 accumulation of fuel once the stand has been affected. These are likely reasons for the greater
512 variability in the timing of salvage logging related to insect outbreaks than after disturbance
513 by fire or wind.

514 The intensity of salvage logging can be another crucial factor explaining salvage logging
515 effects, as already identified more than six decades ago (Roy 1956). The studies in the
516 systematic map included a wide range of salvage logging intensity for the three disturbance
24

517 types considered, although intensity was mostly categorised in excess of 90%. Salvage
518 logging intensity ranged between 25 and 100%, and it averaged $80 \pm 24\%$ (including up to 4
519 values per publication). Average intensities were $79 \pm 24\%$ for wildfire, $90 \pm 15\%$ for insect
520 outbreaks, and $79 \pm 27\%$ for wind damage (Fig 5C; as with disturbance severity, note the
521 limitations in these data, described in Appendix A1). In some cases, the effect of different
522 logging intensity was assessed within individual studies; this often included qualitative
523 differences in logging practices such as the removal of slash or the retention of standing dead
524 trees. Notably, in one experimental study, stands under five classes of logging intensity were
525 established, ranging from 0 to 100% (Ritchie et al. 2013). The authors further assessed the
526 effect of amount of basal area retained, which explained the variation in some of the response
527 variables better than the categorical experimental factor (Ritchie et al. 2013). Such studies
528 can provide important insights into the responses to salvage logging and can evaluate the
529 effectiveness of Best Management Practices, as logging –and other disturbances– may not
530 necessarily produce generalizable effects but rather effects that vary nonlinearly according to
531 disturbance intensity or severity (Buma 2015, Foster et al. 2016, Leverkus et al. 2018). This
532 has long been acknowledged in traditional green-tree silviculture, where the retention
533 forestry approach was created under the acknowledgement that the effects of commercial
534 clearcutting can be greatly mitigated by leaving behind structures that favour the continuity
535 of the forest ecosystem (Gustafsson et al. 2012, Lindenmayer et al. 2012). The rapid
536 deterioration of wood quality following disturbance-induced mortality reduces the
537 profitability of salvage operations compared to green-tree silviculture, and this could be a
538 limitation for retention approaches. Nevertheless, the potential benefits of the retention of

539 biological legacies (Franklin et al. 2000) during post-disturbance harvest operations should
540 be more profoundly explored (Lindenmayer et al. 2018, Thorn et al. 2018).

541 The methods employed in salvage logging operations can also modulate the effect of the
542 intervention. For example, mechanized harvesting equipment is more likely to compact soils
543 than manual cutting with chainsaws, but it may also produce novel, positive effects like
544 forming ruts that fill with water and create persistent aquatic habitat (Ernst et al. 2016).
545 Logging operations were often not described well enough in publications included in the
546 systematic map to identify logging methods, sometimes because the operations were not
547 observed by the researchers. Harvesting with feller-bunchers was mentioned in 15 studies
548 (not publications), and manual cutting in 10 studies. Ground-based yarding was mentioned in
549 20 studies, and by helicopter in two studies. Extraction of wood by helicopter is well known
550 to reduce soil impacts compared to ground-based yarding. However, helicopter use is
551 extremely costly; this, combined with the low economic value of disturbance-affected timber
552 and depressed price that typically follow large disturbance events, are likely reasons for the
553 scant mentions of helicopters.

554 **Stand characteristics**

555 Of the 49 studies included in the systematic map, 11 were established in broadleaf forests or
556 included broadleaf stands, 33 were established in or included conifer stands, 10 included
557 mixed stands, and 3 included combinations of stand types without differentiation. In most
558 cases, the stands fell into the “mature” category. There were 37 tree species dominating or

559 co-dominating the stands addressed in the retrieved publications. For further details on the
560 characteristics of stands among the retrieved studies, see Appendix A3.

561 **Characteristics of study designs**

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

574 In 11 of the 49 studies, the selection of stands for management intervention was at least
575 under partial control by the researchers and thus included randomisation in the allocation of
576 treatments to spatial units. In the rest of the studies, researchers made use of areas that were
577 either salvaged or left unsalvaged to achieve management objectives rather than to conduct
578 research. Both approaches provided several advantages and disadvantages.
579 Non-experimental studies have a risk of bias between intervention and comparator stands, for

580 example due to the selection of more productive stands, or those nearest to roads, for salvage
581 operations. Further, the choice not to salvage log particular stands is sometimes justified by
582 reasons such as fiscal constraints and litigation; stream, hillside, and habitat protection; or
583 inaccessibility (McGinnis et al. 2010), highlighting the potential for bias. Still, in
584 non-experimental studies, care was generally taken to select salvaged and unsalvaged stands
585 of similar pre-disturbance conditions to minimise such bias. In addition, some studies
586 controlled for random spatial variation by implementing a BACI design –i.e. by measuring
587 how the response variables changed over time from pre-logging to post-logging and in stands
588 with and without the salvage logging intervention, thus providing a robust method for
589 addressing bias. Such a BACI design was implemented in 36% of the 11 studies where
590 salvage logging was performed experimentally and in 19% of the 37 non-experimental
591 studies. One good example of experimental design is the one established after the Summit
592 Fire in Oregon, which included randomisation, blocking, treatments applied at an appropriate
593 spatial scale, replication, consideration of disturbance severity and salvage logging intensity,
594 and a BACI sampling design (McIver and Ottmar 2007). Such studies are extremely difficult
595 to implement, as exemplified by one paper that reports the conceptualisation of a randomised
596 complete block design that, however, could not be turned to practice due to legal constraints
597 and which resulted in a pseudo-replicated design comparing salvaged private forest vs
598 unsalvaged public land (Slesak et al. 2015) –hence leading to exclusion from our systematic
599 map.

600 Not all true experimental studies are necessarily ideal, and some can suffer problems of
601 inappropriate spatial scale and lack of replication (e.g., Francos et al. 2018) –but such

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

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

622 **Characteristics of the responses** Studies explicitly focusing on the response of
623 ecosystem services to salvage logging were scant. Most publications addressed ecosystem
624 elements and structures, fewer studied ecosystem functions, and very few addressed the
625 human well-being component of ecosystem services directly (Fig 1). This is consistent with
626 the findings of a global literature review on ecosystem service studies (Boerema et al.
627 2016), and it highlights the need to better address the human component of salvage logging
628 effects to improve the transferability of results to management decisions (Leverkus and
629 Castro 2017). It should also be noted that most of the publications (79%) included data on
630 one or two measurements of the response variable undertaken at different times, and the
631 maximum was 20 measurements (Fig 7, inset). Four publications included continuous
632 measurements taken over 3 or 6 years.

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

643 Second in importance were the response variables related to ground cover (addressed by
644 42% of publications). Typically, this would include vegetation cover, a useful measure of
645 protection from soil erosion or primary productivity. Cover of pits and mounds, as well as
646 cover of deadwood, may be used as indicators of the microclimatic and micro-topographic
647 habitat availability and heterogeneity. Bare soil cover could be an indicator of available
648 seedbed in measurements made right after the disturbance, or of ground disturbance and lack
649 of regeneration in both early and subsequent measurements. Finally, skid trail cover would
650 indicate soil disturbance and compaction.

651 The third most frequent response variable type was related to the availability and
652 characteristics of deadwood (addressed by 41% of publications). This included snags,
653 downed logs, branches and twigs, often separated by species, size and decay stage.
654 Deadwood after disturbance is an important component associated with many
655 post-disturbance specialists, including birds and beetles (Thorn et al. 2018). Standing trees
656 can act as habitat for species that live in tree hollows (Lindenmayer and Possingham 1996)
657 and as perches or visual cues for seed dispersers (Castro et al. 2012, Cavallero et al. 2013).
658 Deadwood constitutes a pool of nutrients that is released to the soil in the mid- and long-term
659 through decomposition (Marañón-Jiménez and Castro 2013, Molinas González et al. 2017).
660 It can also ameliorate microclimatic conditions to enhance tree regeneration (Castro et al.
661 2011) and help reduce herbivory by large ungulates (Leverkus et al. 2015b). However, there
662 is also a risk that the wood left behind by disturbance constitutes the means of propagation of
663 a subsequent disturbance such as wildfire or insect outbreaks. As a result, in many studies,
664 the aim of deadwood characterisation was to assess the amount and features of fuels,

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

686 The fourth most frequent type of response variable was non-tree vegetation (beyond
687 mere percent cover values; addressed by 28% of publications). Although we avoided
688 including biodiversity responses in this map due to the existence of a recent review on the
689 topic (Thorn et al. 2018), we did include vegetation as an indicator of the recovery of
690 ecosystem structure, habitat, and soil retention.

691 Next, soil physical and chemical properties (addressed by 26% of publications) included
692 measurements related to soil fertility. The remaining response variable categories were
693 addressed by <15% of the publications (Fig 7). Both erosion control and the abundance of
694 exotic or invasive species were addressed in only six publications, which is surprising given
695 that they constitute some of the core concerns of managers after natural disturbances.
696 Negative results and the absence of invasive species could partially explain the lack of
697 published results on this topic (e.g., Leverkus et al. 2014). Next, non-deadwood C pool was
698 addressed in five studies. Biological indicators of nutrient cycling and riparian ecosystem
699 functioning were addressed in four publications. Again, the latter variable comes as one of
700 the main concerns regarding salvage logging yet with very little research (Karr et al. 2004).
701 This likely has to do with the spatial scale defined for inclusion in the systematic map (that of
702 salvage logging intervention), which excluded several studies implemented at the scale of
703 watersheds and with problems of replication. Only one study addressed seed dispersal and
704 one addressed drinking water quality (perhaps the one publication most clearly focusing on
705 the human well-being side of the ecosystem services cascade; Fig 1). Avalanche protection in
706 steep hills is another important ecosystem service affected by salvage logging (Wohlgemuth

707 et al. 2017), yet it was not included in the systematic map as a response because the one study
708 addressing it (Schönenberger et al. 2005) lacked replication.

709 **Conclusions**

710 The systematic map presented here provides a rigorous account of the empirical studies
711 addressing the effects of salvage logging on supporting and regulating ecosystem services
712 that fulfil some qualitative requirements. It shows that substantial research has been
713 conducted in the last two decades, particularly after the publication of an article in Science in
714 2004 calling for a careful revision of post-disturbance management practices (Lindenmayer
715 et al. 2004). Our systematic map is based on a comprehensive and systematic screening of the
716 scientific literature on post-disturbance logging written in English and considers a range of
717 stand, disturbance and logging characteristics and of outcomes. It should help managers and
718 policy makers identify the most relevant studies addressing the effects of salvage logging and
719 thus spare them the work of searching from scratch. It is also relevant for scientists who aim
720 to synthesize previous work and it identifies knowledge gaps to help direct future work. For
721 example, we identified a large geographic gap across all continents except Europe and North
722 America. We also found that there has been only very limited research focusing on the link
723 between ecosystem elements and processes and the benefits and values for human society,
724 which ultimately define many management schemes. It should also be noted that very few of
725 the retrieved studies specifically addressed the effects of deadwood retention. Whereas
726 small-scale retention is nowadays a well-known practice in green-tree harvesting and much
727 research has been conducted on the topic (Fedrowitz et al. 2014), the benefits of such

728 practices in disturbed forests are not yet well known and require substantial additional
729 research (Lindenmayer et al. 2018, Thorn et al. 2018). Finally, the systematic map identified
730 some areas with substantial research where systematic review or meta-analysis can be
731 performed:

- 732 • The effect of salvage logging on recalcitrant vs. labile deadwood components (i.e. C
733 pool vs. fuel loads) and how these vary over time.
- 734 • The effect of salvage logging on tree regeneration.
- 735 • The effect of the time between disturbance and subsequent logging on response
736 variables.
- 737 • The effect of disturbance type on the ecological effects of salvage logging.

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745

746 **References**

- 747 [Millennium Ecosystem Assessment], M. 2003. MA Conceptual Framework. *In* Ecosystems
748 and human well-being: A framework for assessment. Island Press. pp. 25–36.
749 doi:10.1079/PHN2003467.
- 750 Águas, A., Ferreira, A., Maia, P., Fernandes, P.M., Roxo, L., Keizer, J., Silva, J.S., Rego,
751 F.C., and Moreira, F. 2014. Natural establishment of *Eucalyptus globulus* Labill. in
752 burnt stands in Portugal. *For. Ecol. Manage.* **323**: 47–56. Elsevier B.V.
753 doi:10.1016/j.foreco.2014.03.012.
- 754 Beghin, R., Lingua, E., Garbarino, M., Lonati, M., Bovio, G., Motta, R., and Marzano, R.
755 2010. *Pinus sylvestris* forest regeneration under different post-fire restoration practices
756 in the northwestern Italian Alps. *Ecol. Eng.* **36**(10): 1365–1372. Elsevier B.V.
757 doi:10.1016/j.ecoleng.2010.06.014.
- 758 Bernes, C., Jonsson, B.G., Junninen, K., Löhmus, A., Macdonald, E., Müller, J., and
759 Sandström, J. 2015. What is the impact of active management on biodiversity in boreal
760 and temperate forests set aside for conservation or restoration? A systematic map.
761 *Environ. Evid.* **4**(1): 25. BioMed Central. doi:10.1186/s13750-015-0050-7.
- 762 Beschta, R.L., Rhodes, J.J., Kauffman, J.B., Gresswell, R.E., Minshall, G.W., Karr, J.R.,
763 Perry, D.A., Hauer, F.R., and Frissell, C.A. 2004. Postfire management on forested
764 public lands of the Western United States. *Conserv. Biol.* **18**(4): 957–967.
765 doi:10.1111/j.1523-1739.2004.00495.x.
- 766 Beudert, B., Bässler, C., Thorn, S., Noss, R., Schröder, B., Dieffenbach-Fries, H., Foullois,
767 N., and Müller, J. 2015. Bark beetles increase biodiversity while maintaining drinking

- 768 water quality. *Conserv. Lett.* **8**(4): 272–281. doi:10.1111/conl.12153.
- 769 Blair, D.P., McBurney, L.M., Blanchard, W., Banks, S.C., and Lindenmayer, D.B. 2016.
770 Disturbance gradient shows logging affects plant functional groups more than fire. *Ecol.*
771 *Appl.*: n/a-n/a. doi:10.1002/eap.1369.
- 772 Boerema, A., Rebelo, A.J., Bodi, M.B., Esler, K.J., and Meire, P. 2016. Are ecosystem
773 services adequately quantified? *J. Appl. Ecol.* **In press**: 10.1111/1365-2664.12696.
774 doi:10.1111/1365-2664.12696.
- 775 Boucher, D., Gauthier, S., Noël, J., Greene, D.F., and Bergeron, Y. 2014. Salvage logging
776 affects early post-fire tree composition in Canadian boreal forest. *For. Ecol. Manage.*
777 **325**: 118–127. Elsevier B.V. doi:10.1016/j.foreco.2014.04.002.
- 778 Brewer, J.S., Bertz, C.A., Cannon, J.B., Chesser, J.D., and Maynard, E.E. 2012. Do natural
779 disturbances or the forestry practices that follow them convert forests to
780 early-successional communities? *Ecol. Appl.* **22**(2): 442–458. doi:10.1890/11-0386.1.
- 781 Buma, B. 2015. Disturbance interactions: characterization, prediction, and the potential for
782 cascading effects. *Ecosphere* **6**(April): Art70. doi:10.1890/ES15-00058.1.
- 783 Buma, B., and Wessman, C.A. 2012. Differential species responses to compounded
784 perturbations and implications for landscape heterogeneity and resilience. *For. Ecol.*
785 *Manage.* **266**: 25–33. Elsevier B.V. doi:10.1016/j.foreco.2011.10.040.
- 786 Castro, J. 2013. Postfire Burnt-Wood Management Affects Plant Damage by Ungulate
787 Herbivores. *Int. J. For. Res.* **2013**: 1–6. doi:10.1155/2013/965461.

- 788 Castro, J., Allen, C.D., Molina-Morales, M., Marañón-Jiménez, S., Sánchez-Miranda, Á.,
789 and Zamora, R. 2011. Salvage logging versus the use of burnt wood as a nurse object to
790 promote post-fire tree seedling establishment. *Restor. Ecol.* **19**(4): 537–544.
791 doi:10.1111/j.1526-100X.2009.00619.x.
- 792 Castro, J., Moreno-Rueda, G., and Hódar, J.A. 2010. Experimental test of postfire
793 management in pine forests: Impact of salvage logging versus partial cutting and
794 nonintervention on bird-species assemblages. *Conserv. Biol.* **24**(3): 810–819.
795 doi:10.1111/j.1523-1739.2009.01382.x.
- 796 Castro, J., Puerta-Piñero, C., Leverkus, A.B., Moreno-Rueda, G., and Sánchez-Miranda, A.
797 2012. Post-fire salvage logging alters a key plant-animal interaction for forest
798 regeneration. *Ecosphere* **3**(10): art90.
- 799 Cavallero, L., Raffaele, E., and Aizen, M.A. 2013. Birds as mediators of passive restoration
800 during early post-fire recovery. *Biol. Conserv.* **158**: 342–350.
801 doi:10.1016/j.biocon.2012.10.004.
- 802 CEBC. 2010. Guidelines for Systematic Reviews in Environmental Management Version 4.0.
803 *In* Environmental Evidence. Bangor, UK.
- 804 Collins, B.J., Rhoades, C.C., Battaglia, M.A., and Hubbard, R.M. 2012. The effects of bark
805 beetle outbreaks on forest development, fuel loads and potential fire behavior in salvage
806 logged and untreated lodgepole pine forests. *For. Ecol. Manage.* **284**: 260–268. Elsevier
807 B.V. doi:10.1016/j.foreco.2012.07.027.
- 808 Collins, B.J., Rhoades, C.C., Hubbard, R.M., and Battaglia, M.A. 2011. Tree regeneration

- 809 and future stand development after bark beetle infestation and harvesting in Colorado
810 lodgepole pine stands. *For. Ecol. Manage.* **261**(11): 2168–2175. Elsevier B.V.
811 doi:10.1016/j.foreco.2011.03.016.
- 812 Collins, B.J., Rhoades, C.C., Underhill, J., and Hubbard, R.M. 2010. Post-harvest seedling
813 recruitment following mountain pine beetle infestation of Colorado lodgepole pine
814 stands: a comparison using historic survey records. *Can. J. For. Res.* **40**(12): 2452–
815 2456. doi:10.1139/X10-172.
- 816 Crouzeilles, R., Ferreira, M.S., Chazdon, R.L., Lindenmayer, D.B., Sansevero, J.B.B.,
817 Monteiro, L., Iribarrem, A., Latawiec, A.E., and Strassburg, B.B.N. 2017. Ecological
818 restoration success is higher for natural regeneration than for active restoration in
819 tropical forests. *Sci. Adv.* **3**: 1701345. doi:10.1126/sciadv.1701345.
- 820 DellaSala, D.A., Karr, J.R., Schoennagel, T., Perry, D., Noss, R.F., Lindenmayer, D.,
821 Beschta, R., Hutto, R.L., Swanson, M.E., and Evans, J. 2006. Post-fire logging debate
822 ignores many issues. *Science* (80-.). **314**(October): 51–52.
- 823 Donato, D.C., Fontaine, J.B., Campbell, J.L., Robinson, W.D., Kauffman, J.B., and Law,
824 B.E. 2006. Post-wildfire logging hinders regeneration and increases fire risk. *Science*
825 (80-.). **311**: 352. doi:10.1126/science.1127481.
- 826 Donato, D.C., Simard, M., Romme, W.H., Harvey, B.J., and Turner, M.G. 2013. Evaluating
827 post-outbreak management effects on future fuel profiles and stand structure in bark
828 beetle-impacted forests of Greater Yellowstone. *For. Ecol. Manage.* **303**: 160–174.
829 Elsevier B.V. doi:10.1016/j.foreco.2013.04.022.

- 830 Ernst, R., Hölting, M., Rodney, K., Benn, V., Thomas-Caesar, R., and Wegmann, M. 2016. A
831 frog's eye view: logging roads buffer against further diversity loss. *Front. Ecol.*
832 *Environ.* **14**(7): 353–355.
- 833 Fedrowitz, K., Koricheva, J., Baker, S.C., Lindenmayer, D.B., Palik, B., Rosenvald, R.,
834 Beese, W., Franklin, J.F., Kouki, J., Macdonald, E., Messier, C., Sverdrup-Thygeson,
835 A., and Gustafsson, L. 2014. Can retention forestry help conserve biodiversity? A
836 meta-analysis. *J. Appl. Ecol.* **51**: 1669–1679. doi:10.1111/1365-2664.12289.
- 837 Fornwalt, P.J., Rhoades, C.C., Hubbard, R.M., Harris, R.L., Faist, A.M., and Bowman, W.D.
838 2017. Short-term response of understory plant communities to salvage logging in
839 beetle-affected lodgepole pine forests, Colorado, USA. *For. Ecol. Manage.* **409**(July
840 2017): 84–93. Elsevier. doi:10.1016/j.foreco.2017.10.056.
- 841 Foster, C.N., Sato, C.F., Lindenmayer, D.B., and Barton, P.S. 2016. Integrating theory into
842 disturbance interaction experiments to better inform ecosystem management. *Glob.*
843 *Chang. Biol.* **22**(4): 1325–1335. doi:10.1111/gcb.13155.
- 844 Francos, M., Pereira, P., Alcañiz, M., and Úbeda, X. 2018. Post-wildfire management effects
845 on short-term evolution of soil properties (Catalonia, Spain, SW-Europe). *Sci. Total*
846 *Environ.* **633**: 285–292. Elsevier B.V. doi:10.1016/j.scitotenv.2018.03.195.
- 847 Franklin, J.F., Lindenmayer, D., Macmahon, J.A., Mckee, A., Perry, D.A., Waide, R., and
848 Foster, D. 2000. Threads of continuity. *Conserv. Pract.* **1**(1): 8–17.
- 849 Fraver, S., Jain, T., Bradford, J.B., D'Amato, A.W., Kastendick, D., Palik, B., Shinneman,
850 D., and Stanovick, J. 2011. The efficacy of salvage logging in reducing subsequent fire

- 851 severity in conifer-dominated forests of Minnesota, USA. *Ecol. Appl.* **21**(May 2007):
852 1895–1901.
- 853 Greene, D.F., Gauthier, S., Noël, J., Rousseau, M., and Bergeron, Y. 2006. A field
854 experiment to determine the effect of post-fire salvage on seedbeds and tree
855 regeneration. *Front. Ecol. Environ.* **4**(2): 69–74.
856 doi:10.1890/1540-9295(2006)004[0069:AFETDT]2.0.CO;2.
- 857 Gustafsson, L., Baker, S.C., Bauhus, J., Beese, W.J., Brodie, A., Kouki, J., Lindenmayer,
858 D.B., Löhmus, A., Martínez Pastur, G., Messier, C., Neyland, M., Palik, B.,
859 Sverdrup-Thygeson, A., Volney, W.J.A., Wayne, A., and Franklin, J.F. 2012. Retention
860 forestry to maintain multifunctional forests: A world perspective. *Bioscience* **62**(7):
861 633–645. doi:10.1525/bio.2012.62.7.6.
- 862 Haines-Young, R., and Potschin, M. 2010. The links between biodiversity, ecosystem
863 services and human well-being. *In Ecosystem Ecology: A new Synthesis. Edited by*
864 *D.G. Raffaelli and C.L. Frid. Cambridge University Press. pp. 110–139.*
865 doi:10.1017/CBO9780511750458.007.
- 866 Hernández-Hernández, R., Castro, J., Del Arco Aguilar, M., Fernández-López, Á.B., and
867 González-Mancebo, J.M. 2017. Post-fire salvage logging imposes a new disturbance
868 that retards succession: The case of bryophyte communities in a Macaronesian laurel
869 forest. *Forests* **8**(7): 252. doi:10.3390/f8070252.
- 870 Holzmueller, E.J., and Jose, S. 2012. Response of the invasive grass *Imperata cylindrica* to
871 disturbance in the southeastern forests, USA. *Forests* **3**(4): 853–863.

- 872 doi:10.3390/f3040853.
- 873 Hood, P.R., Nelson, K.N., Rhoades, C.C., and Tinker, D.B. 2017. The effect of salvage
874 logging on surface fuel loads and fuel moisture in beetle-infested lodgepole pine forests.
875 *For. Ecol. Manage.* **390**: 80–88. Elsevier B.V. doi:10.1016/j.foreco.2017.01.003.
- 876 James, K.L., Randall, N.P., and Haddaway, N.R. 2016. A methodology for systematic
877 mapping in environmental sciences. *Environ. Evid.* **5**(1): 7. BioMed Central.
878 doi:10.1186/s13750-016-0059-6.
- 879 Johnstone, J.F., Allen, C.D., Franklin, J.F., Frelich, L.E., Harvey, B.J., Higuera, P.E., Mack,
880 M.C., Meentemeyer, R.K., Metz, M.R., Perry, G.L.W., Schoennagel, T., and Turner,
881 M.G. 2016. Changing disturbance regimes, ecological memory, and forest resilience.
882 *Front. Ecol. Environ.* **14**(7): 369–378. doi:10.1002/fee.1311.
- 883 Karr, J.R., Rhodes, J.J., Minshall, G.W., Hauer, F.R., Beschta, R.L., Frissell, C.A., and Perry,
884 D.A. 2004a. The effects of postfire salvage logging on aquatic ecosystems in the
885 American West. *Bioscience* **54**(11): 1029–1033. doi:10.1641/0006-3568.
- 886 Karr, J.R., Rhodes, J.J., Minshall, G.W., Hauer, F.R., Beschta, R.L., Frissell, C. a., and Perry,
887 D. a. 2004b. The effects of postfire salvage logging on aquatic ecosystems in the
888 American West. *Bioscience* **54**(11): 1029.
889 doi:10.1641/0006-3568(2004)054[1029:TEOPSL]2.0.CO;2.
- 890 Keyser, T.L., Smith, F.W., and Shepperd, W.D. 2009. Short-term impact of post-fire salvage
891 logging on regeneration, hazardous fuel accumulation, and understory development in
892 ponderosa pine forests of the Black Hills, SD, USA. *Int. J. Wildl. Fire* **18**: 451–458.

- 893 doi:10.1071/WF08004.
- 894 Kishchuk, B.E., Thiffault, E., Lorente, M., Quideau, S., Keddy, T., and Sidders, D. 2015.
- 895 Decadal soil and stand response to fire, harvest, and salvage-logging disturbances in the
- 896 western boreal mixedwood forest of Alberta, Canada. *Can. J. For. Res.* **45**: 141–152.
- 897 Koricheva, J., Gurevitch, J., and Mengersen, K. (*Editors*). 2013. *Handbook of Meta-analysis*
- 898 in Ecology and Evolution. Princeton University Press, Princeton and Oxford.
- 899 Kramer, K., Brang, P., Bachofen, H., Bugmann, H., and Wohlgemuth, T. 2014. Site factors
- 900 are more important than salvage logging for tree regeneration after wind disturbance in
- 901 Central European forests. *For. Ecol. Manage.* **331**: 116–128. Elsevier B.V.
- 902 doi:10.1016/j.foreco.2014.08.002.
- 903 Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata,
- 904 T., and Safranyik, L. 2008. Mountain pine beetle and forest carbon feedback to climate
- 905 change. *Nature* **452**(April): 987–990. doi:10.1038/nature06777.
- 906 Lee, E.-J., Lee, W.-S., and Rhim, S.-J. 2008. Characteristics of small rodent populations in
- 907 post-fire silvicultural management stands within pine forest. *For. Ecol. Manage.* **255**(5–
- 908 6): 1418–1422. doi:10.1016/j.foreco.2007.10.055.
- 909 Leverkus, A.B., and Castro, J. 2017. An ecosystem services approach to the ecological
- 910 effects of salvage logging: valuation of seed dispersal. *Ecol. Appl.* **27**(4): 1057–1063.
- 911 doi:10.1002/eap.1539.
- 912 Leverkus, A.B., Gustafsson, L., Rey Benayas, J.M., and Castro, J. 2015a. Does

- 913 post-disturbance salvage logging affect the provision of ecosystem services? A
914 systematic review protocol. *Environ. Evid.* **4**: art16. BioMed Central.
915 doi:10.1186/s13750-015-0042-7.
- 916 Leverkus, A.B., Jaramillo-López, P.F., Brower, L.P., Lindenmayer, D.B., and Williams,
917 E.H. 2017. Mexico's logging threatens butterflies. *Science* (80-.). **358**(6366): 1008.
- 918 Leverkus, A.B., Lorite, J., Navarro, F.B., Sánchez-Cañete, E.P., and Castro, J. 2014. Post-fire
919 salvage logging alters species composition and reduces cover, richness, and diversity in
920 Mediterranean plant communities. *J. Environ. Manage.* **133**: 323–331. Elsevier Ltd.
921 doi:10.1016/j.jenvman.2013.12.014.
- 922 Leverkus, A.B., Puerta-Piñero, C., Guzmán-Álvarez, J.R., Navarro, J., and Castro, J. 2012.
923 Post-fire salvage logging increases restoration costs in a Mediterranean mountain
924 ecosystem. *New For.* **43**(5–6): 601–613. doi:10.1007/s11056-012-9327-7.
- 925 Leverkus, A.B., Rey Benayas, J.M., and Castro, J. 2016. Shifting demographic conflicts
926 across recruitment cohorts in a dynamic post-disturbance landscape. *Ecology* **97**(10):
927 2628–2639.
- 928 Leverkus, A.B., Rojo, M., and Castro, J. 2015b. Habitat complexity and individual acorn
929 protectors enhance the post-fire restoration of oak forests via seed sowing. *Ecol. Eng.*
930 **83**: 276–280. Elsevier B.V. doi:10.1016/j.ecoleng.2015.06.033.
- 931 Leverkus, A.B., Thorn, S., Gustafsson, L., and Lindenmayer, D.B. 2018. Salvage logging in
932 the world's forests: Interactions between natural disturbance and logging need
933 recognition. Under Rev.

- 934 Lewis, K., and Thompson, D. 2011. Degradation of wood in standing lodgepole pine killed
935 by mountain pine beetle. *Wood Fiber Sci.* **43**(2): 130–142.
- 936 Lindenmayer, D., Thorn, S., and Banks, S. 2017. Please do not disturb ecosystems further.
937 *Nat. Ecol. Evol.* **1**(January): art31. Macmillan Publishers Limited.
938 doi:10.1038/s41559-016-0031.
- 939 Lindenmayer, D.B., Burton, P.J., and Franklin, J.F. 2008. Salvage logging and its ecological
940 consequences. Island Press, Washington, D.C.
- 941 Lindenmayer, D.B., Foster, D.R., Franklin, J.F., Hunter, M.L., Noss, R.F., Schmiegelow,
942 F.A., and Perry, D. 2004. Salvage harvesting policies after natural disturbance. *Science*
943 (80-.). **303**(February): 1303.
- 944 Lindenmayer, D.B., Franklin, J.F., Löhmus, a., Baker, S.C., Bauhus, J., Beese, W., Brodie,
945 a., Kiehl, B., Kouki, J., Pastur, G.M., Messier, C., Neyland, M., Palik, B.,
946 Sverdrup-Thygeson, a., Volney, J., Wayne, a., and Gustafsson, L. 2012. A major
947 shift to the retention approach for forestry can help resolve some global forest
948 sustainability issues. *Conserv. Lett.* **5**(6): 421–431.
949 doi:10.1111/j.1755-263X.2012.00257.x.
- 950 Lindenmayer, D.B., McBurney, L., Blair, D., Wood, J., and Banks, S.C. 2018. From unburnt
951 to salvage logged: quantifying bird responses to different levels of disturbance severity.
952 *J. Appl. Ecol.* **In press**.
- 953 Lindenmayer, D.B., and Noss, R.F. 2006. Salvage logging, ecosystem processes, and
954 biodiversity conservation. *Conserv. Biol.* **20**(4): 949–958.

- 955 doi:10.1111/j.1523-1739.2006.00497.x.
- 956 Lindenmayer, D.B., and Possingham, H.P. 1996. Ranking Conservation and Timber
957 Management Options for Leadbeater ' s Possum in Southeastern Australia Using
958 Population Viability Analysis. *Conserv. Biol.* **10**(1): 235–251.
- 959 Macdonald, S.E. 2007. Effects of partial post-fire salvage harvesting on vegetation
960 communities in the boreal mixedwood forest region of northeastern Alberta, Canada.
961 *For. Ecol. Manage.* **239**(1–3): 21–31. doi:10.1016/j.foreco.2006.11.006.
- 962 Man, R., Chen, H.Y.H., and Schafer, A. 2013. Salvage logging and forest renewal affect
963 early aspen stand structure after catastrophic wind. *For. Ecol. Manage.* **308**: 1–8.
964 Elsevier B.V. doi:10.1016/j.foreco.2013.07.039.
- 965 Mansuy, N., Thiffault, E., Lemieux, S., Manka, F., Paré, D., and Lebel, L. 2015. Sustainable
966 biomass supply chains from salvage logging of fire-killed stands: a case study for wood
967 pellet production in eastern Canada. *Appl. Energy* **154**: 62–73. Elsevier Ltd, Oxford.
968 doi:10.1016/j.apenergy.2015.04.048.
- 969 Marañón-Jiménez, S., and Castro, J. 2013. Effect of decomposing post-fire coarse woody
970 debris on soil fertility and nutrient availability in a Mediterranean ecosystem.
971 *Biogeochemistry* **112**(1–3): 519–535. doi:10.1007/s10533-012-9744-x.
- 972 Martín-López, B., Gómez-Baggethun, E., García-Llorente, M., and Montes, C. 2014.
973 Trade-offs across value-domains in ecosystem services assessment. *Ecol. Indic.*
974 **37**(PART A): 220–228. Elsevier Ltd. doi:10.1016/j.ecolind.2013.03.003.

- 975 Martínez-Sánchez, J.J., Ferrandis, P., De las Heras, J., and Herranz, J.M. 1999. Effect of
976 burnt wood removal on the natural regeneration of *Pinus halepensis* after fire in a pine
977 forest in Tus valley (SE Spain). *For. Ecol. Manage.* **123**: 1–10.
- 978 Marzano, R., Garbarino, M., Marcolin, E., Pividori, M., and Lingua, E. 2013. Deadwood
979 anisotropic facilitation on seedling establishment after a stand-replacing wildfire in
980 Aosta Valley (NW Italy). *Ecol. Eng.* **51**: 117–122. Elsevier B.V.
981 doi:10.1016/j.ecoleng.2012.12.030.
- 982 McGinnis, T.W., Keeley, J.E., Stephens, S.L., and Roller, G.B. 2010. Fuel buildup and
983 potential fire behavior after stand-replacing fires, logging fire-killed trees and herbicide
984 shrub removal in Sierra Nevada forests. *For. Ecol. Manage.* **260**(1): 22–35. Elsevier
985 B.V. doi:10.1016/j.foreco.2010.03.026.
- 986 McIver, J.D., and McNeil, R. 2006. Soil disturbance and hill-slope sediment transport after
987 logging of a severely burned site in Northeastern Oregon. *West. J. Appl. For.* **21**: 123–
988 133.
- 989 McIver, J.D., and Ottmar, R. 2007. Fuel mass and stand structure after post-fire logging of a
990 severely burned ponderosa pine forest in northeastern Oregon. *For. Ecol. Manage.*
991 **238**(1–3): 268–279. doi:10.1016/j.foreco.2006.10.021.
- 992 McIver, J.D., and Starr, L. 2000. Environmental effects of postfire logging: Literature review
993 and annotated bibliography. Gen. Tech. Rep. PNW-GTR-486. Portland, OR: U.S.
994 Department of Agriculture, Forest Service, Pacific Northwest Research Station.
- 995 Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., and The PRISMA Group. 2009. Preferred

- 996 reporting items for systematic reviews and meta-analyses: The PRISMA statement.
997 PLoS Med. **6**(7). doi:10.1371/journal.pmed.1000097.
- 998 Molinas-González, C.R., Leverkus, A.B., Marañón-Jiménez, S., and Castro, J. 2017. Fall rate
999 of burnt pines across an elevational gradient in a mediterranean mountain. Eur. J. For.
1000 Res. **136**(3): 401–409. doi:10.1007/s10342-017-1040-9.
- 1001 Molinas González, C., Castro, J., and Leverkus, A.B. 2017. Deadwood decay in a burnt
1002 Mediterranean pine reforestation. Forests **8**: art158.
- 1003 Müller, J., Noss, R., Thorn, S., Bässler, C., Leverkus, A.B., and Lindenmayer, D. 2018.
1004 Increasing disturbance demands new policies to conserve intact forest. Conserv. Lett.:
1005 e12449. doi:10.1111/conl.12449.
- 1006 Ne'eman, G., Perevolotsky, A., and Schiller, G. 1997. The management implications of the
1007 Mt. Carmel research project. Int. J. Wildl. Fire **7**(4): 343–350.
1008 doi:10.1071/WF9970343.
- 1009 Van Nieuwstadt, M.G.. L., Sheil, D., and Kartawinata, K. 2001. The Ecological
1010 Consequences of Logging in the Burned Forests of East Kalimantan, Indonesia.
1011 Conserv. Biol. **15**(4): 1183–1186. doi:10.1046/j.1523-1739.2001.0150041183.x.
- 1012 Noss, R.F., Franklin, J.F., Baker, W.L., Schoennagel, T., and Moyle, P.B. 2006. Managing
1013 fire-prone forests in the western United States. Front. Ecol. Environ. **4**: 481–487.
- 1014 Noss, R.F., and Lindenmayer, D.B. 2006. The ecological effects of salvage logging after
1015 natural disturbance. Conserv. Biol. **20**(4): 946–948.

- 1016 doi:10.1111/j.1523-1739.2006.00498.x.
- 1017 Pausas, J.G., and Fernández-Muñoz, S. 2012. Fire regime changes in the Western
1018 Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Clim. Change*
1019 **110**(1–2): 215–226.
- 1020 Peterson, D.W., and Dodson, E.K. 2016. Post-fire logging produces minimal persistent
1021 impacts on understory vegetation in northeastern Oregon, USA. *For. Ecol. Manage.*
1022 **370**: 56–64. Elsevier B.V. doi:10.1016/j.foreco.2016.04.004.
- 1023 Peterson, D.W., Dodson, E.K., and Harrod, R.J. 2015. Post-fire logging reduces surface
1024 woody fuels up to four decades following wildfire. *For. Ecol. Manage.* **338**: 84–91.
1025 Elsevier B.V. doi:10.1016/j.foreco.2014.11.016.
- 1026 Powers, E.M., Marshall, J.D., Zhang, J., and Wei, L. 2013. Post-fire management regimes
1027 affect carbon sequestration and storage in a Sierra Nevada mixed conifer forest. *For.*
1028 *Ecol. Manage.* **291**: 268–277. doi:10.1016/j.foreco.2012.07.038.
- 1029 Prestemon, J.P., and Holmes, T.P. 2010. Economic impacts of hurricanes on forest owners.
1030 *In* U S Forest Service Pacific Northwest Research Station General Technical Report
1031 PNW-GTR 802, Part 1. pp. 207–221.
- 1032 Priewasser, K., Brang, P., Bachofen, H., Bugmann, H., and Wohlgemuth, T. 2013. Impacts of
1033 salvage-logging on the status of deadwood after windthrow in Swiss forests. *Eur. J. For.*
1034 *Res.* **132**(2): 231–240. doi:10.1007/s10342-012-0670-1.
- 1035 Puerta-Piñero, C., Sánchez-Miranda, A., Leverkus, A., and Castro, J. 2010. Management of

- 1036 burnt wood after fire affects post-dispersal acorn predation. *For. Ecol. Manage.* **260**(3):
1037 345–352. ELSEVIER SCIENCE BV. doi:10.1016/j.foreco.2010.04.023.
- 1038 Pullin, A.S., Knight, T.M., Stone, D.A., and Charman, K. 2004. Do conservation managers
1039 use scientific evidence to support their decision-making? *Biol. Conserv.* **119**(2): 245–
1040 252. doi:10.1016/j.biocon.2003.11.007.
- 1041 Pullin, A.S., and Stewart, G.B. 2006. Guidelines for systematic review in conservation and
1042 environmental management. *Conserv. Biol.* **20**(6): 1647–1656.
1043 doi:10.1111/j.1523-1739.2006.00485.x.
- 1044 R Core Team. 2016. R: A language and environment for statistical computing. R Foundation
1045 for Statistical Computing, Vienna, Austria, R Foundation for Statistical Computing,
1046 Vienna, Austria.
- 1047 Rhoades, C.C., Pelz, K.A., Fornwalt, P.J., Wolk, B.H., and Cheng, A.S. 2018. Overlapping
1048 bark beetle outbreaks, salvage logging and wildfire restructure a lodgepole pine
1049 ecosystem. *Forests* **In press**.
- 1050 Ritchie, M.W., Knapp, E.E., and Skinner, C.N. 2013. Snag longevity and surface fuel
1051 accumulation following post-fire logging in a ponderosa pine dominated forest. *For.*
1052 *Ecol. Manage.* **287**: 113–122. Elsevier B.V. doi:10.1016/j.foreco.2012.09.001.
- 1053 Roy, D.F. 1956. Salvage logging may destroy Douglas-fir reproduction. USDA For. Serv.
1054 Calif. For. Range Exp. Station. For. Res. Notes No. 107: 5.
- 1055 Royo, A.A., Peterson, C.J., Stanovick, J.S., and Carson, W.P. 2016. Evaluating the

- 1056 ecological impacts of salvage logging: Can natural and anthropogenic disturbances
1057 promote coexistence? *Ecology* **97**(6): 1566–1582. doi:10.1890/15-1093.1.
- 1058 Schelhaas, M.J., Nabuurs, G.J., and Schuck, A. 2003. Natural disturbances in the European
1059 forests in the 19th and 20th centuries. *Glob. Chang. Biol.* **9**: 1620–1633.
1060 doi:10.1046/j.1365-2486.2003.00684.x.
- 1061 Schiermeier, Q. 2016. Pristine forest at risk. *Nature* **530**: 393. doi:10.1038/530394a.
- 1062 Schönenberger, W., Noack, A., and Thee, P. 2005. Effect of timber removal from windthrow
1063 slopes on the risk of snow avalanches and rockfall. *For. Ecol. Manage.* **213**(1–3): 197–
1064 208. doi:10.1016/j.foreco.2005.03.062.
- 1065 Schroeder, L.M., and Lindelöw, A. 2002. Attacks on living spruce trees by the bark beetle *Ips*
1066 *typographus* (Col. Scolytidae) following a storm-felling: a comparison between stands
1067 with and without removal of wind-felled trees. *Agric.* **4**: 47–56.
- 1068 Secretariat of the Convention on Biological Diversity. 2000. Sustaining life on Earth: How
1069 the Convention on Biological Diversity promotes nature and human well-being. *Secr.*
1070 *Conv. Biol. Divers.*: 14.
- 1071 Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J.,
1072 Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda,
1073 M., Fabrika, M., Nagel, T.A., and Reyer, C.P.O. 2017. Forest disturbances under
1074 climate change. *Nat. Clim. Chang.* **7**(6): 395–402. Nature Publishing Group.
1075 doi:10.1038/nclimate3303.

- 1076 Serrano-Ortiz, P., Marañón-Jiménez, S., Reverter, B.R., Sánchez-Cañete, E.P., Castro, J.,
1077 Zamora, R., and Kowalski, A.S. 2011a. Post-fire salvage logging reduces carbon
1078 sequestration in Mediterranean coniferous forest. *For. Ecol. Manage.* **262**(12): 2287–
1079 2296. Elsevier B.V. doi:10.1016/j.foreco.2011.08.023.
- 1080 Serrano-Ortiz, P., Marañón-Jiménez, S., Reverter, B.R., Sánchez-Cañete, E.P., Castro, J.,
1081 Zamora, R., and Kowalski, A.S. 2011b. Post-fire salvage logging reduces carbon
1082 sequestration in Mediterranean coniferous forest. *For. Ecol. Manage.* **262**(12): 2287–
1083 2296. doi:10.1016/j.foreco.2011.08.023.
- 1084 Slesak, R.A., Schoenholtz, S.H., and Evans, D. 2015. Hillslope erosion two and three years
1085 after wildfire, skyline salvage logging, and site preparation in southern Oregon, USA.
1086 *For. Ecol. Manage.* **342**: 1–7. Elsevier B.V. doi:10.1016/j.foreco.2015.01.007.
- 1087 Smith-Ramírez, C., Maturana, V., Gaxiola, A., and Carmona, M. 2014. Salvage logging by
1088 indigenous people in a Chilean conifer forest. *For. Sci.* **60**(6): 1100–1106.
- 1089 Sullivan, T.P., Sullivan, D.S., Lindgren, P.M.F., and Ransome, D.B. 2010. Green-tree
1090 retention and life after the beetle: Stand structure and small mammals 30 years after
1091 salvage harvesting. *Silva Fenn.* **44**(5): 749–774.
- 1092 Sun, Y., Gu, L., Dickinson, R.E., and Zhou, B. 2012. Forest greenness after the massive 2008
1093 Chinese ice storm: integrated effects of natural processes and human intervention.
1094 *Environ. Res. Lett.* **7**(3): 35702. doi:10.1088/1748-9326/7/3/035702.
- 1095 Sutherland, W.J., Pullin, A.S., Dolman, P.M., and Knight, T.M. 2004a. The need for
1096 evidence-based conservation. *Trends Ecol. Evol.* **19**(6): 305–308.

- 1097 doi:10.1016/j.tree.2004.03.018.
- 1098 Sutherland, W.J., Pullin, A.S., Dolman, P.M., and Knight, T.M. 2004b. The need for
1099 evidence-based conservation. *Trends Ecol. Evol.* **19**(6): 305–8.
1100 doi:10.1016/j.tree.2004.03.018.
- 1101 Thorn, S., Bässler, C., Bernhardt-Römermann, M., Cadotte, M., Heibl, C., Schäfer, H.,
1102 Seibold, S., and Müller, J. 2015a. Changes in the dominant assembly mechanism drives
1103 species loss caused by declining resources. *Ecol. Lett.* **19**(2): 109–215.
1104 doi:10.1111/ele.12548.
- 1105 Thorn, S., Bässler, C., Brandl, R., Burton, P., Cahall, R., Campbell, J.L., Castro, J., Choi,
1106 C.-Y., Cobb, T., Donato, D., Durska, E., Fontaine, J., Gauthier, S., Hebert, C., Hothorn,
1107 T., Hutto, R., Lee, E.-J., Leverkus, A., Lindenmayer, D., Obrist, M., Rost, J., Seibold,
1108 S., Seidl, R., Thom, D., Waldron, K; Wermelinger, B., Winter, M.-B., Zmihorski, M.,
1109 and Müller, J. 2018. Impacts of salvage logging on biodiversity – a meta-analysis. *J.*
1110 *Appl. Ecol.* **55**: 279–289. doi:10.1111/1365-2664.12945.
- 1111 Thorn, S., Bässler, C., Svoboda, M., and Müller, J. 2016. Effects of natural disturbances and
1112 salvage logging on biodiversity – Lessons from the Bohemian Forest. *For. Ecol.*
1113 *Manage. Elsevier B.V.* doi:10.1016/j.foreco.2016.06.006.
- 1114 Thorn, S., Hacker, H.H., Seibold, S., Jehl, H., Bässler, C., and Müller, J. 2015b.
1115 Guild-specific responses of forest Lepidoptera highlight conservation-oriented forest
1116 management – Implications from conifer-dominated forests. *For. Ecol. Manage.* **337**:
1117 41–47. Elsevier B.V. doi:10.1016/j.foreco.2014.10.031.

- 1118 Titus, J.H., and Householder, E. 2007. Salvage logging and replanting reduce understory
1119 cover and richness compared to unsalvaged-unplanted sites at Mount St. Helens,
1120 Washington. *West. North Am. Nat.* **67**(2): 219–231.
1121 doi:10.3398/1527-0904(2007)67[219:SLARRU]2.0.CO;2.
- 1122 Turner, M.G. 2010. Disturbance and landscape dynamics in a changing world. *Ecology*
1123 **91**(10): 2833–2849. doi:10.1890/10-0097.1.
- 1124 Wagenbrenner, J.W., MacDonald, L.H., Coats, R.N., Robichaud, P.R., and Brown, R.E.
1125 2015. Effects of post-fire salvage logging and a skid trail treatment on ground cover,
1126 soils, and sediment production in the interior western United States. *For. Ecol. Manage.*
1127 **335**: 176–193. Elsevier B.V. doi:10.1016/j.foreco.2014.09.016.
- 1128 Wagenbrenner, J.W., Robichaud, P.R., and Brown, R.E. 2016. Rill erosion in burned and
1129 salvage logged western montane forests: Effects of logging equipment type, traffic
1130 level, and slash treatment. *J. Hydrol.* **541**(Part B): 889–901. Elsevier B.V.
1131 doi:10.1016/j.jhydrol.2016.07.049.
- 1132 Waldron, K., Ruel, J.C., and Gauthier, S. 2013. Forest structural attributes after windthrow
1133 and consequences of salvage logging. *For. Ecol. Manage.* **289**: 28–37. Elsevier B.V.
1134 doi:10.1016/j.foreco.2012.10.006.
- 1135 Waldron, K., Ruel, J.C., Gauthier, S., De Grandpré, L., and Peterson, C.J. 2014. Effects of
1136 post-windthrow salvage logging on microsites, plant composition and regeneration.
1137 *Appl. Veg. Sci.* **17**(2): 323–337. doi:10.1111/avsc.12061.
- 1138 Wohlgemuth, T., Kull, P., and Wüthrich, H. 2002. Disturbance of microsites and early tree

1139 regeneration after windthrow in Swiss mountain forests due to the winter storm Vivian
1140 1990. *For. Snow Landsc. Res.* **77**(1/2): 17–47.

1141 Wohlgemuth, T., Schwitter, R., Bebi, P., Sutter, F., and Brang, P. 2017. Post-windthrow
1142 management in protection forests of the Swiss Alps. *Eur. J. For. Res.* **136**: 1029–1040.
1143 Springer Berlin Heidelberg. doi:10.1007/s10342-017-1031-x.

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1146 **Tables**

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1148 **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

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1151 **Figure captions**

1152 **Figure 1. Ecosystem services cascade illustrated for the case of seed dispersal by**
1153 **European jays (*Garrulus glandarius* L.) within a post-fire management**
1154 **experimental setting.** The diagram shows the link between the biophysical and the
1155 human well-being components of ecosystem services. Particular elements of the
1156 ecosystem perform functions that produce benefits for society via an ecosystem service.
1157 Society places a value on these benefits, whether economic or not. The resulting value
1158 feeds back to affect the ecosystem elements through management decisions. In the
1159 example (shown in the dashed boxes below each component of the conceptual diagram),
1160 burnt snags represent a supporting element for the seed caching activity of a major seed
1161 disperser, whose activity yields natural colonisation of the burnt area and reduces the
1162 economic cost of reforestation. Appreciation of this value can enhance the likelihood
1163 that snags be retained in post-fire management. Figure adapted from Haines-Young and
1164 Potschin (2010), Martín-López et al. (2014), and Leverkus and Castro (2017).
1165 References in the diagram: (1) = Molinas-González et al. (2017); (2) = Castro et al.
1166 (2012); (3) = Leverkus et al. (2016); (4) = Leverkus and Castro (2017).

1167

1168 **Figure 2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses**
1169 **(PRISMA) diagram.** Shown are the numbers of publications retrieved in the literature
1170 searches and the number excluded in each step. Diagram adapted from Moher et al.
1171 (2009).

1172

1173 **Figure 3. Cumulative number of publications per disturbance type included in this**
1174 **systematic map.**

1175 **Figure 4. Location of the individual studies included in the systematic map.** Number
1176 codes are indicated for reference (column Site_ref in the systematic map database, Table
1177 S3). Inset: Korean Peninsula.

1178

1179 **Figure 5. Disturbance and salvage logging characteristics.** A) Disturbance severity
1180 considered in the analysed publications. This includes 1-3 points per publication,
1181 according to whether one general disturbance severity was reported or the publication
1182 explicitly included sampling areas of different severity levels. B) Time elapsed between
1183 the disturbance and subsequent salvage logging. Each data point represents one
1184 publication. C) Logging intensity in the analysed publications. This includes 1-4 points
1185 per publication. Note that this applies to the Intervention only, as each publication also
1186 included a Comparator with 0% logging intensity. In all plots, the thick horizontal lines
1187 are medians, and the boxes indicate the first and third quartiles of the values. Whiskers
1188 are either the minimum/maximum values or 1.5 times the interquartile range of the data,
1189 in which case outliers are shown as points. The values of disturbance severity and
1190 logging intensity are broad approximations. Sample sizes for the graphics are: for fire
1191 53, 51 and 69 (panels A, B and C, respectively); for insect outbreaks 15, 13 and 15; and
1192 for wind 31, 26 and 21 for wind.

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1194 **Figure 6. The number of spatially independent salvage logging replicate units used**
1195 **in the 90 publications, classified by disturbance type.**

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1197 **Figure 7. Number of publications that reported different measured response**
1198 **variables, for each disturbance type.** Nutrient= biological indicators of nutrient
1199 cycling; Carbon= non-wood carbon pool; Water= drinking water quality; Erosion= soil

1200 erosion by wind or water; Invasives= Invasive and/or exotic species; Cover= ground
1201 cover, including cover of vegetation; Resilience= capacity to regenerate after subsequent
1202 wildfire (i.e. wildfire after salvage logging); Riparian= riparian ecosystem functioning;
1203 Dispersal= seed dispersal; Soil chem.= soil chemical properties; Soil phys.= soil
1204 physical properties; Deadwood= stand structure and deadwood amount and
1205 characteristics; Temp.= air, water or soil temperature; Regen.= tree regeneration;
1206 Vegetation= Vegetation composition. Note that biodiversity responses were excluded
1207 from the systematic map. Inset: distribution of publications according to the number of
1208 individual measurements taken for the response variables. Both y axes have the same
1209 meaning.

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1213 **Supporting Information**

1214 Appendix A1. **Systematic map database and data coding strategy**

1215 Appendix A2. **Literature searches and screening –Results**

1216 Appendix A3. **Stand characteristics –Results and Discussion**

1217 Table S1. **Search strings used in the systematic map.**

1218 Table S2. **Publications excluded at full-text screening and reasons for exclusion.**

1219 Table S3. **Systematic Map Database.** For details on coding and variable names, see

1220 Appendix A1.

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