

# A climate risk analysis of Earth's forests in the 21st century

Anderegg, William R. L.; Wu, Chao; Acil, Nezha; Carvalhais, Nuno; Pugh, Thomas A. M.; Sadler, Jon P.; Seidl, Rupert

DOI:

[10.1126/science.abp9723](https://doi.org/10.1126/science.abp9723)

License:

Other (please specify with Rights Statement)

*Document Version*

Peer reviewed version

*Citation for published version (Harvard):*

Anderegg, WRL, Wu, C, Acil, N, Carvalhais, N, Pugh, TAM, Sadler, JP & Seidl, R 2022, 'A climate risk analysis of Earth's forests in the 21st century', *Science*, vol. 377, no. 6610, pp. 1099–1103.  
<https://doi.org/10.1126/science.abp9723>

[Link to publication on Research at Birmingham portal](#)

## **Publisher Rights Statement:**

This is the author's version of the work. It is posted here by permission of the AAAS for personal use, not for redistribution. The definitive version was published in *Science* on Vol 377, Issue 6610, 1 Sep 2022, DOI: 10.1126/science.abp9723.

## **General rights**

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

## **Take down policy**

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact [UBIRA@lists.bham.ac.uk](mailto:UBIRA@lists.bham.ac.uk) providing details and we will remove access to the work immediately and investigate.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22

## **A climate risk analysis of Earth’s forests in the 21st century**

William R. L. Anderegg<sup>1,2\*</sup>, Chao Wu<sup>2</sup>, Nezha Acil<sup>3,4</sup>, Nuno Carvalhais<sup>5,6</sup>, Thomas A. M. Pugh<sup>3,4,7</sup>, Jon P. Sadler<sup>3,4</sup>, Rupert Seidl<sup>8,9</sup>

*<sup>1</sup>Wilkes Center for Climate Science and Policy, University of Utah, Salt Lake City, UT 84103 USA; <sup>2</sup>School of Biological Sciences, University of Utah, Salt Lake City, UT 84103 USA; <sup>3</sup>School of Geography Earth and Environmental Sciences, University of Birmingham, Birmingham, UK; <sup>4</sup>Birmingham Institute of Forest Research, University of Birmingham, Birmingham, U.K.; <sup>5</sup>Max Planck Institute for Biogeochemistry, Jena, Germany; <sup>6</sup>Departamento de Ciências e Engenharia do Ambiente, DCEA, Faculdade de Ciências e Tecnologia, FCT, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal; <sup>7</sup>Department of Physical Geography and Ecosystem Science, Lund University, Lund, Sweden; <sup>8</sup>School of Life Sciences, Technical University of Munich, Freising, Germany; <sup>9</sup>Berchtesgaden National Park, Berchtesgaden, Germany.*

*Short title:* Climate risks to forests

*Key words:* Carbon cycle feedback, drought, wildfire, disturbance, nature-based climate solutions

*One Sentence Summary:* A multi-method synthesis of climate risks to forests globally.

23 *Abstract*

24 Earth's forests harbor extensive biodiversity and are currently a major carbon sink. Forest  
25 conservation and restoration can help to mitigate climate change. Yet climate change could  
26 fundamentally imperil forests in many regions and undermine their ability to provide such  
27 mitigation. The extent of climate risks facing forests has not been synthesized globally, nor have  
28 different approaches to quantifying forest climate risks been systematically compared. Here we  
29 combine outputs from multiple mechanistic and empirical approaches to modeling carbon,  
30 biodiversity, and disturbance risks to conduct a synthetic climate risk analysis for Earth's forests  
31 in the 21<sup>st</sup> century. Despite large uncertainty in most regions, we find some forests consistently at  
32 higher risk, including southern boreal forests, western North America, and parts of the Amazon.

33

34

35

36

37

38

39

40

41

42

43

44

45

46 *Main text*

47 Earth's forests store carbon, support enormous terrestrial biodiversity, and provide  
48 trillions of dollars each year in ecosystem goods and services to society (1, 2). Due to forests'  
49 potential carbon sequestration capacity and co-benefits, there is widespread and growing interest  
50 in leveraging forests for climate mitigation through nature-based climate solutions (3, 4). Yet the  
51 future of forests globally is uncertain due to both land-use decisions and climate change (5–7).  
52 Forests face substantial climate risks that could trigger carbon-cycle feedbacks, accelerating  
53 climate change and fundamentally undermining their role in climate mitigation (7–9). Critical  
54 climate-sensitive risks to forest stability, biodiversity, and long-term carbon storage include  
55 disturbance triggered by extreme weather (e.g. fire, drought, hurricanes), biotic agents and  
56 invasive species, and large-scale demographic shifts (e.g. elevated mortality rates, species  
57 turnover, physiological limits to growth or regeneration) (7, 10–12).

58 The large-scale and cross-biome patterns of climate risks to forests are not well-  
59 understood. With respect to ecosystems, the Intergovernmental Panel on Climate Change (IPCC)  
60 defines risk as the potential for adverse consequences for ecological systems and highlights that  
61 risk results from the dynamic interaction of climate-related hazards, exposure, susceptibility and  
62 (lack of) adaptive capacity of a system (5, 13). Three major approaches have been used to  
63 examine key determinants of forest risk, each considering different processes, with distinct  
64 uncertainties and limitations. First, global mechanistic vegetation models, such as those included  
65 in Earth system models, simulate forest carbon fluxes and pools, climate impacts on those  
66 processes, some key climate-sensitive disturbances such as fire, and dynamic growth and  
67 recovery after disturbances (14, 15). Second, 'climate envelope' approaches use empirical  
68 models based on relationships between observed climate patterns and forest attributes, such as

69 biomass, species presence/abundance, or ecoregion/life-zone presence (16–18). Third, empirical  
70 assessments of climatic controls on stand-replacing disturbances, typically based on satellite data  
71 of forest loss or meta-analyses of field studies, are other common approaches (11, 19). These  
72 major approaches roughly capture different ‘axes’ of forest climate risk to: (i) carbon  
73 stocks/storage (hereafter ‘C risk’), (ii) species composition changes (‘species risk’), and (iii)  
74 disturbance regime change (‘disturbance risk’). These approaches have different inherent  
75 strengths and weaknesses, but a synthesis of approaches at a global scale is lacking. A multi-  
76 method analysis to quantify risks spatially and estimate which regions may be particularly  
77 vulnerable in future climates is urgently needed to inform land management, conservation, and  
78 climate mitigation efforts.

79         Here, we compare results from these three types of approaches to provide a global  
80 assessment of climate risks facing Earth’s forests in the 21<sup>st</sup> century. We ask: i) what are the  
81 mean and uncertainty in projections of forest carbon storage and potential forest carbon losses in  
82 mechanistic vegetation models included in Earth system models (e.g. ‘C risk’), ii) what do  
83 empirical ‘climate envelope’ and ‘climate-sensitive disturbance’ approaches estimate for spatial  
84 and temporal climate risks to forests (e.g. ‘species risk’ and ‘disturbance risk’), and iii) what  
85 broader risk patterns emerge from the synthesis and comparisons of these three different axes of  
86 risks?

87         We first examined simulations of the live carbon in vegetation in forested areas (‘C risk’)  
88 from mechanistic vegetation models from the Coupled Model Intercomparison Project – Phase 6  
89 (CMIP6: 23 models total, 13 with prognostic fire and 6 with dynamic vegetation, Table S1),  
90 removing the direct influences of human land use change, to contextualize overall forest carbon  
91 changes (20). Comparing 2081-2100 with 1995-2014, these models on average show carbon

92 gains in currently forested areas in both high and low emissions scenarios (Fig. 1, Fig. S1). The  
93 multi-model mean was positive across most of the world, but with very high variation and  
94 uncertainty across models, particularly in the tropics and swaths of the boreal forests (Fig. 1A,  
95 1B, Fig. S1). We examined relative agreement in spatial patterns of carbon gains and losses  
96 across models and found that spatial correlations across models for carbon changes were modest,  
97 with an average of  $r=0.30$  across the 23 models considered here (Fig. S2).

98 We calculated two complementary metrics of potential climate C risk from these models  
99 as: 1) the number of models with carbon losses by 2081-2100 compared to 1995-2014 and 2) the  
100 percent change from tree functional types to other vegetation in a grid cell between those two  
101 periods for the subset of models (N=14) that reported data on vegetation change (20). The first  
102 metric uses the inherent variability in the model ensemble and assumes that the higher the  
103 number of models with C loss, the greater the risk, whereas the second metric directly calculates  
104 forest loss in models where it is represented. With the first metric, large areas of the Neotropics,  
105 the Mediterranean region and eastern Europe, as well as southwestern North America show  
106 notable risk (Fig. 1C). With the second metric, subtropical and southern boreal regions were  
107 more likely to lose tree functional types (Fig. 1D). We further found that these two metrics  
108 showed similar patterns of higher projected risk in southern boreal and drier regions in the  
109 Amazon and African tropics. Spatial patterns of carbon changes and climate risks were broadly  
110 similar between emissions scenarios (Fig. 1, Fig. S1) and between models with versus without  
111 prognostic fire simulated (Fig. S3).

112 We then examined forest ‘species risk’, estimated via empirical climate envelope models  
113 in three recently published papers. Using observed climate relationships at global scales, two  
114 papers estimated ecoregion/life-zone transitions (i.e. shifts from one ecoregion/life-zone to

115 another) and the third modeled changes in forest species richness within a biome (17, 21, 22).  
116 Ecoregion transitions were projected to be most likely at current biome boundaries (sub-tropic –  
117 temperate, temperate – boreal, and tropical – subtropical biomes; Fig. 2A, 2B). We note that  
118 there could be similarly large transitions in terms of species composition within individual  
119 biomes, but that by their inherent ecoregion-focused structure the underlying analyses in Fig 2A-  
120 B would not capture community-level changes. Considering the third paper’s analyses, risk of  
121 species loss estimates were highest in boreal regions and western North America and generally  
122 lower in tropical regions (Fig. 2C).

123 To quantify climate-sensitive ‘disturbance risk’, we used two complementary methods: 1)  
124 an empirical random-forest model linking observed climate to stand-replacing disturbance  
125 estimates based on satellite data from 2002-2014 with human land-use conversion removed (but  
126 harvest included, (20)), and 2) upscaled climate-dependent rates of disturbance in 103 protected  
127 areas from temperate and boreal biomes (19). For both methods, the models were built with  
128 observed relationships in the historical period. We estimated the change in stand-replacing  
129 disturbance rates using climate model output from the same 23 climate models we used for C  
130 risk for 2081-2100, with a moderate climate scenario (SSP2-4.5). The model of stand-replacing  
131 disturbances indicated that if current forests were exposed to projected future temperatures and  
132 precipitation, the largest increases of disturbance would be expected to occur in the tropics and  
133 southern boreal forests (Fig. 3A, 3B), whereas upscaled relationships from protected areas  
134 indicated high disturbance vulnerability broadly across boreal forests, although this dataset did  
135 not include tropical forests (Fig. 3B).

136 We emphasize that these three distinct axes of risk are capturing different aspects and  
137 dimensions of climate risks to forests, all of which are generally considered important responses

138 of forests to climate change (20). The spatial and cross-biome relative risk patterns within each  
139 approach are likely what is most insightful and important in these comparisons, rather than the  
140 absolute values. Thus, we compared the spatial correlations in relative projected risk patterns  
141 with a correlation matrix and computed spatial covariation of risk percentiles across all metrics.  
142 Strikingly, none of the different metrics were significantly spatially correlated with each other  
143 ( $p > 0.05$ ), leading to high variability across risk metrics in many regions (Fig. S4), and the  
144 mechanistic vegetation model projections tended to be slightly negatively correlated with the  
145 other approaches (Fig. 4B). Despite this broad-scale disagreement, identification of regions that  
146 are at relatively higher or lower risk in a majority of approaches can still provide useful  
147 information for risk management. Aggregating risk metrics by the average percentile across all  
148 metrics with data in a given grid cell, southern boreal regions (e.g. central Canada) and drier  
149 regions of the tropics (e.g. southeast Amazonia) emerged as regions with higher than average  
150 risk across metrics, consistent with multiple observational studies (e.g. 23, 24). By contrast,  
151 eastern North America, western Amazonia, and southeast Asia exhibited lower than average risk  
152 (Fig. 4A, Fig. S5); a recent pan-tropical study also observed lower vulnerability in southeast  
153 Asian tropics (25). These regional patterns were generally robust in a sensitivity analysis that  
154 sequentially excluded individual risk maps (Fig. S6). Considering biome-wide patterns, tropical  
155 forests had slightly higher average median risk percentiles (51%ile and 62%ile for tropical moist  
156 broadleaf and tropical/subtropical dry broadleaf forests, respectively) than boreal (44%ile) or  
157 temperate (35%ile and 42%ile for broadleaf and coniferous, respectively) forests (Fig. S7).

158 All of the different approaches to estimating forest climate risk have limitations and  
159 different uncertainties that are worth bearing in mind. Mechanistic model projections (C risk  
160 axis) include the benefits of rising atmospheric CO<sub>2</sub> concentrations on forest productivity (i.e.



161 CO<sub>2</sub> fertilization), as well as coarse estimates of climate sensitivities of plant functional types  
162 and fire disturbance. However, these models are generally thought to be lacking a substantial  
163 range of key impacts of climate on tree mortality and other disturbances, making it likely that  
164 risk estimates from this approach are overly conservative and carbon gains may be overestimated  
165 (26). Furthermore, these models do not realistically capture current tropical forest carbon  
166 dynamics (27) and the potential for biome shifts remains very uncertain in these models (14, 28),  
167 in part because they frequently neglect processes of tree regeneration (29).

168         The empirical species distribution and ecoregion biome transition models (species risk  
169 axis) are correlative in nature and do not directly include mechanistic processes of growth,  
170 mortality, CO<sub>2</sub>-related effects, or disturbance. They are, nevertheless, widely used across the  
171 globe for conservation planning efforts (16, 30), as they provide a powerful approach to estimate  
172 the species pool under given climatic conditions. Empirical disturbance models (disturbance risk  
173 axis) capture only one key component of forest carbon cycling and do not account for regrowth,  
174 species turnover, and other dynamics. Nonetheless, a broad body of literature has demonstrated  
175 that changes in disturbance regimes have strong leverage on forest carbon cycling in many  
176 ecosystems globally (9, 12, 28). Finally, all of these approaches treat direct human impacts of  
177 land-use change and management distinctly. Forest management, as a key disturbance and arbiter  
178 of forest risk, is included implicitly or explicitly in all methods here. Whilst we have made  
179 extensive efforts to screen out changes due to land conversion (20), land management remains an  
180 important uncertainty and caveat in these analyses. A previous global risk analysis for forest loss  
181 using a single, older mechanistic vegetation model (31) projected highest forest loss in the  
182 eastern Amazon, eastern North American boreal, and broad areas of the European and Asian

183 boreal forests, which is partially consistent with the species turnover and biome transition  
184 estimates presented here (e.g. Fig 2A) and the multi-method aggregate map.

185         Ultimately, our analysis reveals a strikingly divergent set of projections when comparing  
186 across a wide range of methods and approaches to examine the vulnerability of Earth’s forests to  
187 climate risks. If forests are tapped to play an important role in climate mitigation, an enormous  
188 scientific effort is needed to better shed light on when and where forests will be resilient to  
189 climate change in the 21<sup>st</sup> century. These results highlight an urgent need for more detailed  
190 treatment of climate-sensitive disturbances in mechanistic vegetation models, more extensive  
191 benchmarking of those models against disturbance and mortality datasets, and better  
192 identification of agents of change in observational datasets to underlie more nuanced empirical  
193 approaches. Continuing the long-term monitoring efforts that enable such work will be  
194 fundamental to improving such models. Our results also underscore key needs to focus on  
195 climate-driven biome transitions. Currently, enormous uncertainty remains about the spatial and  
196 temporal patterns of forest vulnerability to climate change. They further emphasize that the  
197 effectiveness of nature-based climate solutions currently under discussion (3, 4) are faced with  
198 great uncertainties, given the profound climate impacts on forests expected in the 21<sup>st</sup> century.

199

200

201

202

203

204

205

- 207 1. G. B. Bonan, Forests and climate change: Forcings, feedbacks, and the climate benefits of  
208 forests. *Science*. **320**, 1444–1449 (2008).
- 209 2. FAO and UNEP, “The State of the World’s Forests 2020. Forests, biodiversity and people”  
210 (Rome, 2020).
- 211 3. B. W. Griscom, J. Adams, P. W. Ellis, R. A. Houghton, G. Lomax, D. A. Miteva, W. H.  
212 Schlesinger, D. Shoch, J. V. Siikamäki, P. Smith, Natural climate solutions. *Proc. Natl.*  
213 *Acad. Sci.* **114**, 11645–11650 (2017).
- 214 4. S. Roe, C. Streck, M. Obersteiner, S. Frank, B. Griscom, L. Drouet, O. Fricko, M. Gusti, N.  
215 Harris, T. Hasegawa, Contribution of the land sector to a 1.5° C world. *Nat. Clim.*  
216 *Change*, 1–12 (2019).
- 217 5. IPCC, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change*  
218 *Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel*  
219 *on Climate Change* (Cambridge University Press, Cambridge, United Kingdom, and New  
220 York, NY, USA, 2012).
- 221 6. T. J. Brodribb, J. Powers, H. Cochard, B. Choat, Hanging by a thread? Forests and drought.  
222 *Science*. **368**, 261–266 (2020).
- 223 7. W. R. Anderegg, A. T. Trugman, G. Badgley, C. M. Anderson, A. Bartuska, P. Ciais, D.  
224 Cullenward, C. B. Field, J. Freeman, S. J. Goetz, Climate-driven risks to the climate  
225 mitigation potential of forests. *Science*. **368** (2020).
- 226 8. P. Friedlingstein, M. Meinshausen, V. K. Arora, C. D. Jones, A. Anav, S. K. Liddicoat, R.  
227 Knutti, Uncertainties in CMIP5 Climate Projections due to Carbon Cycle Feedbacks. *J.*  
228 *Clim.* **27** (2014).
- 229 9. W. A. Kurz, C. C. Dymond, G. Stinson, G. J. Rampley, E. T. Neilson, A. L. Carroll, T.  
230 Ebata, L. Safranyik, Mountain pine beetle and forest carbon feedback to climate change.  
231 *Nature*. **452**, 987–990 (2008).
- 232 10. C. D. Allen, A. K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T.  
233 Kitzberger, A. Rigling, D. D. Breshears, E. H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang,  
234 J. Castro, N. Demidova, J. H. Lim, G. Allard, S. W. Running, A. Semerci, N. Cobb, A  
235 global overview of drought and heat-induced tree mortality reveals emerging climate  
236 change risks for forests. *For. Ecol. Manag.* **259**, 660–684 (2010).
- 237 11. R. Seidl, D. Thom, M. Kautz, D. Martin-Benito, M. Peltoniemi, G. Vacchiano, J. Wild, D.  
238 Ascoli, M. Petr, J. Honkaniemi, Forest disturbances under climate change. *Nat. Clim.*  
239 *Change*. **7**, 395 (2017).
- 240 12. J. A. Wang, A. Baccini, M. Farina, J. T. Randerson, M. A. Friedl, Disturbance suppresses  
241 the aboveground carbon sink in North American boreal forests. *Nat. Clim. Change*. **11**,  
242 435–441 (2021).
- 243 13. J. Lecina-Diaz, J. Martínez-Vilalta, A. Alvarez, M. Banqué, J. Birkmann, D. Feldmeyer, J.  
244 Vayreda, J. Retana, Characterizing forest vulnerability and risk to climate-change  
245 hazards. *Front. Ecol. Environ.* **19**, 126–133 (2021).
- 246 14. R. A. Fisher, C. D. Koven, W. R. Anderegg, B. O. Christoffersen, M. C. Dietze, C. E.  
247 Farrior, J. A. Holm, G. C. Hurtt, R. G. Knox, P. J. Lawrence, Vegetation demographics in  
248 Earth System Models: A review of progress and priorities. *Glob. Change Biol.* **24**, 35–54  
249 (2018).
- 250 15. S. Hantson, D. I. Kelley, A. Arneeth, S. P. Harrison, S. Archibald, D. Bachelet, M. Forrest,

- 251 T. Hickler, G. Lasslop, F. Li, Quantitative assessment of fire and vegetation properties in  
252 simulations with fire-enabled vegetation models from the Fire Model Intercomparison  
253 Project. *Geosci. Model Dev.* **13**, 3299–3318 (2020).
- 254 16. J. Elith\*, C. H. Graham\*, R. P. Anderson, M. Dudík, S. Ferrier, A. Guisan, R. J. Hijmans,  
255 F. Huettmann, J. R. Leathwick, A. Lehmann, J. Li, L. G. Lohmann, B. A. Loiselle, G.  
256 Manion, C. Moritz, M. Nakamura, Y. Nakazawa, J. McC. M. Overton, A. Townsend  
257 Peterson, S. J. Phillips, K. Richardson, R. Scachetti-Pereira, R. E. Schapire, J. Soberón,  
258 S. Williams, M. S. Wisz, N. E. Zimmermann, Novel methods improve prediction of  
259 species' distributions from occurrence data. *Ecography*. **29**, 129–151 (2006).
- 260 17. S. Z. Dobrowski, C. E. Littlefield, D. S. Lyons, C. Hollenberg, C. Carroll, S. A. Parks, J. T.  
261 Abatzoglou, K. Hegewisch, J. Gage, Protected-area targets could be undermined by  
262 climate change-driven shifts in ecoregions and biomes. *Commun. Earth Environ.* **2**, 1–11  
263 (2021).
- 264 18. S. R. Coffield, K. S. Hemes, C. D. Koven, M. L. Goulden, J. T. Randerson, Climate-driven  
265 limits to future carbon storage in California's wildland ecosystems. *AGU Adv.*, 2(3),  
266 e2021AV000384 (2021).
- 267 19. R. Seidl, J. Honkaniemi, T. Aakala, A. Aleinikov, P. Angelstam, M. Bouchard, et al,  
268 Globally consistent climate sensitivity of natural disturbances across boreal and  
269 temperate forest ecosystems. *Ecography*. **43**, 967–978 (2020).
- 270 20. See Supplementary Methods and Materials.
- 271 21. A. S. Mori, L. E. Dee, A. Gonzalez, H. Ohashi, J. Cowles, A. J. Wright, M. Loreau, Y.  
272 Hautier, T. Newbold, P. B. Reich, Biodiversity–productivity relationships are key to  
273 nature-based climate solutions. *Nat. Clim. Change*. **11**, 543–550 (2021).
- 274 22. P. R. Elsen, E. C. Saxon, B. A. Simmons, M. Ward, B. A. Williams, H. S. Grantham, S.  
275 Kark, N. Levin, K.-V. Perez-Hammerle, A. E. Reside, Accelerated shifts in terrestrial life  
276 zones under rapid climate change. *Glob. Change Biol.* **28**, 918–935 (2022).
- 277 23. M. Michaelian, E.H. Hogg, R.J. Hall, E. Arsenault, Massive mortality of aspen following  
278 severe drought along the southern edge of the Canadian boreal forest. *Glob. Change Biol*,  
279 **17**, 2084-2094 (2011).
- 280 24. L.V. Gatti, L.S. Basso, J.B. Miller, M. Gloor, L. Gatti Domingues, H.L. Cassol, H. L., ... &  
281 R.A. Neves, Amazonia as a carbon source linked to deforestation and climate change.  
282 *Nature*, **595**, 388-393 (2021).
- 283 25. Saatchi S, Longo M, Xu L et al. Detecting vulnerability of humid tropical forests to  
284 multiple stressors. *One Earth*, **4**, 988-1003 (2021)
- 285 26. B. M. Sanderson, R. A. Fisher, A fiery wake-up call for climate science. *Nat. Clim.*  
286 *Change*. **10**, 175–177 (2020).
- 287 27. A. Koch, W. Hubau, S. L. Lewis, *Earths Future*, 9(5), e2020EF001874 (2021).
- 288 28. T. A. Pugh, A. Arneth, M. Kautz, B. Poulter, B. Smith, Important role of forest  
289 disturbances in the global biomass turnover and carbon sinks. *Nat. Geosci.* **12**, 730–735  
290 (2019).
- 291 29. K. Albrich, W. Rammer, M. G. Turner, Z. Ratajczak, K. H. Braziunas, W. D. Hansen, R.  
292 Seidl, Simulating forest resilience: A review. *Glob. Ecol. Biogeogr.* **29**, 2082–2096  
293 (2020).
- 294 30. L. L. Porfirio, R. M. Harris, E. C. Lefroy, S. Hugh, S. F. Gould, G. Lee, N. L. Bindoff, B.  
295 Mackey, Improving the use of species distribution models in conservation planning and

- 296 management under climate change. *PLoS One*. **9**, e113749 (2014).
- 297 31. M. Scholze, W. Knorr, N. W. Arnell, I. C. Prentice, A climate-change risk analysis for  
298 world ecosystems. *Proc. Natl. Acad. Sci.* **103**, 13116–13120 (2006).
- 299 32. M. A. Moritz, M.-A. Parisien, E. Batllori, M. A. Krawchuk, J. Van Dorn, D. J. Ganz, K.  
300 Hayhoe, Climate change and disruptions to global fire activity. *Ecosphere*. **3**, 1–22  
301 (2012).
- 302 33. W. Knorr, A. Arneth, L. Jiang, Demographic controls of future global fire risk. *Nat. Clim.*  
303 *Change*. **6**, 781 (2016).
- 304 34. G. C. Hurtt, L. Chini, R. Sahajpal, S. Frolking, B. L. Boudris, K. Calvin, J. C. Doelman, J.  
305 Fisk, S. Fujimori, K. Klein Goldewijk, Harmonization of global land use change and  
306 management for the period 850–2100 (LUH2) for CMIP6. *Geosci. Model Dev.* **13**, 5425–  
307 5464 (2020).
- 308 35. M. Hansen, P. Potapov, R. Moore, M. Hancher, S. Turubanova, A. Tyukavina, D. Thau, S.  
309 Stehman, S. Goetz, T. Loveland, High-Resolution Global Maps of 21st-Century Forest  
310 Cover Change. *Science*. **342**, 850–853 (2013).
- 311 36. A. J. Meddens, J. A. Hicke, A. K. Macalady, P. C. Buotte, T. R. Cowles, C. D. Allen,  
312 Patterns and causes of observed piñon pine mortality in the southwestern United States.  
313 *New Phytol.* **206**, 91–97 (2015).
- 314 37. Y. Qin, J. T. Abatzoglou, S. Siebert, L. S. Huning, A. AghaKouchak, J. S. Mankin, C.  
315 Hong, D. Tong, S. J. Davis, N. D. Mueller, Agricultural risks from changing snowmelt.  
316 *Nat. Clim. Change*. **10**, 459–465 (2020).
- 317 38. L. R. Holdridge, Life zone ecology. *Life Zone Ecol.* (1967).
- 318 39. C. Parmesan, Ecological and evolutionary responses to recent climate change. *Annu Rev*  
319 *Ecol Evol Syst.* **37**, 637–669 (2006).
- 320 40. M. C. Urban, Accelerating extinction risk from climate change. *Science*. **348**, 571–573  
321 (2015).
- 322 41. R. G. Pearson, Species’ distribution modeling for conservation educators and practitioners.  
323 *Synth. Am. Mus. Nat. Hist.* **50**, 54–89 (2007).
- 324 42. L. L. Porfirio, R. M. Harris, E. C. Lefroy, S. Hugh, S. F. Gould, G. Lee, N. L. Bindoff, B.  
325 Mackey, Improving the use of species distribution models in conservation planning and  
326 management under climate change. *PLoS One*. **9**, e113749 (2014).
- 327 43. D. M. Olson, E. Dinerstein, E. D. Wikramanayake, N. D. Burgess, G. V. Powell, E. C.  
328 Underwood, J. A. D’amico, I. Itoua, H. E. Strand, J. C. Morrison, others, Terrestrial  
329 Ecoregions of the World: A New Map of Life on Earth: A new global map of terrestrial  
330 ecoregions provides an innovative tool for conserving biodiversity. *BioScience*. **51**, 933–  
331 938 (2001).
- 332 44. ESA, “Land Cover CCI Product User Guide Version 2” (Tech. Rep., 2017), (available at  
333 [maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2\\_2.0.pdf](https://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf)).
- 334 45. H. Hersbach, B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas,  
335 C. Peubey, R. Radu, I. Rozum, ERA5 hourly data on single levels from 1979 to present.  
336 *Copernic. Clim. Change Serv. C3S Clim. Data Store CDS*. **10** (2018).
- 337 46. S. A. Spawn, C. C. Sullivan, T. J. Lark, H. K. Gibbs, Harmonized global maps of above  
338 and belowground biomass carbon density in the year 2010. *Sci. Data*. **7**, 1–22 (2020).
- 339 47. F. Kimura, A. Kitoh, Downscaling by pseudo global warming method. *Final Rep. ICCAP*.  
340 **4346**, 435 (2007).

- 341 48. A. South, rworldmap: A New R package for Mapping Global Data. *R J.* **3** (2011) (available  
342 at [http://www.academia.edu/download/30318942/rjournal\\_2011-1.pdf#page=35](http://www.academia.edu/download/30318942/rjournal_2011-1.pdf#page=35)).
- 343 49. R. J. Hijmans, J. van Etten, raster: Geographic data analysis and modeling. *R Package*  
344 *Version.* **2**, 15 (2014).
- 345 50. P. Michna, M. Woods, RNetCDF—A Package for Reading and Writing NetCDF Datasets.  
346 *Peer-Rev. Open-Access Publ. R Found. Stat. Comput.*, **29** (2013).
- 347 51. A. Liaw, M. Wiener, L. Breiman, A. Cutler, Package “randomForest.” *Retrieved Dec.* **12**,  
348 2009 (2009).
- 349 52. T. Wei, V. Simko, M. Levy, Y. Xie, Y. Jin, J. Zemla, Package ‘corrplot.’ *Statistician.* **56**,  
350 e24 (2017).
- 351 53. R. Furrer, D. Nychka, S. Sain, M. D. Nychka, Package ‘fields.’ *R Found. Stat. Comput.*  
352 *Vienna Austria Httpwww Idg PlmirrorsCRANwebpackagesfieldsfields Pdf Last Accessed*  
353 *22 Dec. 2012* (2009).
- 354 54. D. Adler, M. D. Adler, Package ‘vioplot’ (2021).
- 355 55. R. Bivand, T. Keitt, B. Rowlingson, E. Pebesma, M. Sumner, R. Hijmans, E. Rouault, M.  
356 R. Bivand, Package ‘rgdal.’ *Bind. Geospatial Data Abstr. Libr. Available Online Httpscran*  
357 *R-Proj. Orgwebpackagesrgdalindex Html Accessed 15 Oct. 2017* (2015).
- 358 56. G. Danabasoglu, NCAR CESM2 model output prepared for CMIP6 CMIP historical  
359 (2019), , doi:10.22033/ESGF/CMIP6.7627.
- 360 57. G. Danabasoglu, J.-F. Lamarque, J. Bacmeister, D. A. Bailey, A. K. DuVivier, J. Edwards,  
361 L. K. Emmons, J. Fasullo, R. Garcia, A. Gettelman, *J. Adv. Model. Earth Syst.*, in press.
- 362 58. G. Danabasoglu, NCAR CESM2-WACCM model output prepared for CMIP6  
363 ScenarioMIP. *Earth Syst. Grid Fed. Httpsdoi Org1022033ESGF/CMIP6.* **10026** (2019).
- 364 59. A. Cherchi, P. G. Fogli, T. Lovato, D. Peano, D. Iovino, S. Gualdi, S. Masina, E.  
365 Scoccimarro, S. Materia, A. Bellucci, Global mean climate and main patterns of variability  
366 in the CMCC-CM2 coupled model. *J. Adv. Model. Earth Syst.* **11**, 185–209 (2019).
- 367 60. T. Lovato, D. Peano, CMCC CMCC-CM2-SR5 Model Output Prepared for CMIP6  
368 ScenarioMIP. *Earth Syst. Grid Fed.* (2020), doi:doi:10.22033/ESGF/CMIP6.1365.
- 369 61. R. Seferian, CNRM-CERFACS CNRM-ESM2-1 model output prepared for CMIP6  
370 ScenarioMIP. *Earth Syst. Grid Fed. Httpsdoi Org1022033ESGF/CMIP6.* **1395** (2019).
- 371 62. R. Séférian, P. Nabat, M. Michou, D. Saint-Martin, A. Voldoire, J. Colin, B. Decharme, C.  
372 Delire, S. Berthet, M. Chevallier, Evaluation of CNRM earth system model, CNRM-  
373 ESM2-1: Role of earth system processes in present-day and future climate. *J. Adv. Model.*  
374 *Earth Syst.* **11**, 4182–4227 (2019).
- 375 63. J.-C. Golaz, P. M. Caldwell, L. P. Van Roekel, M. R. Petersen, Q. Tang, J. D. Wolfe, G.  
376 Abeshu, V. Anantharaj, X. S. Asay-Davis, D. C. Bader, The DOE E3SM coupled model  
377 version 1: Overview and evaluation at standard resolution. *J. Adv. Model. Earth Syst.* **11**,  
378 2089–2129 (2019).
- 379 64. D. C. Bader, et al, E3SM-Project E3SM1.1 Model Output Prepared for CMIP6  
380 ScenarioMIP. *Earth Syst. Grid Fed.* (2020), doi:doi:10.22033/ESGF/CMIP6.15103.
- 381 65. EC-Earth Consortium, EC-Earth-Consortium EC-Earth3-CC Model Output Prepared for  
382 CMIP6 ScenarioMIP. *Earth Syst. Grid Fed.* (2021),  
383 doi:doi:10.22033/ESGF/CMIP6.15327.
- 384 66. R. Döscher, M. Acosta, A. Alessandri, P. Anthoni, A. Arneth, T. Arsouze, T. Bergmann, R.  
385 Bernadello, S. Bousetta, L.-P. Caron, The EC-earth3 Earth system model for the climate

- 386 model intercomparison project 6. *Geosci. Model Dev. Discuss.*, 1–90 (2021).
- 387 67. T. Mauritsen, J. Bader, T. Becker, J. Behrens, M. Bittner, R. Brokopf, V. Brovkin, M.  
388 Claussen, T. Crueger, M. Esch, Developments in the MPI-M Earth System Model version  
389 1.2 (MPI-ESM1. 2) and its response to increasing CO<sub>2</sub>. *J. Adv. Model. Earth Syst.* **11**, 998–  
390 1038 (2019).
- 391 68. K. H. Wieners, M. Giorgetta, J. Jungclaus, C. Reick, M. Esch, M. Bittner, V. Gayler, H.  
392 Haak, P. de Vrese, T. Raddatz, MPI-M MPIESM1. 2-LR model output prepared for CMIP6  
393 ScenarioMIP. *Earth Syst. Grid Fed. <https://doi.org/10.22033/ESGF/CMIP6>*. **793** (2019).
- 394 69. Ø. Seland, M. Bentsen, D. Olivieri, T. Toniazzo, A. Gjermundsen, L. S. Graff, J. B.  
395 Debernard, A. K. Gupta, Y.-C. He, A. Kirkevåg, Overview of the Norwegian Earth System  
396 Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario  
397 simulations. *Geosci. Model Dev.* **13**, 6165–6200 (2020).
- 398 70. Ø. Seland, M. Bentsen, D. J. L. Olivieri, T. Toniazzo, A. Gjermundsen, L. S. Graff, J. B.  
399 Debernard, A. K. Gupta, Y. He, A. Kirkevåg, NCC NorESM2-LM model output prepared  
400 for CMIP6 ScenarioMIP ssp585 (2019).
- 401 71. M. Bentsen, D. J. L. Olivieri, y Seland, T. Toniazzo, A. Gjermundsen, L. S. Graff, M.  
402 Schulz, NCC NorESM2-MM model output prepared for CMIP6 ScenarioMIP. *Earth Syst.*  
403 *Grid Fed. [URL <https://doi.org/10.22033/ESGF/CMIP6>](https://doi.org/10.22033/ESGF/CMIP6)*. **608** (2019).
- 404 72. W.-L. Lee, Y.-C. Wang, C.-J. Shiu, I. -chun Tsai, C.-Y. Tu, Y.-Y. Lan, J.-P. Chen, H.-L.  
405 Pan, H.-H. Hsu, Taiwan Earth System Model Version 1: description and evaluation of  
406 mean state. *Geosci. Model Dev.* **13**, 3887–3904 (2020).
- 407 73. W.-L. Lee, H.-C. Liang, TaiESM1.0 Model Output Prepared for CMIP6 ScenarioMIP.  
408 *Earth Syst. Grid Fed.* (2020), doi:doi:10.22033/ESGF/CMIP6.9688.
- 409 74. T. Ziehn, M. A. Chamberlain, R. M. Law, A. Lenton, R. W. Bodman, M. Dix, L. Stevens,  
410 Y.-P. Wang, J. Srbinovsky, The Australian earth system model: ACCESS-ESM1. 5. *J.*  
411 *South. Hemisphere Earth Syst. Sci.* **70**, 193–214 (2020).
- 412 75. T. Ziehn, M. Chamberlain, A. Lenton, R. Law, R. Bodman, M. Dix, K. Druken, CSIRO  
413 ACCESS-ESM1. 5 model output prepared for CMIP6 ScenarioMIP ssp585. *Earth Syst.*  
414 *Grid Fed.* (2019).
- 415 76. T. Wu, Y. Lu, Y. Fang, X. Xin, L. Li, W. Li, W. Jie, J. Zhang, Y. Liu, L. Zhang, The  
416 Beijing Climate Center climate system model (BCC-CSM): the main progress from CMIP5  
417 to CMIP6. *Geosci. Model Dev.* **12**, 1573–1600 (2019).
- 418 77. X. Xin, T. Wu, X. Shi, F. Zhang, J. Li, M. Chu, Q. Liu, J. Yan, Q. Ma, M. Wei, in *Version*  
419 *20201101, Earth System Grid Federation* (2019).
- 420 78. N. C. Swart, J. N. Cole, V. V. Kharin, M. Lazare, J. F. Scinocca, N. P. Gillett, J. Anstey, V.  
421 Arora, J. R. Christian, S. Hanna, The Canadian Earth System Model version 5 (CanESM5.  
422 0.3). *Geosci. Model Dev.* **12**, 4823–4873 (2019).
- 423 79. N. C. Swart, J. N. Cole, V. V. Kharin, M. Lazare, J. F. Scinocca, N. P. Gillett, J. Anstey, V.  
424 Arora, J. R. Christian, Y. Jiao, CCCma CanESM5 model output prepared for CMIP6  
425 ScenarioMIP. *Earth Syst. Grid Fed.* (2019).
- 426 80. E. M. Volodin, E. V. Mortikov, S. V. Kostykin, V. Y. Galin, V. N. Lykossov, A. S.  
427 Gritsun, N. A. Diansky, A. V. Gusev, N. G. Iakovlev, Simulation of the present-day  
428 climate with the climate model INMCM5. *Clim. Dyn.* **49**, 3715–3734 (2017).
- 429 81. E. Volodin, E. Mortikov, A. Gritsun, V. Lykossov, V. Galin, N. Diansky, A. Gusev, S.  
430 Kostykin, N. Iakovlev, A. Shestakova, INM INM-CM4-8 model output prepared for

- 431 CMIP6 ScenarioMIP. *Earth Syst. Grid Fed.* URL <https://doi.org/10.22033/ESGF/CMIP6>.  
432 **12321** (2019).
- 433 82. O. Boucher, J. Servonnat, A. L. Albright, O. Aumont, Y. Balkanski, V. Bastrikov, S.  
434 Bekki, R. Bonnet, S. Bony, L. Bopp, *J. Adv. Model. Earth Syst.*, in press.
- 435 83. O. Boucher, S. Denvil, G. Levvasseur, A. Cozic, A. Caubel, M. A. Foujols, Y.  
436 Meurdesoif, P. Cadule, M. Devilliers, E. Dupont, IPSL IPSL-CM6A-LR model output  
437 prepared for CMIP6 ScenarioMIP, Version 20200601 (2019).
- 438 84. Y. Kim, et al, KIOST KIOST-ESM Model Output Prepared for CMIP6 ScenarioMIP.  
439 *Earth Syst. Grid Fed.* (2019), doi:doi:10.22033/ESGF/CMIP6.11241.
- 440 85. T. Hajima, M. Watanabe, A. Yamamoto, H. Tatebe, M. A. Noguchi, M. Abe, R. Ohgaito,  
441 A. Ito, D. Yamazaki, H. Okajima, Development of the MIROC-ES2L Earth system model  
442 and the evaluation of biogeochemical processes and feedbacks. *Geosci. Model Dev.* **13**,  
443 2197–2244 (2020).
- 444 86. K. Tachiiri, M. Abe, T. Hajima, O. Arakawa, T. Suzuki, Y. Komuro, K. Ogochi, M.  
445 Watanabe, A. Yamamoto, H. Tatebe, MIROC MIROC-ES2L model output prepared for  
446 CMIP6 ScenarioMIP. *Earth Syst. Grid Fed.* Retrieved [http://cera-www.dkrz.de/WDC/CMIP6/CMIP6\\_ScenarioMIP\\_MIROC\\_MIROC-ES2L](http://cera-www.dkrz.de/WDC/CMIP6/CMIP6_ScenarioMIP_MIROC_MIROC-ES2L)  
447 (2019).
- 448 87. A. A. Sellar, J. Walton, C. G. Jones, R. Wood, N. L. Abraham, M. Andrejczuk, M. B.  
449 Andrews, T. Andrews, A. T. Archibald, L. de Mora, *J. Adv. Model. Earth Syst.*, in press.
- 450 88. P. Good, A. Sellar, Y. Tang, S. Rumbold, R. Ellis, D. Kelley, T. Kuhlbrodt, J. Walton,  
451 MOHC UKESM1. 0-LL model output prepared for CMIP6 ScenarioMIP. *Earth Syst. Grid*  
452 *Fed.* <https://doi.org/10.22033/ESGF/CMIP6>. **1567** (2019).  
453

454

455

456 **Funding:** WRLA acknowledges support from the David and Lucille Packard Foundation, US  
457 National Science Foundation grants 1802880, 2003017 and 2044937, and USDA National  
458 Institute of Food and Agriculture, Agricultural and Food Research Initiative Competitive  
459 Programme, Ecosystem Services and Agro-Ecosystem Management, grant no. 2018-67019-  
460 27850. CW acknowledges support from the David and Lucille Packard Foundation. RS, NA and  
461 TP acknowledge support from the European Research Council (ERC) under the European  
462 Union’s Horizon 2020 research and innovation programme (RS: grant agreement No 101001905,  
463 FORWARD; NA and TP grant agreement No 758873, TreeMort). This study contributes to the  
464 strategic research areas BECC and MERGE.



465

466 **Author contributions:** WRLA designed the study with input from all co-authors. WRLA, CW,  
467 and NA analyzed the data. WRLA wrote an initial draft and CW, NA, NC, TAMP, JPS, and RS  
468 provided extensive comments and revisions.

469

470 **Competing interests:** The authors declare no competing interests.

471

472 **Data and materials availability:** Analysis code and processed data underlying the paper  
473 analyses can be found at <https://figshare.com/s/b97c7071e2af904955e7>. Google Earth Engine  
474 code for disturbance analysis can be found at:

475 [https://code.earthengine.google.com/?accept\\_repo=users/NXA807/ForestGlobalClimateRisks](https://code.earthengine.google.com/?accept_repo=users/NXA807/ForestGlobalClimateRisks)

476 All CMIP6 data and datasets underlying the empirical model analysis are publicly available from  
477 the CMIP6 data portal or published article reference.

478

479

## 480 **Supplementary Content**

481 Materials and Methods

482 Figs. S1 to S10

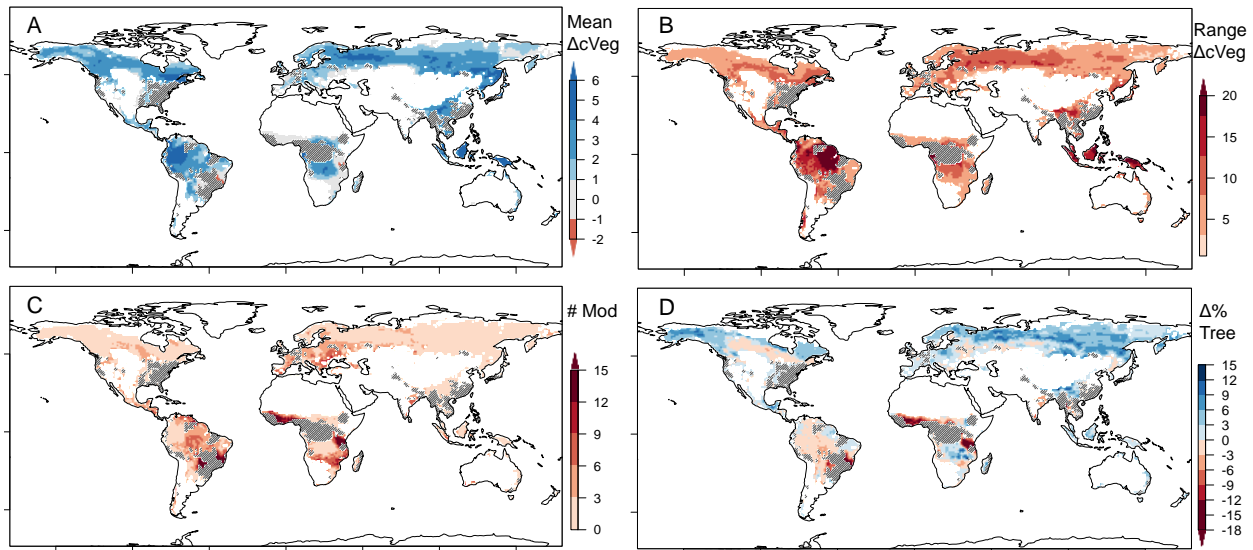
483 Table S1

484 References (32-88)

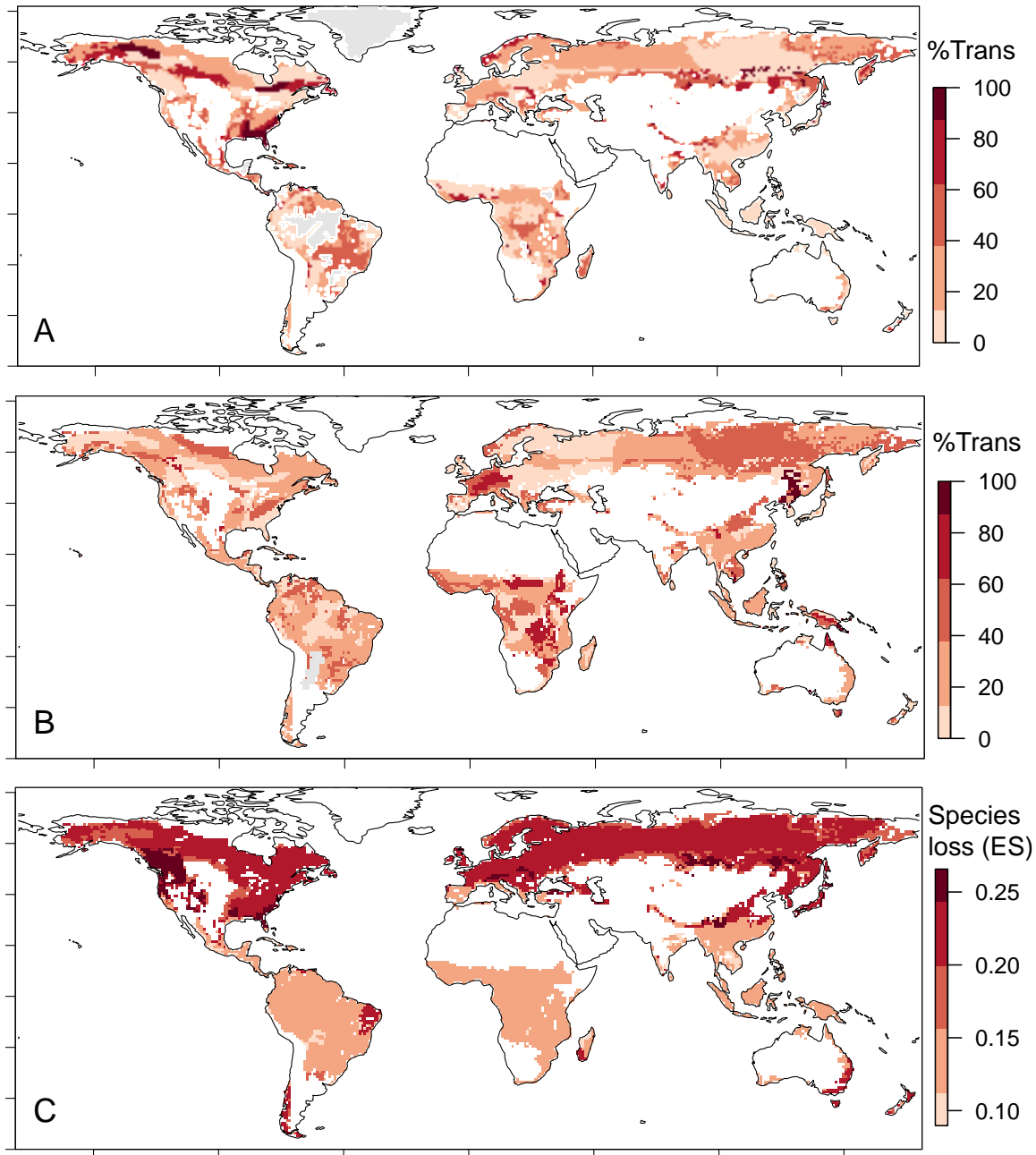
485

486

487

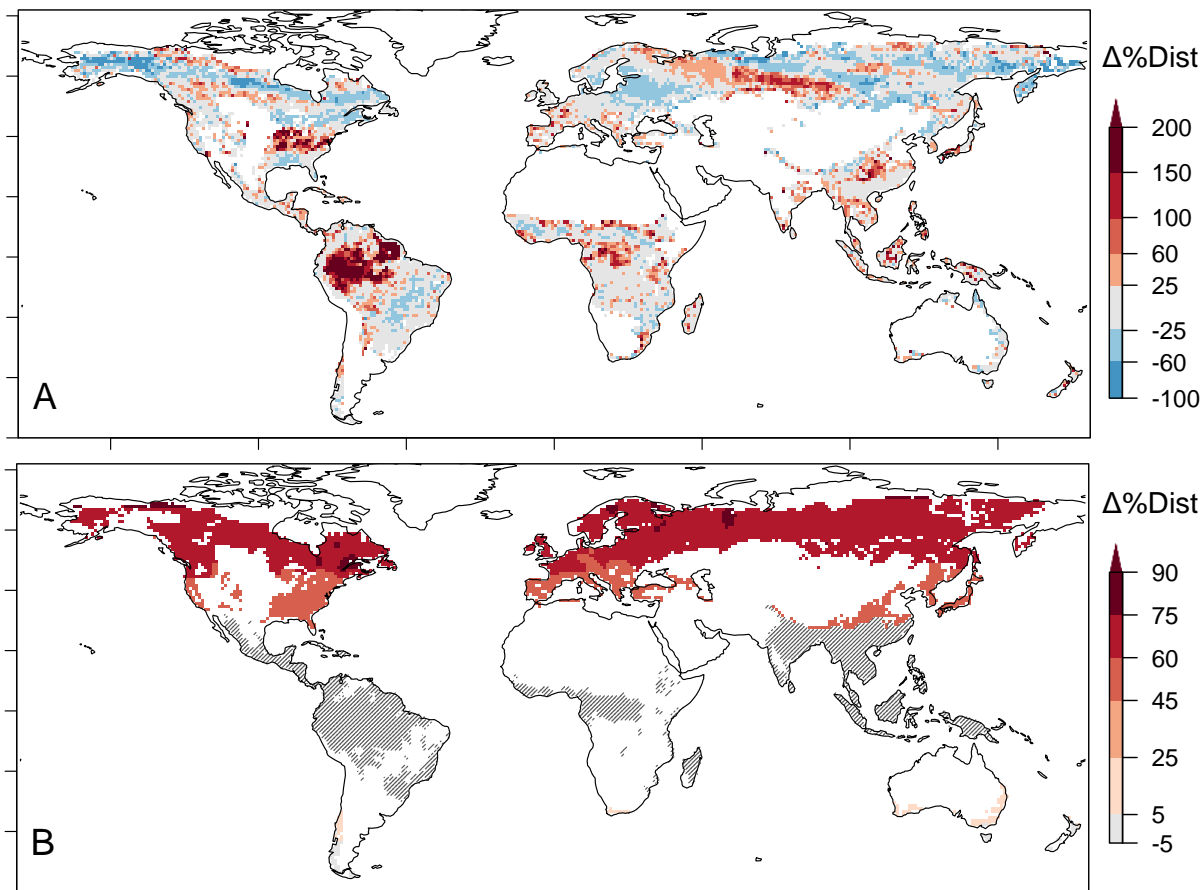


489  
 490 Figure 1: Future forest carbon and climate risk projections from mechanistic vegetation models.  
 491 All panels analyze the change between 2081-2100 in Shared Socioeconomic Pathway 5-8.5  
 492 (SSP585) compared to 1995-2014 historical simulations and are masked by present forested  
 493 areas. Multi-model mean (A) and range (B) of the change in live carbon mass in vegetation  
 494 ( $\text{kg}\cdot\text{m}^{-2}$ ) across 23 models. (C) Number of models projecting vegetation carbon losses in a grid  
 495 cell over the same time period. (D) Multi-model mean spatial patterns of the percent change in  
 496 fraction of tree plant functional types in a grid cell. Gray hatched areas indicate grid cells  
 497 removed from analysis due to land use-driven forest loss.



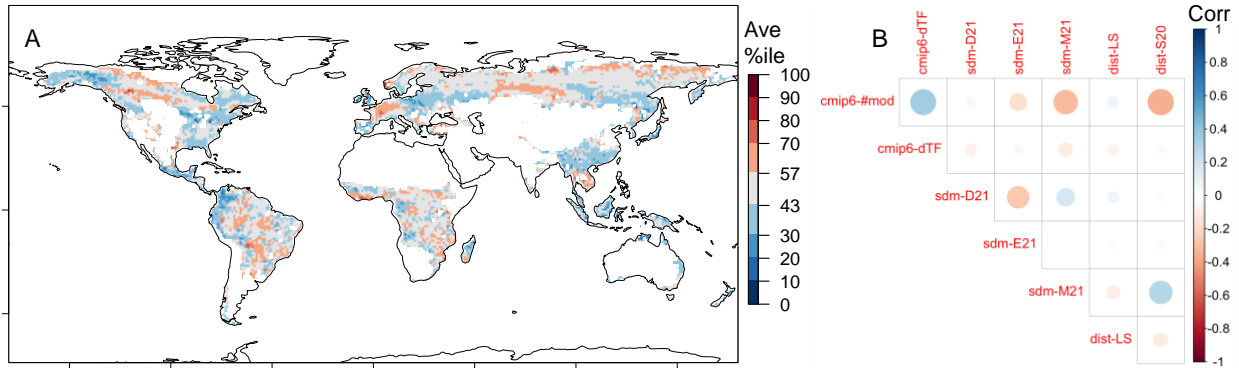
498

499 Figure 2: Global forest risk estimates from 'climate envelope' approaches. (A) Projected percent  
 500 transition (%Trans) of ecoregions to another ecoregion with a warming of +2 C above pre-  
 501 pre-industrial from Dobrowski et al. 2021<sup>17</sup>. (B) Projected percent transition of climate 'life-zones'  
 502 between 1979-2013 and 2061-2080 in a moderate (RCP 4.5) climate scenario from Elsen et al.  
 503 2021<sup>21</sup>. (C) Risk of loss in species richness (quantified as an 'effect size' (ES) of  $-1 \times$   
 504  $\log(\Delta \text{SpeciesRichness}_{\text{Highcc-mitigation}} / \Delta \text{SR}_{\text{baseline}})$ ) where higher numbers indicate more risk of  
 505 species loss) in the 2070s in a high climate change (RCP 8.5) scenario from Mori et al. 2021<sup>20</sup>.



506  
 507 Figure 3: Projected change in climate-sensitive disturbance risks. (A) Average change in percent  
 508 disturbed in a grid cell from random-forest model projections of Landsat-based stand-replacing  
 509 disturbances for 2081-2100 in a moderate climate change scenario (Shared Socioeconomic  
 510 Pathway 2-4.5 (SSP245)) compared to 1995-2014. (B) Average change in percent disturbed in a  
 511 grid cell from protected area disturbance models for only temperate and boreal ecosystems in  
 512 2081-2100 in a moderate climate change scenario (SSP245) compared to 1995-2014. Gray  
 513 hatching in grid cells indicates no data from this data source.

514  
 515  
 516  
 517  
 518



519  
 520 Figure 4: Comparisons and syntheses across different climate risk axes. (A) Average percentile  
 521 of risk combined across all metrics where 0%ile is lowest climate risk and 100%ile is highest  
 522 climate risk, averaged across all datasets that covered a given grid cell. (B) Correlation matrix  
 523 between different climate risk axes and metrics where the size and color are proportionate to  
 524 correlation strength and magnitude (all correlations n.s.). Risk axes and metrics: number of  
 525 models showing carbon losses in forested regions in Coupled Model Intercomparison Project  
 526 Phase 6 data (cmip6-#mod), change in tree fraction in the subset of CMIP6 models (cmip6-dTF),  
 527 species distribution/climate niche models of ecoregion percent changes from Dobrowski et al.  
 528 (2021)<sup>17</sup> (sdm-D21), species distribution/climate niche models of life-zone percent changes from  
 529 Elsen et al. (2021)<sup>20</sup> (sdm-E21), species distribution models of loss of species richness from Mori  
 530 et al. (2021)<sup>21</sup> (sdm-M21), random-forest based projections of Landsat-detected stand-replacing  
 531 disturbances (dist-LS), and change in percent disturbed in a grid cell from protected area  
 532 disturbance models from Seidl et al. (2020)<sup>19</sup> (dist-S20).  
 533

534