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**This is a pre print version of the following article:**

*Original Citation:*

*Availability:*

This version is available <http://hdl.handle.net/2318/1661982> since 2018-03-13T00:51:07Z

*Published version:*

DOI:10.1038/nclimate3303

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# Forest disturbances under climate change

Rupert Seidl<sup>1,\*</sup>, Dominik Thom<sup>1</sup>, Markus Kautz<sup>2</sup>, Dario Martin-Benito<sup>3</sup>, Mikko Peltoniemi<sup>4</sup>,  
Giorgio Vacchiano<sup>5</sup>, Jan Wild<sup>6,7</sup>, Davide Ascoli<sup>8</sup>, Michal Petr<sup>9</sup>, Juha Honkaniemi<sup>4</sup>, Manfred J.  
Lexer<sup>1</sup>, Volodymyr Trotsiuk<sup>10</sup>, Paola Mairota<sup>11</sup>, Miroslav Svoboda<sup>10</sup>, Marek Fabrika<sup>12</sup>,  
Thomas A. Nagel<sup>10,13</sup>, Christopher P. O. Reyer<sup>14</sup>

<sup>1</sup> Institute of Silviculture, Department of Forest- and Soil Sciences, University of Natural Resources and Life Sciences (BOKU) Vienna, Peter Jordan Straße 82, 1190 Wien, Austria

<sup>2</sup> Institute of Meteorology and Climate Research – Atmospheric Environmental Research (IMK-IFU), Karlsruhe Institute of Technology (KIT), Kreuzeckbahnstr. 19, 82467 Garmisch-Partenkirchen, Germany

<sup>3</sup> Forest Ecology, Department of Environmental Sciences, Swiss Federal Inst. of Technology, ETH Zurich, Universitätstrasse 16, CH-8092 Zürich, Switzerland

<sup>4</sup> Natural Resources Institute Finland (Luke), Management and Production of Renewable Resources, Latokartanonkaari 9, 00790 Helsinki, Finland

<sup>5</sup> DISAFA, University of Torino, Largo Braccini 2, 10095 Grugliasco (TO), Italy

<sup>6</sup> Institute of Botany, The Czech Academy of Sciences, Zámek 1, CZ-252 43 Průhonice, Czech Republic

<sup>7</sup> Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamýcká 129, CZ-165 21 Prague 6 – Suchdol, Czech Republic

<sup>8</sup> Dipartimento di Agraria, University of Naples Federico II, via Università 100, 80055 Portici, Napoli, Italy

<sup>9</sup> Forest Research, Forestry Commission, Northern Research Station, EH25 9SY, Roslin, UK

<sup>10</sup> Department of Forest Ecology, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences, Kamýcká 129, Praha 6 Suchdol, 16521, Czech Republic

27 <sup>11</sup> Department of Agri-Environmental and Territorial Sciences, University of Bari “Aldo  
28 Moro”, via Amendola 165/A, 70126, Bari, Italy

29 <sup>12</sup> Department of Forest Management and Geodesy, Technical University in Zvolen, T. G.  
30 Masaryka 24, Zvolen, 96053, Slovakia

31 <sup>13</sup> Department of forestry and renewable forest resources, Biotechnical Faculty, University of  
32 Ljubljana, Večna pot 83, Ljubljana 1000, Slovenia

33 <sup>14</sup> Potsdam-Institute for Climate Impact Research, P.O. Box 60 12 03, D-14412 Potsdam

34

35 \* corresponding author: Email: [rupert.seidl@boku.ac.at](mailto:rupert.seidl@boku.ac.at), Tel: +43-1-47654-91328

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37 **Key words:** tree mortality; climate change impacts; abiotic disturbance; biotic disturbance;  
38 disturbance interaction; forest health

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42 **Around the globe forest disturbances are responding to ongoing changes in climate,**  
43 **increasingly challenging the sustainable provisioning of ecosystem services. Yet, our**  
44 **understanding of disturbance change remains fragmented, as disturbance processes are**  
45 **frequently studied independently and at local scales, disregarding interactions and**  
46 **large-scale patterns. Here we provide a comprehensive global synthesis of climate**  
47 **change effects on important abiotic (fire, drought, wind, snow & ice) and biotic (insects,**  
48 **pathogens) disturbance agents. Warmer and drier conditions particularly facilitate fire,**  
49 **drought, and insects, while warmer and wetter conditions increase disturbances from**  
50 **wind and pathogens. Widespread interactions between agents are likely to amplify**  
51 **disturbances, while indirect climate effects (e.g., vegetation changes) can dampen long-**  
52 **term climate sensitivities. Disturbance change is likely to be most pronounced in**  
53 **coniferous forests and the boreal biome. The emerging disturbance trajectories call for a**  
54 **preparation of both ecosystems and society for an increasingly disturbed future of**  
55 **forests.**

56

57 Natural disturbances such as fires, insect outbreaks or windthrows are an integral part  
58 of ecosystem dynamics in forests around the globe. They occur as relatively discrete events,  
59 and form characteristic regimes of typical disturbance frequencies, sizes, and severities over  
60 extended spatial and temporal scales <sup>1,2</sup>. Disturbances disrupt the structure, composition, and  
61 function of an ecosystem, community, or population, and change resource availability or the  
62 physical environment <sup>3</sup>. In doing so they create heterogeneity on the landscape <sup>4</sup>, foster  
63 diversity across a wide range of guilds and species <sup>5,6</sup>, and can initiate ecosystem renewal and  
64 reorganization <sup>7,8</sup>.

65 Disturbance regimes have changed profoundly in many forest ecosystems in recent  
66 years, with climate and land use being prominent drivers of disturbance change <sup>9</sup>. An increase

67 in disturbance occurrence and severity has been documented over large parts of the globe,  
68 e.g., for fire <sup>10,11</sup>, insect outbreaks <sup>12,13</sup>, and drought <sup>14,15</sup>. Such alterations of disturbance  
69 regimes have the potential to strongly impact the ability of forests to provide ecosystem  
70 services to society <sup>6</sup>. Moreover, a climate-mediated increase in disturbances could exceed the  
71 ecological resilience of forests, resulting in lastingly altered ecosystems or shifts to non-forest  
72 ecosystems as tipping points are crossed <sup>16-18</sup>. Consequently, disturbance change is expected  
73 to be among the most profound impacts that climate change will have on forest ecosystems in  
74 the coming decades <sup>19</sup>.

75         The ongoing changes in disturbance regimes in combination with their strong and  
76 lasting impacts on ecosystems have led to an intensification of disturbance research in recent  
77 years. While the publication of the seminal work by Pickett and White <sup>3</sup> thirty years ago can  
78 be seen as the starting point of systematic research on disturbance ecology, more recently the  
79 links between disturbance and climate change have come into focus, stimulated by the  
80 influential work by Dale et al. <sup>20</sup>. Recent syntheses on the effects of climate change on  
81 important disturbance agents such as fire <sup>21</sup>, bark beetles <sup>22</sup>, pathogens <sup>23</sup>, or drought <sup>15</sup>  
82 summarize recent advances of a highly prolific field of study. Considerably less synthetic  
83 knowledge is available on interactions among individual disturbance agents <sup>24-26</sup>.  
84 Furthermore, to date no global synthesis exists that integrates insights on changing  
85 disturbance regimes across agents and regions. Yet, the main drivers of disturbance change  
86 are global in scale (e.g., climate warming), rendering such a global synthesis highly relevant  
87 <sup>27,28</sup>.

88         Specifically, a comprehensive analysis of the multiple pathways via which climate  
89 might influence forest disturbances is still lacking. Interactions between different disturbance  
90 agents can, for instance, result in strong and nonlinear effects of climate change on  
91 disturbance activity <sup>29</sup>. In contrast, climate-mediated vegetation changes can dampen the  
92 climate sensitivity of disturbances <sup>30</sup>. Many assessments of disturbances under climate change

93 currently neglect such complex effect pathways<sup>31,32</sup>. More commonly still, the effects of  
94 changing disturbance regimes are disregarded entirely in analyses of future forest  
95 development<sup>33,34</sup> and studies quantifying the climate change mitigation potential of forest  
96 ecosystems<sup>35</sup>, potentially inducing significant bias<sup>36,37</sup>.

97 Here we review the current understanding of forest disturbances under climate  
98 change, focusing on naturally occurring agents of disturbance. Specifically, we synthesize the  
99 existing knowledge of how climate change may affect disturbance regimes via direct, indirect,  
100 and interaction effects. We reviewed the disturbance literature applying a consistent analysis  
101 framework over a diverse set of major forest disturbance agents, including four abiotic agents  
102 (i.e., fire, drought, wind, snow & ice) and two biotic agents (i.e., insects, pathogens). We  
103 compiled evidence for climate effects from all biomes and continents, and analyzed it in a  
104 qualitative modeling framework. We tested the hypothesis that climate change will  
105 considerably increase forest disturbance activity at the global scale, and specifically that  
106 positive, amplifying effects of climate change on disturbances dominate negative, dampening  
107 effects.

108

## 109 **Literature review and analysis**

110 We screened the literature for peer-reviewed English-language papers addressing the climate  
111 sensitivity of forest disturbances (i.e., the change in disturbance in response to a change in  
112 climate). We focused on research emerging from the year 2001 onwards. This year marks the  
113 publication of the first comprehensive assessment of climate change impacts on forest  
114 disturbances<sup>20</sup>, as well as of the Third Assessment Report of the IPCC, which was the first  
115 such report to feature a dedicated subchapter on forest disturbances<sup>38</sup>. Material was selected  
116 by searching for the six focal disturbance agents of this study (i.e., fire, drought, wind, snow  
117 & ice, insects, and pathogens) or applicable aliases (e.g., bark beetle or defoliator for the  
118 insects category), in combination with the terms climate and/ or climatic change in the title,

119 abstract, and/ or key words of published papers. In the context of drought it is important to  
120 note that we here applied an ecological definition rather than a meteorological one, i.e., we  
121 focused on events of severe water limitation that affect ecosystem structure and functioning,  
122 and thus fall under the disturbance definition given in the introduction. After initially  
123 screening the abstracts of several thousands of papers, studies not directly addressing climatic  
124 controls of disturbances (e.g., work describing disturbance patterns but not their climatic  
125 drivers), and those unrelated to the subject matter (e.g., work on insect species that are  
126 reproducing in dead trees and are thus not acting as disturbance agent) were excluded, and  
127 574 papers were selected for detailed review. As individual papers frequently contained  
128 evidence for more than one climatic effect on disturbances, 1,500 observations were extracted  
129 from the selected papers (see Supplementary Text as well as Table S1, and Figure S1-S2 in  
130 the Supplementary Information). We conducted an in-depth uncertainty analysis of the  
131 information synthesized from the literature, analyzing how well the data corresponded with  
132 the variable of interest in our current analysis (i.e., disturbance activity and changes therein),  
133 and assessing the methodological rigor applied in its generation (see Supplementary Text,  
134 Figures S3-S5). We omitted information that we deemed to be a poor proxy for disturbance  
135 change or of limited methodological rigor, resulting in 1,455 observations available for  
136 analysis (Supplementary Dataset 1).

137         We applied a common analysis scheme to all reviewed papers. For each paper we  
138 recorded meta-data on study location, methodological approach (i.e., empirical, experimental,  
139 or simulation-based), and the disturbance agent(s) studied. We distinguished direct, indirect,  
140 and interaction effects<sup>39-41</sup> of climate change on disturbances in our analysis of the literature.  
141 Direct effects were defined as the unmediated impacts of climate variables on disturbance  
142 processes. Examples included changes in the frequency or severity of wind events and  
143 drought periods, changes in lightning activity, or climate-mediated changes in the metabolic  
144 rates of pests and pathogens. Indirect effects were defined as changes in the disturbance

145 regime through climate effects on vegetation and other ecosystem processes not directly  
146 related to disturbances. Prominent processes considered here are climate-mediated changes in  
147 the tree population and community composition, and include an alteration of the disturbance  
148 susceptibility through a change in tree species composition, size, density (e.g., fuel available  
149 for burning), and distribution, as well as changes in tree-level vulnerability (e.g., changes in  
150 soil anchorage of trees against wind due to variation in soil frost). Interaction effects were  
151 defined as linked or compounding relationships between disturbance agents <sup>24</sup>, such as an  
152 increased risk of bark beetle outbreaks resulting from wind disturbance (creating large  
153 amounts of effectively defenseless breeding material supporting the build-up of beetle  
154 population) or drought (weakening tree defenses against beetles). Only interactions between  
155 the six agents investigated here were considered explicitly.

156         To characterize the climate sensitivity of disturbances we first collated the evidence  
157 for direct, indirect, and interaction effects of climate change for each of the six disturbance  
158 agents studied. We screened the information deduced from the disturbance literature for key  
159 climatic drivers of disturbances, and analyzed their variation over biomes. As an auxiliary  
160 variable we determined the response time of the ecosystem (i.e., the time needed to respond to  
161 a respective change in a climate driver) on an ordinal scale. Subsequently, we synthesized the  
162 literature regarding potential future changes in the disturbance regime. This analysis was  
163 conducted at two levels: First, the sign of the climate effect (i.e., positive: more disturbance,  
164 negative: less disturbance) in response to changes in the respective climate variable(s) was  
165 assessed. Interaction effects were grouped by directionality (links between individual agents)  
166 and also analyzed for the sign of the interaction. This information was synthesized  
167 qualitatively, scrutinizing whether amplifying or dampening climate change impacts prevail  
168 for each disturbance agent (Figure S6). We conducted this analysis separately for two broad  
169 trajectories of change: (1) Warmer and wetter conditions, which assume an increase in both  
170 indicators of the thermal environment and water availability (e.g., warmer temperatures,



171 higher levels of precipitation and soil moisture, or lower levels of water deficit and drought  
172 indices), and (2) warmer and drier conditions, with an opposite direction of change for  
173 indicators of water availability under warming temperatures (see Supplementary Text for  
174 details). Second, we derived a relative effect size (disturbance change in response to future  
175 climate change relative to baseline climate conditions, with a value of 1 indicating no change)  
176 across all the potential future climate conditions studied in the literature. Relative effect sizes  
177 were tested against the null hypothesis of no change in disturbance as a result of climate  
178 change using Wilcoxon signed rank sum test. All analyses were conducted using the R  
179 language and environment for statistical computing <sup>42</sup>.

180

### 181 **Pathways of climate influence**

182 We found evidence for a substantial influence of climate on disturbances via all three  
183 scrutinized pathways, i.e., direct, indirect, and interaction effects. More than half of the  
184 observations reported in the literature related to direct climate effects (57.0%), which were the  
185 most prominent pathway of climate influence for all analyzed agents except insects (Figure  
186 1). Direct effects were found to be particularly pronounced for abiotic agents: Abiotic  
187 disturbances often are the direct consequence of climatic extremes, and are thus highly  
188 sensitive to changes in their occurrence, intensity, and duration (Table 1). Furthermore, 24.6%  
189 of the analyzed observations reported on indirect effects of climate change on disturbances.  
190 Climate-mediated changes in forest structure and composition were particularly relevant in  
191 the context of wind disturbance. Also interactions between disturbance agents are well  
192 documented in the analyzed literature (18.4% of the overall observations). For insects, for  
193 instance, 43.1% of the reported effects were associated with disturbance interactions. Links  
194 between abiotic (influencing agent) to biotic (influenced agent) disturbances were found to be  
195 particularly strong (Figure 2a). The large majority of the recorded interaction effects were  
196 positive or predominately positive (71.4%), indicating an amplification of disturbance as a

197 result of the interaction between agents. In particular, disturbances by drought and wind  
198 strongly facilitate the activity of other disturbance agents, such as insects and fire (Figure 2b,  
199 Table S2). Overall, only 16.1% of the studies on disturbance interactions reported a negative  
200 or predominately negative (i.e., dampening) effect between interacting disturbance agents.

201

### 202 **Climate drivers and response times**

203 The climatic drivers of disturbances varied strongly with agent and region. However,  
204 temperature-related variables were the most prominent climatic drivers reported in the forest  
205 disturbance literature (41.0%). Water availability, including precipitation levels and drought  
206 indices, was a second important climatic influence on disturbance regimes (37.6%). The  
207 importance of temperature-related variables on the disturbance regime increased with latitude  
208 and was highest in the boreal biome (Figure S9). Conversely, the importance of water  
209 availability decreased with latitude and was highest in the tropics. In addition to temperature  
210 and water availability, a wide range of other climate-related variables were associated with  
211 disturbance change, ranging from wind speed and atmospheric moisture content to snow pack  
212 and atmospheric CO<sub>2</sub> concentration.

213         The response times of the disturbance regime to changes in the climate system varied  
214 widely, ranging from annual to centennial scales. Response times were clearly related to the  
215 type of climate effect, with disturbance interactions constituting the fastest responding  
216 pathway and indirect effects being slowest (Figure S10). For interaction effects, the analyzed  
217 literature reports a response time of <6 years in 82.7% of the reviewed cases, with only 8.0%  
218 of the studied interaction effects having a response time of >25 years. For indirect effects,  
219 only 37.5% of the systems responded within the first five years of the respective climatic  
220 change, while 42.1% of the responses took >25 years.

221

### 222 **Potential future disturbance change**

223 At the global scale, our analysis suggests that disturbances from five out of the six analyzed  
224 agents are likely to increase in a warming world. The exception are disturbances from snow &  
225 ice, which are likely to decrease in the future, especially under warmer and drier conditions.  
226 For warmer and dryer future conditions, the large majority of studies suggested an increase in  
227 fires (83.2% of the observations), drought (73.3%), and insect activity (74.2%) (Figure 3).  
228 Under warmer and wetter conditions, on the other hand, the evidence for increased activity  
229 from these disturbance agents was significantly reduced (53.0%, 42.5%, and 58.3%,  
230 respectively). Wetter conditions were found to particularly foster wind disturbance (expected  
231 to increase in 83.9% of the cases) and pathogen activity (69.0%). Indirect climate effects were  
232 dampening the overall climate sensitivity of the system more often than direct climate effects  
233 (Table S2, Figures S7-S8), although no significant differences in effect sizes were found  
234 (Figure S13). Interaction effects were largely amplifying climate sensitivity (Figure 2).

235 Across all scenarios considered in the analyzed literature, the ratio between  
236 disturbances under future climate to disturbances under baseline conditions (effect size) was  
237 significantly positive ( $p < 0.05$ ). The exception were disturbances from snow & ice, which  
238 decreased significantly (median effect size of 0.345 over all studies and climate change  
239 scenarios, see Figure S11). Disturbances from all other agents increased under future climate  
240 change, with median effect sizes of between 1.34 and 1.51. Climate-related disturbance  
241 effects were positive across all biomes ( $p < 0.001$ ) and moderately increased with latitude  
242 (Figure S12), with the values reported for the boreal zone (1.75). Furthermore, coniferous  
243 forests had a significantly higher future disturbance effect size than broadleaved and mixed  
244 forest types (Figure S14). Also, longer response times of disturbances to climate change were  
245 associated with elevated effect sizes (Figure S15).

246

## 247 **Discussion and conclusion**

248 We found strong support for the hypothesis that climate change could markedly modify future  
249 forest disturbance regimes at the global scale. Our analysis of the global forest disturbance  
250 literature suggests that particularly disturbances from fire, insects, and pathogens are likely to  
251 increase in a warming world. These agents and their interactions currently dominate  
252 disturbance regimes in many forests of the world, such as in western North America, large  
253 parts of Australia and Asia, and will likely gain further importance globally in the coming  
254 decades. Future changes of disturbances caused by other agents such as drought, wind, and  
255 snow will be strongly contingent on changes in water availability, which can be expected to  
256 vary more strongly locally and intra-annually than temperature changes. Changes in wind  
257 disturbance, for instance, which is currently the most important disturbance agent in Europe  
258 <sup>37</sup>, are expected to respond more strongly to changes in precipitation (and the corresponding  
259 changes in tree soil anchorage and tree growth) than to warming temperatures (cf. Figure  
260 3a,b). Yet the most influential climate variable determining wind disturbance remains the  
261 frequency and intensity of strong winds, for which current and future trends remain  
262 inconclusive <sup>43,44</sup>. In general, our global summary of the climate sensitivity of forest  
263 disturbance regimes suggests that the recently observed increases in disturbance activity  
264 <sup>10,37,45</sup> are likely to continue in the coming decades as climate warms further <sup>46,47</sup>.

265 Our synthesis of effect pathways showed that direct climate effects were by far the  
266 most prominently reported impact in the analyzed literature. This underlines the importance of  
267 climatic drivers as inciting factors of tree mortality, and highlights the strong dependence of  
268 developmental rates of biotic disturbance agents on climatic conditions <sup>23,32</sup>. However, the  
269 prominence of direct effects in the literature may at least partially also result from the fact that  
270 they are easier to study and isolate (e.g., in laboratory experiments <sup>48</sup>) than indirect and  
271 interaction effects. Publication bias might thus result in an overestimation of the importance  
272 of direct effects relative to indirect and interaction effects in our analysis.

273 Indirect effects, mediated by climate-related changes in vegetation structure and  
274 composition, were most frequently reported for wind disturbance, but were documented in the  
275 literature for all six studied disturbance agents. They are slower than climate effects via direct  
276 and interaction pathways, with response times frequently in the range of several decades.  
277 Also, indirect effects are often dampening disturbance increases (Table S2, Figures S7-S8),  
278 e.g., when trees susceptible to an increasingly aggressive insect pest are outcompeted by  
279 individuals or species better adapted to warmer climates, resulting in a system less vulnerable  
280 to disturbances<sup>30,49</sup>. A second important class of dampening indirect effects occur when a  
281 previous disturbance event lowers the probability for subsequent disturbances by the same  
282 agent, e.g., through a disturbance-induced alteration of forest structure or the depletion of the  
283 resource a disturbance agent depends upon<sup>50-52</sup>. The temporal mismatch observed between  
284 direct and indirect effects (Figure S10) suggests that disturbances will likely increase further  
285 in the coming decades, as dampening effects of changes in forest structure and composition  
286 take effect only with a considerable delay. Here it has to be noted that our estimate of  
287 response times to climatic changes is necessarily truncated by the observation periods of the  
288 underlying studies. It might thus be biased against long-term effects<sup>8</sup> and underestimate the  
289 full temporal extent of climate effects on disturbances.

290 Evidence for potential changes in disturbance interactions was found for all six  
291 investigated agents. In this context it is noteworthy that the large majority of the interaction  
292 effects reported in the literature are positive, i.e., amplifying disturbance activity. We showed  
293 that interactions are especially important for the dynamics of biotic disturbance agents. As a  
294 generally increasing disturbance activity under climate change also means an increasing  
295 propensity for disturbance interactions, these agents could be particularly prone to further  
296 intensification via the influence of other disturbance agents<sup>26,53</sup>. This is of growing concern as  
297 amplification of disturbances through interaction could increase the potential for the  
298 exceedance of ecological thresholds and tipping points<sup>24,54</sup>.

299           Particularly indirect and interaction effects of climate change on disturbance regimes  
300 need to be better understood to comprehensively assess future trajectories of disturbance in a  
301 changing world. The complexity of disturbance interactions complicates predictions of future  
302 forest change, and highlights the need for further research comprising several disturbance  
303 agents and larger spatiotemporal scales. Dynamic vegetation models are prime tools for this  
304 domain of inquiry <sup>55</sup>. Simulation models are able to consistently track vegetation –  
305 disturbance feedbacks over time frames of decades to centuries <sup>30,56</sup>, and allow controlled  
306 experiments to isolate the effects of interactions between different agents <sup>29,56</sup>. However,  
307 many current disturbance models either do not explicitly consider vegetation processes, or  
308 disturbance agents are simulated in isolation, neglecting potential interaction effects. Future  
309 work should thus focus on integrating disturbance and vegetation dynamics in models, in  
310 order to address the complex interrelations between climate, vegetation, and disturbance <sup>57,58</sup>.  
311 Furthermore, long-term ecological observations and dedicated experimentation are needed to  
312 improve our understanding of changing disturbance regimes, and provide the data needed for  
313 parameterizing and evaluating the above mentioned simulation models <sup>55</sup>.

314           Our analysis revealed a strong bias of the literature towards agents such as fire,  
315 drought, insects, and pathogens, as well as ecosystems located in North America and Europe  
316 (Table S1, Figure S1). However, climate change is a global phenomenon, affecting forests in  
317 all regions of the world. To obtain a more comprehensive understanding of the global patterns  
318 of disturbance change, considerable knowledge gaps on the climate sensitivity of disturbance  
319 regimes need to be filled. It remains unclear, for instance, if the increasing effect of future  
320 climate change with latitude reported here (Figure S9) is the result of an increased exposure of  
321 boreal forests to climate change in combination with a naturally lower tree species diversity,  
322 or whether it is simply the effect of a publication bias towards these ecosystems. Furthermore,  
323 the fact that disturbance research is currently focused on a limited number of agents could be  
324 increasingly problematic in the future, as agents that were of little regional relevance in the

325 past could gain importance under changing climatic conditions. In this regard it should be  
326 noted that invasive alien species<sup>59,60</sup> were not in the focus of our analysis, but are likely to  
327 contribute considerably to future changes in disturbance regimes.

328 Climate-induced changes in the disturbance regime are a major challenge for the  
329 sustainable provisioning of ecosystem services to society<sup>6,14</sup>. Our finding of prominent  
330 indirect effects suggests that forest management can actively modulate the climate sensitivity  
331 of disturbance regimes via modifying forest structure and composition. However, mitigating  
332 the direct effects of a changing climate through management will be rarely possible, which  
333 suggests that future management will need to find ways of coping with changing disturbance  
334 regimes. A promising approach in this regard is to foster the resilience of forests to changing  
335 disturbance regimes and enable their recovery from and adaptation to disturbances<sup>17,61</sup>, to  
336 ensure a continuous provisioning of ecosystem services<sup>18</sup>, and ultimately prepare both  
337 ecosystems and society for an increasingly disturbed future of forests.

338

339

#### 340 **Acknowledgements**

341 This work is the result of a working group within the EU COST Action PROFOUND  
342 (FP1304) and the IUFRO Task Force on Climate Change and Forest Health. R. Seidl  
343 acknowledges funding from a START grant of the Austrian Science Fund FWF (Y 895-B25).  
344 M. Kautz acknowledges funding from the EU FP7 project LUC4C, grant 603542. M.  
345 Peltoniemi was funded by EU Life+ (LIFE12 ENV/FI/000409). C.P.O. Reyer acknowledges  
346 funding from the German Federal Ministry of Education and Research (BMBF, grant no.  
347 01LS1201A1). D. Martin-Benito was funded by a Marie-Curie IEF Grant (EU-Grant 329935).  
348 J. Wild was funded by the long-term research and development project RVO 67985939 (The  
349 Czech Academy of Sciences). M. Svoboda, V. Trotsiuk and J. Wild acknowledge support by a  
350 project of the Ministry of Education, Youth and Sports no. LD15158. M. Petr acknowledges

351 funding support from Forestry Commission (UK) funded research on climate change impacts.  
352 J. Honkaniemi acknowledges funding from the Foundation for Research of Natural Resources  
353 in Finland, grant no. 2015090. M. Svoboda and V. Trotsiuk acknowledge funding from the  
354 project GAČR 15-14840S. We thank four anonymous reviewers for helpful comments on an  
355 earlier version of the manuscript.

356

### 357 **Author contributions**

358 R.Seidl and C.P.O. Reyer initiated the research. R. Seidl and D. Thom designed the study,  
359 with feedback from authors during workshops in Vienna, Austria (April 2015) and Novi Sad,  
360 Serbia (November 2015). G. Vacchiano, D. Ascoli, P. Mairota, and R. Seidl reviewed the fire  
361 literature. D. Martin-Benito, M. Petr, and V. Trotsiuk reviewed the drought literature. J. Wild,  
362 M.J. Lexer, M. Fabrika, and T. Nagel reviewed the wind literature. D. Thom and T. Nagel  
363 reviewed the snow & ice literature. M. Kautz, D. Thom, M.J. Lexer, M. Svoboda, and J. Wild  
364 reviewed the literature on insects. M. Peltoniemi, J. Honkaniemi, and M. Petr reviewed the  
365 literature on pathogens. R. Seidl conducted the analyses. All authors contributed to writing  
366 and revising the manuscript.

367

### 368 **Additional information**

369 Supplementary information is available in the online version of the paper.

370

371

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603 **Tables**

604

605 Table 1: Important processes through which climate influences forest disturbances.

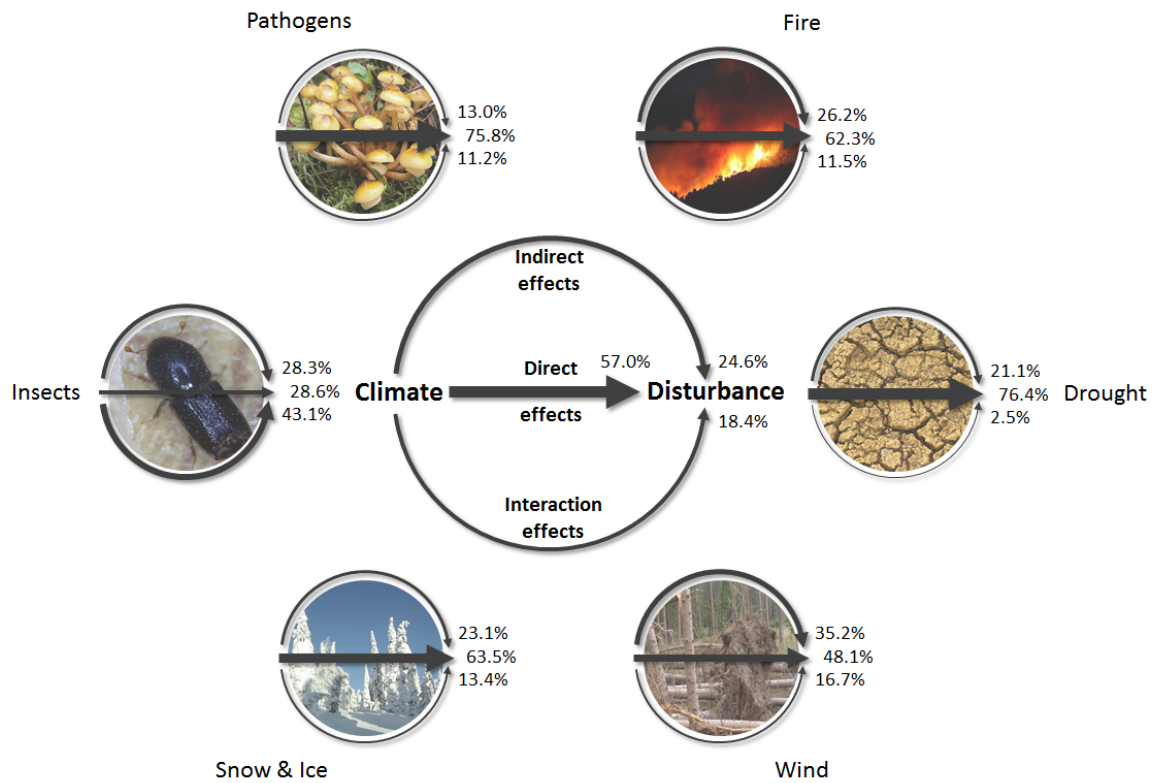
Disturbance agent	Direct effects: Climate impact through changes in...	Indirect effects: Climate impact through changes in...	Interaction effects: Climate impact through changes in...
Fire	Fuel moisture <sup>21</sup> Ignition (e.g., lightning activity) Fire spread (e.g., wind speed <sup>62</sup> )	Fuel availability (e.g., vegetation productivity <sup>63</sup> ) Flammability (e.g., vegetation composition) Fuel continuity (e.g., vegetation structure <sup>64</sup> )	Fuel availability (e.g., via wind or insect disturbance) Fuel continuity (e.g., avalanche paths as fuel breaks <sup>65</sup> )
Drought	Occurrence of water limitation Duration of water limitation <sup>66</sup> Intensity of water deficit <sup>66</sup>	Water use and water use efficiency (e.g., tree density and competition) Susceptibility to water deficit (e.g., tree species composition <sup>67</sup> )	Water use and water use efficiency (e.g., insect-related density changes) Susceptibility to water deficit (e.g., fire-mediated changes in forest structure <sup>68</sup> )
Wind	Occurrence of strong winds <sup>69</sup> Duration of wind events <sup>70</sup> Intensity of wind events (e.g., peak wind speeds) <sup>71</sup>	Tree anchorage (e.g., soil frost <sup>71</sup> ) Wind exposure (e.g., tree growth <sup>72</sup> ) Wind resistance (e.g., tree species composition <sup>50</sup> )	Wind exposure (e.g., insect disturbances increases canopy roughness) Soil anchorage (e.g., pathogens decrease rooting stability <sup>73</sup> ) Resistance to stem breakage (e.g., pathogens decrease stability)
Snow & Ice	Snow occurrence <sup>74</sup> Snow duration <sup>75</sup> Occurrence of freezing rain <sup>76</sup>	Exposure of forest to snow <sup>77</sup> Avalanche risk <sup>78</sup>	Avalanche risk (e.g., through gap formation by bark beetles <sup>79</sup> )

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Insects	Agent metabolic rate (e.g., reproduction <sup>32</sup> ) Agent behavior (e.g., consumption <sup>80</sup> ) Agent survival <sup>81</sup>	Host distribution and range <sup>82</sup> Agent - host synchronization (e.g., budburst <sup>83</sup> ) Host defense (e.g., carbohydrate reserves)	Host presence and abundance <sup>30</sup> Host resistance and defense (e.g., through changes in drought <sup>84</sup> )
Pathogens	Agent metabolic rate (e.g., respiration <sup>48</sup> ) Agent abundance <sup>85</sup>	Host abundance and diversity <sup>86</sup> Host defense <sup>87</sup>	Agent interaction and asynchrony <sup>88</sup> Agent dispersal (e.g., through vector insects <sup>89</sup> )

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607

608 **Figure 1: Distribution of evidence for direct, indirect, and interaction effects of climate**

609 **change on forest disturbance agents in the reviewed literature.** For every agent, arrow

610 widths and percentages indicate the relative prominence of the respective effect as expressed

611 by the number of observations extracted from the analyzed literature supporting it. The central

612 panel displays the aggregate result over all disturbance agents. Direct effects are unmediated

613 impacts of climate on disturbance processes, while indirect effects describe a climate

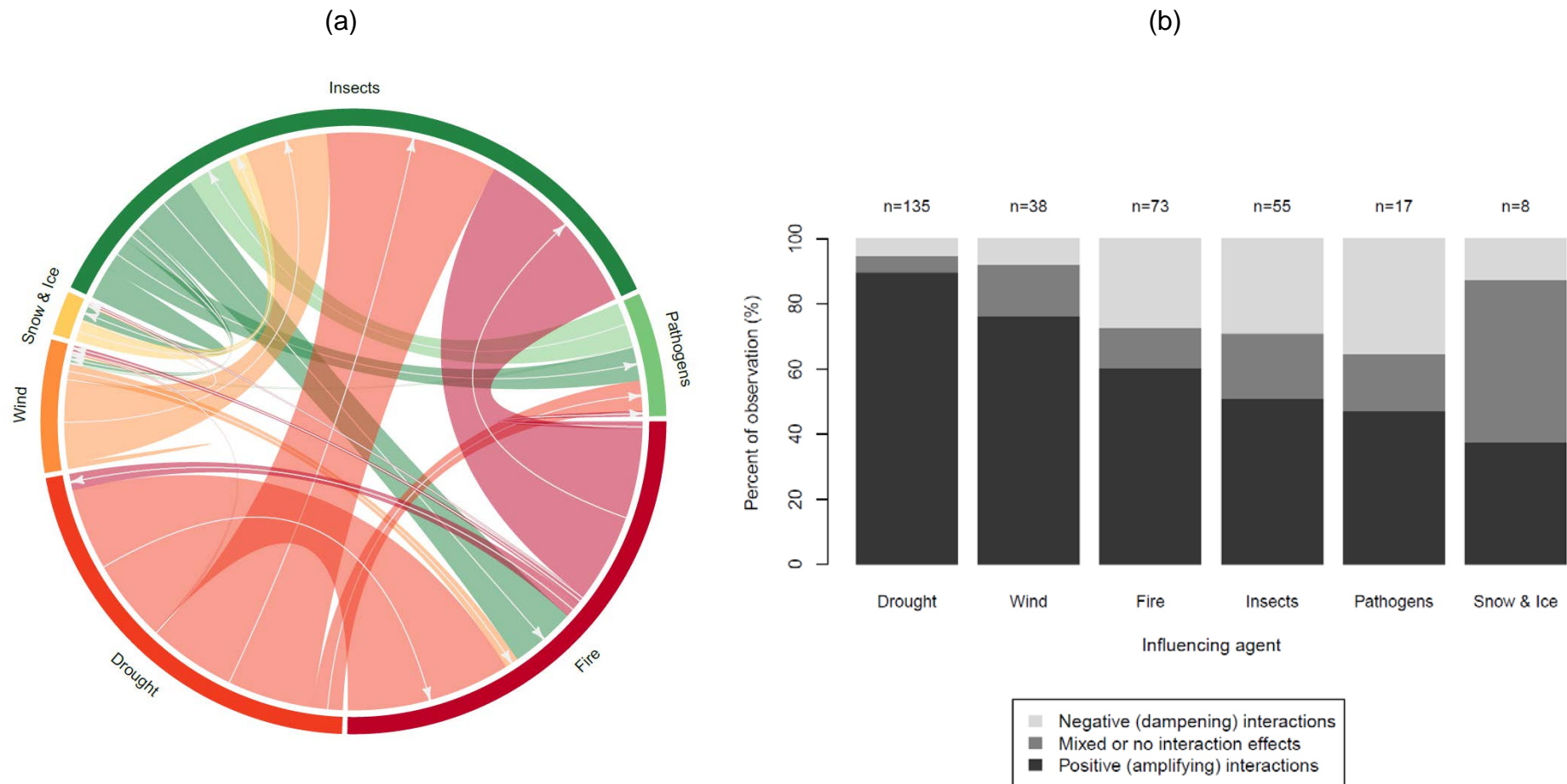
614 influence on disturbances through effects on vegetation and other ecosystem processes.

615 Interaction effects refer to the focal agent being influenced by other disturbance agents. Image

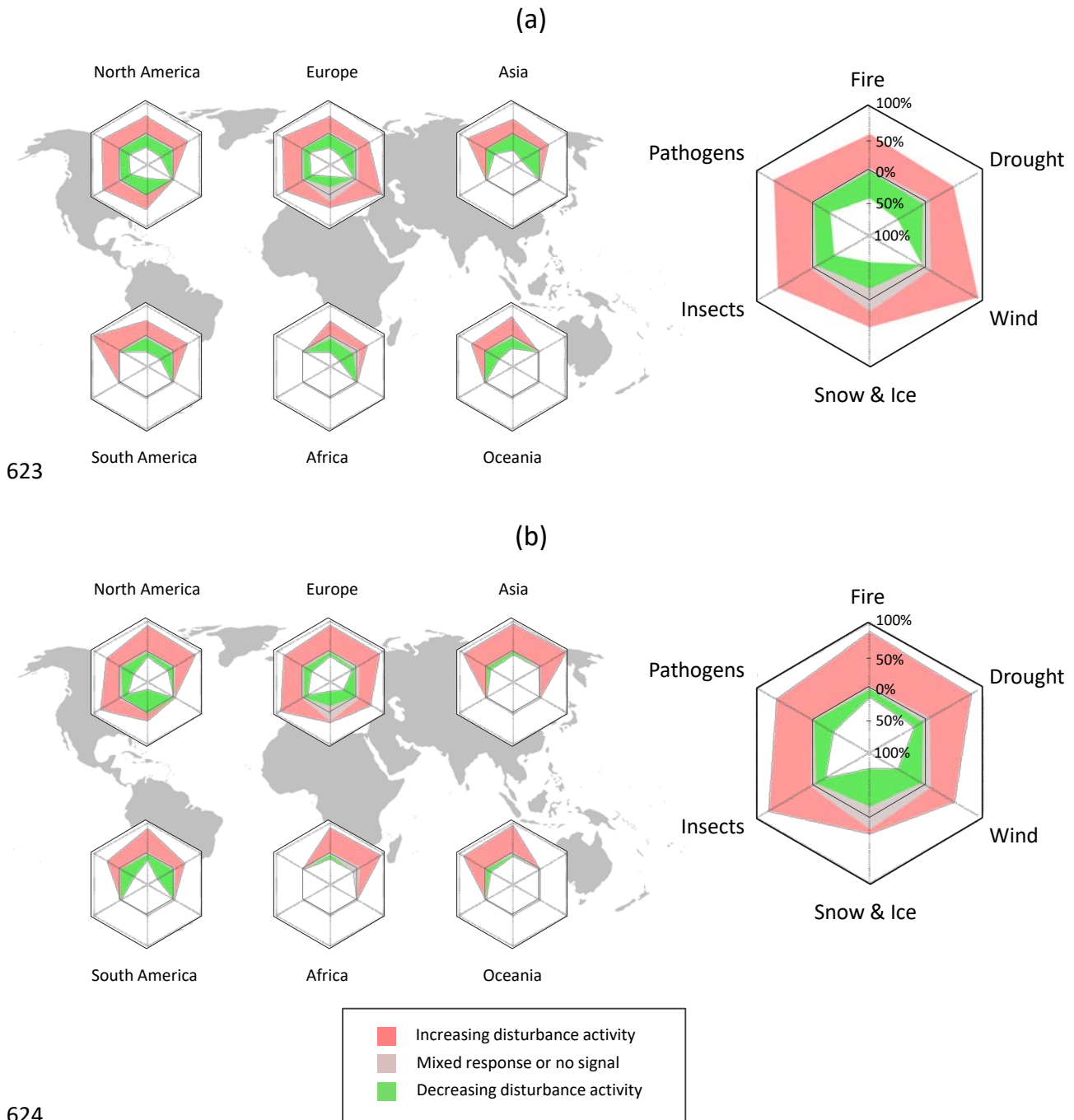
616 credits: Wikimedia Commons.

617





619 **Figure 2: Interactions between forest disturbance agents.** (a) The sector size in the outer circle indicates the distribution of interactions over  
 620 agents, while the flows through the center of the circle illustrate the relative importance of interactions between individual agents (as measured by  
 621 the number of observations reporting on the respective interaction). Arrows point from the influencing agent to the agent being influenced by the  
 622 interaction. (b) Sign of the interaction effect induced by the influencing agent on the influenced agent. n= Number of observations.



**Figure 3: Global disturbance response to changing temperature and water availability.**

Radar surfaces indicate the distribution of evidence (% of observations) for increasing or decreasing disturbance activity under (a) warmer and wetter as well as (b) warmer and dryer climate conditions. The large radar plot to the right summarizes the responses over all continents. Disturbance agents with less than four observations were omitted in the analysis. Only direct and indirect climate effects are considered here. More details on the qualitative modeling applied can be found in the Supplementary Material.