Assessing changes in global fire regimes

Sayedeh Sara Sayedi[1]-Benjamin W Abbott[1]- Boris Vannière[2,3,4]- Bérangère Leys[5]- Daniele Colombaroli[6]- Graciela Gil Romera[7]-Michał Słowiński[8]-Julie C. Aleman[5]- Olivier Blarquez[9]- Angelica Feurdean[10,11]- Kendrick Brown[12,13]- Tuomas Aakala[14] - Teija Alenius[15] - Kathryn Allen[16,17,18]-Maja Andric[19]-Yves Bergeron[20,21]-Siria Biagioni[22] -Richard Bradshaw[23]-Laurent Bremond[24]-Elodie Brisset[5]-Joseph Brooks[25]- Sandra Bruegger[26]-Thomas Brussel[27]- Haidee Cadd[28]-Eleonora Cagliero[29,30]- Christopher Carcaillet[31,32]-Vachel Carter[33]-Filipe X. Catry[34]-Antoine Champreux[35]- Emeline Chaste[36,37]-Raphaël Daniel Chavardès[20,38,39]- Melissa Chipman[40] -Marco Conedera[41]- Simon Connor[42]- Mark Constantine[43]-Colin Courtney Mustaphi[44,45,46]-Abraham N Dabengwa[47]- William Daniels[48]-Erik De Boer[49]-Elisabeth Dietze[50,51]-Joan Estrany[52,53] -Paulo Fernandes[54]- Walter Finsinger[55]-Suzette Flantua[56]-Paul Fox-Hughes[57]- Dorian M Gaboriau[20]-Eugenia M.Gayo [58]-Martin.P Girardin[59]-Jeffery Glenn[60]-Ramesh Glückler[50]-Catalina González-Arango[61]- Mariangelica Groves[62]-Rebecca Jenner Hamilton[63]-Douglas Hamilton[64]-Stijn Hantson[65]-K. Anggi Hapsari[22]-Mark Hardiman[66]-Donna Hawthorne[67]-Kira Hoffman[68]-Virginia Iglesias[69] -Jun Inoue[70]-Allison T Karp[71]-Patrik Krebs[41]-Charuta Kulkarni[72]-Niina Kuosmanen[73]-Terri Lacourse[74]- Marie-Pierre Ledru[75]-Marion Lestienne[76]-Colin Long[77]-José Antonio López-Sáez[78]-Nicholas Loughlin[79]-Elizabeth Lynch[80]-Mats Niklasson[81]-Javier Madrigal[82]-S. Yoshi Maezumi [83]- Katarzyna Marcisz[84]-Grant Meyer[85]-Michela Mariani[86]-David McWethy[87]- Chiara Molinari[88] -Encarni Montoya[25-89]-Scott Mooney[90]-Cesar Morales-Molino[91,92] -Jesse Morris[93]-Patrick Moss[94]- Imma Oliveras[95]-José Miguel Pereira[96]-Gianni Boris Pezzatti[41]-Nadine Pickarski[97] – Roberta Pini[98]-Vincent Robin[99]-Emma Rehn[100]-Cecile Remy[101]- Damien Rius[2] -Yanming Ruan[102]-Natalia Rudaya[103,104]-Jeremy Russell-Smith[105]- Heikki Seppä[74]-Lyudmila Shumilovskikh[106]-William T.Sommers[107,108]-Çağatay Tavşanoğlu[109]-Charles Umbanhowar[110]-Erickson Urquiaga[111,112]- Dunia Urrego[113] -Richard Vachula[114] -Tuomo Wallenius[115]-Chao You[116]- Anne-Laure Daniau[117]

Affiliations: The affiliations are placed at the end of the document.

Keywords: Fire regime change, Holocene, Climate change, Ecosystem services, Management, Expert assessment

Corresponding author email: sarasayedi91@gmail.com

Abstract

Human activity has fundamentally altered wildfire on Earth, creating serious consequences for human health, global biodiversity, and climate change. However, it remains difficult to predict fire interactions with land use, management, and climate change, representing a serious knowledge gap and vulnerability. We used expert assessment to combine opinions about past and future fire regimes from 98 wildfire researchers. We asked for quantitative and qualitative assessments of the frequency, type, and implications of fire regime change from the beginning of the Holocene through the year 2300. Respondents indicated that direct human activity was already influencing wildfires locally since at least ~12,000 years BP, though natural climate variability remained the dominant driver of fire regime until around 5000 years BP. Responses showed a ten-fold increase in the rate of wildfire regime change during the last 250 years compared with the rest of the Holocene, corresponding first with the intensification and extensification of land use and later with anthropogenic climate change. Looking to the future, fire

regimes were predicted to intensify, with increases in fire frequency, severity, and/or size in all biomes except grassland ecosystems. Fire regime showed quite different climate sensitivities across biomes, but the likelihood of fire regime change increased with higher greenhouse gas emission scenarios for all biomes. Biodiversity, carbon storage, and other ecosystem services were predicted to decrease for most biomes under higher emission scenarios. We present recommendations for adaptation and mitigation under emerging fire regimes, concluding that management options are seriously constrained under higher emission scenarios.

Introduction

Human alteration of land cover and climate is reshaping wildfire on Earth (Bowman et al., 2020; Davis, 2021; T. M. Ellis et al., 2022; Pereira et al., 2022). Most terrestrial ecosystems have coevolved with fire over millions of years and many require periodic disturbance to maintain ecosystem structure and function (Bond et al., 2005; Harris et al., 2016). Yet, when fires exceed their historical patterns of intensity, extent, severity, seasonality, and frequency (hereafter *fire regime*; Figure.1a), they can deleteriously influence biodiversity (Feng et al., 2021; Kelly et al., 2020), climate (IPCC, 2021), and societies (Doerr & Santín, 2016; Johnston et al., 2021; Jones, 2017). In some regions, recent state changes in fire regime have reduced ecosystem services, including air quality, water availability, habitat, and ecosystem carbon storage (Collins et al., 2021; Crandall et al., 2021; McClure & Jaffe, 2018; Pausas & Keeley, 2019; Xie et al., 2022). These changes in disturbances can cause loss of life and property, degradation of health, acute risk to fire managers, emergency evacuations, and other socioeconomic impacts (Balch et al., 2020; Raymond et al., 2020).

In the past and across large spatial scales, the dominant driver of fire regime has been the interaction between climate and vegetation (Abbott et al., 2016; Girardin et al., 2013; Harris et al., 2016; McDowell et al., 2020; Molinari et al., 2020). All aspects of climate, but especially patterns of precipitation and temperature influence vegetation composition and its moisture content. Climate and weather also control

ignition sources, with lightning being the most common natural source of wildfire. Consequently, climate lays the foundation for fire regimes through fuel availability, flammability, and ignition likelihood (Bowman et al., 2009; Chen et al., 2021; Scholten et al., 2021). As humans modified global patterns of vegetation, ignition, and climate over the past several millennia (Abbott et al., 2019; E. C. Ellis et al., 2021; McDowell et al., 2020; Watson et al., 2018), fire disturbance became progressively more anthropogenically influenced across local to global scales (Figure. 1a). For example, humans have directly modified vegetation type and density for 77% of the Earth's terrestrial surface, primarily through agriculture, with myriad consequences for fuel characteristics and ignition sources (Balch et al., 2017a; Bowman et al., 2011; Marlon et al., 2008; Słowiński et al., 2022; Watson et al., 2018). Understanding the characteristics and sensitivity of fire regime change is crucial for sustainable land management as well as climate change mitigation, adaptation, and planning (Cochrane & Bowman, 2021). However, knowledge of thresholds and tipping points in the relationships linking climate, land use, and fire regimes is lacking.

In this context, we conducted an assessment of scientific opinion about the drivers and consequences of fire regime change in the Holocene and near future. Combining assessments from multiple sources allows an integrative evaluation of the range of possible futures complementary to numerical model projections (Morgan, 2014; Sayedi et al., 2020; Schuur et al., 2013). These assessments can address the current needs of decision-makers and ecosystem managers to better understand and apply the consensus view from the research community. Using the collected informed opinion from experts, we evaluated centennial to millennial-scale state changes (Figure.1a) in past, present, and future fire regimes at both regional and biome levels through four questions: 1. How have fire regimes varied during the Holocene (the last ~11,700 years); 2. How likely are fire regime state changes under different future climate change scenarios; 3. What component of ecosystems will be affected by potential future fire regimes; and 4. What types of human activities could be the most effective for mitigation and adaptation under future fire regimes?

86 We asked experts from around the world (included here as co-authors) to respond to these questions for
87 terrestrial ecosystems in seven biogeographic realms and 14 biomes (Figure1.b) that reflect global
88 bioclimatic, socioeconomic, and fire regime characteristics (Olson et al., 2001). Each expert responded for
89 a biome-scale fire regime within a biogeographic realm (we define this unit "a *fire region"*) of their
90 expertise. We received responses for 70% of flammable land area worldwide (total land surface excluding
91 rock, ice, and lakes; Figure1.b, S1, Table S2).

92 **Methods and materials**

93 We used expert assessment to evaluate the risk of fire regime change and its consequences in the future.
94 After a literature review of both scientific and policy related documents about wildfires and fire regime
95 change, we designed a questionnaire to gather scientific opinion on changes in fire regimes and their
96 effects on ecosystems, climate, and societies (see Supplementary Information). The focus was specifically
97 on centennial-to-millennial changes in past, present and future fire regimes by biogeographic realms and
98 biome to consider long-term processes beyond observational and instrumental records. After two
99 pretesting rounds, the finalized questionnaire was distributed to 430 scientists with fire related expertise.
100 The list of experts was developed based on publications and referees from respondents. We received 123
101 filled surveys from 98 respondents (46% female, 45% male, 9% unspecified) (Table S2) from 23 countries
102 (Figure.S24). The primary research disciplines as self-identified by the respondents were 55%
103 paleoecology, 17% ecology, and 28% other fields such as geography or geosciences.

104 The questionnaire included background information on the concept of fire regime and state change to
105 delineate a standardized definition for this study for experts to use and a description of RCP scenarios and
106 predicted temperature and precipitation (see Supplementary Information). The question section focused
107 on four key topics: 1) past fire regimes, 2) current fire regime states, 3) future fire projections, and 4)
108 interventions and management. For each section, a self-reported expertise, confidence level, sources
109 used to generate estimates (e.g., published or unpublished empirical data, professional opinion)

(Table.S3), along with a list of sources of uncertainty were provided (Table.1). The questionnaire was a combination of quantitative and qualitative questions (full questionnaire included in the Supplementary Information). The qualitative questions included both open-ended questions and numerical responses. The open-ended questions were analyzed using thematic analysis method by coding the responses into categories after reviewing the responses.

For some of the quantitative questions, three quantiles (5% lower, 50% central and 95% upper) were provided to build a credible range of 90% for each question. We primarily used median central estimates for the main manuscript; though full ranges are shown in the Supplementary Information. We used nonparametric boxplots to evaluate the range of responses for each question, with descriptive statistics calculated in R version 3.6.1. We used ArcGIS Pro 3.0 for spatial analyses and visualizations.

Results and discussion

In the following subsections, we present estimates and suggestions based on experts' responses and we compare these opinions of estimates and projections with relevant literature. We focus on general patterns and trends among biomes and biogeographic realms (the comprehensive expert responses by fire region are available in the Supplementary Information). For the purposes of our study, we defined state change broadly as a large and sustained departure from a set of specific system behaviors (details in Supplementary Information-questionnaire). Fire regime state changes can be triggered by pulse or press disturbances, including internal and external drivers (e.g. climate change, vegetation shifts, human behavior), and can be reversible or permanent. For example, a state change in fire regime may be expressed as a shift in the central tendency (a decrease in mean annual area burned), overall variance (an increase in inter-annual variability of area burned), or frequency of events that exceed an ecological threshold (a change in the return interval of crown fires)(Scheffer et al., 2009; Seddon et al., 2014).

Past to present drivers of fire regime

The median estimated number of fire regime state changes during the Holocene ranged from seven (*Temperate grasslands, savannas, and shrublands*) to two (*Tundra*) across biomes (Figure. S2). Regarding the timing of the three largest fire regime state changes, 16% of respondents identified the early Holocene (ca. 11,700–8,200 BP), 27% the mid Holocene (ca. 8,200–4,200 BP), and 57% the late Holocene (ca. 4,200–0 BP). A temporal acceleration of state change occurred after the Industrial Revolution (1760 A.D.), which included 20% of the fire regime changes (Figure. S3). This represents a ~10-fold increase in the rate of fire regime changes over the last 250 years. The *Nearctic* and *Australasia* showed even stronger recent changes in fire regime, with 30% and 36% of the identified fire regime changes occurring in the past 250 years, respectively.

Climate was identified as the main driver of fire regime changes during the Holocene (47% of responses), especially in the early and mid-Holocene. Direct human activity was the second most identified driver (32%). However, the onset of strong human influence on fire regime occurred at different times in different regions (Figure. 2), with the greatest influence during the late Holocene. However, for the post-industrial period (1950 A.D.-present), climate change and direct human activity were mentioned equally often (40% and 46%, respectively). Vegetation and fuel were the least mentioned drivers for each time interval (Figure. S4), likely because these factors respond to climate on centennial timescales, illustrating the importance of temporal scale when considering drivers.

Respondents identified several dimensions of fire regime altered over the past 250 years, including fire frequency, extent, and severity (Figure. S5). A wide range of human-wildfire interactions specific to fire regions were identified. For example, in *Indo-Malayan Tropical forests*, deforestation due to economic development has changed the fuel structure and ignition sources, increasing fire activity in an ecosystem where it was historically rare. Other fire management strategies such as increased fire suppression and exclusion of Indigenous or traditional prescribed burning practices were recognized as drivers of increased fire severity, especially when coupled with recent temperature increases. In seven biomes it was suggested that a change in fire regime occurred since the industrial revolution (Figure. S3), with the

median estimate of current fire regime duration less than 200 years (Figure.S6). For *Tundra, Mediterranean forests, woodlands, and scrub; Tropical and subtropical moist broadleaf forests, and Tropical and subtropical grasslands, savannas, and shrubs*, this duration was less than 70 years (Figure. S6).

Timing and type of future fire regime change

Respondents provided estimates of fire regime change for their fire region in 2050, 2100, and 2300 based on the IPCC representative concentration pathways (RCP) 2.6, 4.5, and 8.5, representing increasingly severe climate change scenarios. Most respondents projected that the likelihood of fire regime change increased with time and climate change severity (Figure. S9-10). Under RCP8.5, nine biomes were projected to have more than 50% chance of experiencing a fire regime change by 2050, compared to one biome for RCP2.6. By 2100 and 2300 even under RCP2.6, five biomes were predicted to have a ≥50% likelihood of fire regime change (Figures. 3a, S9-10). The climate sensitivity (amount of increase in the likelihood of a fire regime change across RCP scenarios) varied substantially among biomes. For example, for *Tundra*, RCP2.6 was enough to initiate a fire regime change, while the projected likelihood of fire regime change was much lower under RCP2.6 than RCP8.5 for *Boreal forests* (Figure.3b, S11-12). Analysis for all scales, years, and scenarios are presented in the Supplementary Inforamtion.

The climate sensitivity estimates from this study were in agreement with many modeling studies projecting future changes in fire activity (Bowman et al., 2020). Climate drivers such as *fire weather* and *fire danger days* are predicted to increase in many areas of the globe (IPCC, 2021), particularly in fire-prone regions such as the Mediterranean basin, southwestern USA, and subtropical regions of the Southern Hemisphere (Bowman et al., 2017; Cook et al., 2022). An increase in extreme *fire behavior* is also predicted in many regions such as the Amazon, western USA, Mediterranean and southern Australia (Bowman et al., 2020). Substantial intensification of fire behavior is projected for higher latitudes through

181 the end of the 21st century (Abbott et al., 2021; Flannigan et al., 2013; Talucci et al., 2022), though local
182 fire patterns are expected to be heterogeneous (McCarty et al., 2021).

183 Respondents projected an intensification of fire regime across biomes, with burned area, frequency, and
184 severity increasing for all but a few biome-time-step combinations (Figure. 4). The magnitude of change
185 generally increased with time and with higher emission scenarios (Figure. S13-16). These predictions are
186 consistent with other studies, suggesting a substantial intensification of fire regimes with greater
187 warming. For example, panarctic wildfire emissions have been predicted to increase by 250% by 2100
188 under RCP8.5 (Abbott et al., 2016). Similarly, fire emissions in Finnish Boreal forests have been predicted
189 to experience a 190% increase, even under RCP4.5 (McCarty et al., 2021). In Europe, burned area is
190 predicted to increase between 180% to 360% until the end of the century under RCP8.5, but less than
191 60% under RCP2.6 (Wu et al., 2015). In another study in southern Europe, burned area is projected to
192 increase 5–50% per decade under high emission scenarios (Dupuy et al., 2020). Another study projected a
193 40–100% increase in burned area with a 1.5° to 3°C warming for Mediterranean Europe (Bowman et al.,
194 2020). An increase in burned area is likewise predicted for the Amazon and western USA (Abatzoglou et
195 al., 2021; Bowman et al., 2020). In the grasslands of central Asia, the potential burned area is expected to
196 increase 13% by 2080 (Zong et al., 2020).

197 Contrary to most regions, less burning was predicted by experts in some parts of Africa under warmer
198 scenarios, consistent with observations (Andela & Van Der Werf, 2014) that reveal a more intense fire
199 regime under cooler and wetter climates that favor fuel build up in these dry regions (Daniau et al., 2013).
200 More generally, fire frequency and severity are expected to decrease in fuel-limited ecosystems under
201 drier conditions, while they should increase in ecosystems with ample humidity (Rogers et al., 2020).

202 When interpreting these survey results, it is important to recognize that within a single fire region,
203 different ecological communities may experience divergent future fire trajectories (Moritz et al., 2012).
204 For example, the risk of fire-climate interactions can vary in different type of conifer forests of western

North America (moist-dry-subalpine) based on their elevation (Halofsky et al., 2020). This community-dependence was mentioned by respondents for most fire regions in this study. For example, substantial differences exist between eastern and western *Boreal forests* of the *Nearctic,* with the latter experiencing increasing trends in burn rates(Chavardès et al., 2022a). Although with projected climate change, convergence towards increasing burn rates is possible for eastern and western *Boreal forests of the Nearactic* during the mid- to late-21st C.(Chavardès et al., 2022b).

Consequences of fire regime change

Biodiversity, carbon stocks, and ecosystem services were anticipated to decrease with future fire regime change. Respondents estimated that the magnitude of change will increase for more extreme warming scenarios and longer timeframes in most biomes (Figure. 5, S17-20). However, the respondents suggested a general increase in albedo in the time frame 2050-2100, which could exert a transitory stabilizing effect on climate, and a further change in direction for some biomes through 2300 (Figure. 5, S21). Analysis for all scales, scenarios, and years are presented in the Supplementary Inforamtion.

While it is difficult to assess agreement between respondents and the broader wildfire literature for such diverse fire regions, the overall results were generally aligned with the literature. It is anticipated that progressive increases in fire activity will impact biodiversity and ecosystem services in most regions, notably because ecosystem response to change and disturbance takes centuries to millenniums to reach equilibrium (Carcaillet et al., 2010, 2020). Local ecosystem services can be substantially altered by novel fire regimes. For example, in the Indian tropical dry forests, an increase in fire activity may negatively alter forest potential for water regulation by changing soil characteristics (Schmerbeck & Fiener, 2015), and atmospheric moisture recycling (Abbott et al., 2019). Similarly, changes in fire regime may also affect forest ecosystems and species that have historically been less affected by fire, as for beech forests (*Fagus sylvatica L.*) of Central Europe (Maringer et al., 2012).

228 In tropical biomes, an increase in extreme wildfires where fires are rare could affect tree mortality leading
229 to habitat loss (Deb et al., 2018; Silveira et al., 2016). In the Mediterranean, an increase in fire events can
230 create favorable conditions for some understory vegetation by temporarily reducing tree cover (Connor et
231 al., 2019; Fournier et al., 2020). In savannas, longer fire intervals and elevated CO_2 may create favorable
232 conditions for woody vegetation (Sage, 2020), which can have a negative impact on biodiversity (Veldman
233 et al., 2015). New fire regimes can also be favorable to some introduced and invasive taxa, including
234 cheatgrass in some desert environments of the USA, tussock grass and pampas grass in Spain, and
235 *Robinia*, *Ailanthus* in Portugal (Maringer et al., 2012). These species exploit novel disturbance niches to
236 outcompete native vegetation during post-fire recovery. Consequently, both direct and indirect effects of
237 fire regime change can alter plant community structure and composition with amplifying feedbacks on
238 different aspects of fire regimes including frequency and extent (Bishop et al., 2020; Wan et al., 2014).

239 The consequences of fire regime change for ecosystem carbon balance are diverse. Novel climatic
240 conditions in peatlands can slow their recovery from disturbances, decreasing carbon stocks (Loisel et al.,
241 2021). More severe and frequent fires can threaten legacy carbon in Boreal forests (Walker et al., 2019),
242 though changes to successional trajectories may offset or negate these losses in some cases (Mack et al.,
243 2021). Respondents in this study projected a net decrease in *Boreal* carbon stocks under warmer
244 scenarios. Another indirect effect of wildfire on carbon balance is local air pollution. For example, ozone
245 produced during combustion can damage plant tissues, potentially doubling carbon losses by reducing
246 photosynthesis post fire (Lasslop et al., 2019). Because human land use and fire regime are so closely
247 linked, human actions such as deforestation coupled with cropland development can decrease carbon
248 stocks at the same time as they modify the fire regime (Bowman et al., 2011; Cochrane & Bowman, 2021).

249 In other studies, it has been suggested that increased vegetation cover in higher latitudes will lead to
250 decreased of albedo, which can have a more pronounced warming effect than greenhouse gases (Field et
251 al., 2007). Not only can fires directly change the albedo of the region by altering land characteristics, but
252 they also affect albedo by the pollutants they produce. For example, enhanced black carbon and soot

253 deposition associated with increased fire disturbance will contribute to accelerated ice melting and
254 decreased albedo (Aubry-Wake et al., 2022; McCarty et al., 2021). Conversely, increased tropical peatland
255 fire can increase albedo (Ohkubo et al., 2021). Albedo may be reduced in the immediate aftermath of fire
256 in sub-Saharan Africa, but it returns to pre-fire conditions within a few years (Gatebe et al., 2014).
257 Perhaps because of the spatiotemporal complexity of the wildfire-albedo interaction, most respondents
258 predicted little change in albedo.

259 **Our capacity to prevent, control, or adapt to future fire regimes**

260 Respondents identified different fire regime drivers depending on the warming scenario and fire region.
261 Under higher emissions (i.e., RCP4.5 and RCP8.5), most experts suggested that climatic factors would be
262 the dominant driver of fire regime change. Conversely, under RCP2.6, only about half of the responses
263 indicated that climatic factors would be the most important driver. Within *Australasia* and *Nearctic* fire
264 regimes, climatic factors were identified as the most important driver for all scenarios. On the other hand,
265 in the *Neotropic, Afrotropic*, and *Indo-Malayan* biogeographic realms, human activities were identified as
266 most important. While vegetation and fuel were also frequently mentioned, these factors were never
267 suggested as the most important driver of future fire regime changes (Figure. S22), highlighting the
268 complex interplay amongst climate, fuel, and fire, especially on centennial timescales.

269 Survey results suggest that human actions for the next 20-50 years will be highly influential in determining
270 how different ecosystem values (e.g., biodiversity, carbon stocks) are likely to change. Only 14% of the
271 respondents indicated human actions have no effect, primarily in the case of albedo (Table. S1). Only 10%
272 of responses recommended non-intervention, which instead was rated as a negative or unhelpful
273 approach, though there were mixed opinions across and within fire regions.

274 About half of the respondents considered direct land management as an important approach for
275 mitigating impacts of changing fire regime. In particular, fuel treatment, vegetation management,
276 urban/suburban landscaping, and agriculture were identified as potentially useful mitigation approaches.

There was high agreement that prescribed burning would help biodiversity and ecosystem services, but there were mixed opinions about its effect on carbon stocks, potentially because the area subject to prescribed burning is relatively small compared to the total burned area each year. There was less agreement about other fuel management techniques such as forest clearing or thinning, potentially because of the variety of vegetation types under consideration, and the lack of consensus in the literature on mechanical treatments. Even though activities such as clear-cutting reduce fuel, fire activity may increase due to the effects on microclimate and residual biomass, therefore changing fuel structure and composition (Bergeron et al., 2010; Cyr et al., 2009; Lindenmayer et al., 2009, 2020; Maxwell et al., 2019; Stephens et al., 2020). Conversely, traditional or Indigenous practices, such as cultural burning, were suggested as beneficial in reinforcing fire regime resilience and reducing damage by preventing extreme wildfire events (Christianson, 2015; Fernandes, 2020; Fletcher et al., 2021). There was a high level of agreement among experts who mentioned restoring vegetation (i.e., native habitat conservation and restoration) as a positive impact on all ecosystem values. There were mixed opinions about introducing fire resilient plants, but agreement on the positive effect of reducing flammable invasive plants. The natural or artificial selection of nonflammable species was mostly considered to have a negative effect on biodiversity and ecosystem services but variable effects on carbon and albedo.

Several landscape management strategies had general support, including increasing landscape heterogeneity, diversification, and reduction of landscape flammability by targeted land use, as well as creating buffer zones around primary and old-growth forests (Barredo et al., 2021). Attention to the human-wildfire interface was a common recommendation, as certain levels of population (housing) density, wildland-urban interface, and landscape connectivity can dramatically affect the characteristics and societal consequences of fire (Archibald et al., 2012; Kelley et al., 2019; Moritz et al., 2014; Syphard et al., 2007).

Direct fire management was recommended in 17% of expert responses. In the case of fire suppression as a direct fire management strategy, there was less agreement about the direction of effects on different

302 factors. In some studies, it has been shown that fire suppression had a negative impact on fire-dependent
303 ecosystems. Such policies have led to fuel accumulation and increased flammability that has contributed
304 to today's extreme wildfire events (Marlon et al., 2012; Parisien et al., 2020; Schoennagel et al., 2017;
305 Valese et al., 2014). A greater proportion of respondents (23%) indicated the importance of social or
306 political awareness and action. These included climate mitigation, education of the public regarding fire
307 danger and ignitions, direct or indirect conservation policies, and incorporation of Indigenous or
308 traditional knowledge (Table. S1). Although we have summarized and combined all the management
309 suggestions from experts of different fire regions, we remind the reader that suitable management
310 applications can significantly vary between and within biomes based on various factors (detailed
311 responses for each fire region can be found in the Supplementary Information).

312 There was strong agreement among experts, except for the *Afrotropic* and the *Indo-Malayan*
313 biogeographic realms, that under RCP8.5, humans will have a decreasing capacity to control wildfires. This
314 was most obvious for the *Neotropic* and *Nearctic*, and *Australasia* for the later years (2100 and 2300).
315 Experts on *Neotropic* and *Nearctic* fire regimes indicated that this same decreased capacity was likely to
316 apply under RCP4.5. 70% of the respondents indicate that under RCP2.6, humans will maintain some
317 ability of managing fire-impacts (Figure. S23).

318 **Charting a course in a world of uncertainty**

319 For each question, respondents identified the main sources of uncertainty (Table 1), which included
320 limited observational data, inadequate modeling frameworks, and system complexity, particularly social
321 dimensions. Respondents emphasized that the impact of different human activities is not completely
322 understood for the past or present and that untangling different fire drivers can be difficult due to
323 multiple interactions and feedbacks, which are often not represented in coupled models. Respondents
324 also mentioned that the unprecedented rate of climate change and diversity of human activity made
325 estimations of fire return intervals and other dimensions of fire regime uncertain. Respondents were
326 uncertain about emergent economic and policy direction, beliefs, and technologies as tools to combat

327 changing fire regime. Additional sources of uncertainty included the exclusion of small fires below the
328 detection of satellite census and a lack of information about fire severity impacting ecological succession,
329 albedo, and carbon-climate feedbacks.

330 While our study may have limited application in many specific management contexts, there were some
331 general patterns that could be informative for policymakers, managers, and researchers. First, there is a
332 high level of agreement across regions that the risk of damaging fire characteristics will be greater under
333 higher emissions. While the specific consequences will vary by fire region and habitat type, the overall
334 message is clear: rapid reduction of greenhouse gas emissions is needed to restore Holocene-like climate
335 conditions. Otherwise, the emergence of novel climates and fire regimes outside of the range of Holocene
336 variability, will complicate our ability to conserve habitats, ensure healthy communities, and preserve
337 terrestrial carbon uptake and storage. Without a reduction in emissions, changes in fire regime could
338 eclipse climate mitigation policies such as negative emissions through reforestation and afforestation
339 (Anderegg et al., 2020; Veldman et al., 2019). Any carbon uptake from recovered or cultivated forests
340 could be negated by the increased fire frequency or intensity projected for many regions (Hammond et
341 al., 2022; Smith et al., 2020).

342 A second overall lesson is that knowledge of past fire regimes provides perspective on how climate,
343 vegetation, and human actions interacted to shape fire in the Earth system (Marlon et al., 2008; Molinari
344 et al., 2018; Pechony & Shindell, 2010). For example, paleo-ecological knowledge about vegetation
345 community and historical amplitude of fire regime change in a given biome can provide estimates of
346 historical thresholds and optimal vegetation structure for management purposes (Hennebelle et al.,
347 2018). Likewise, fire histories show human-vegetation-climate linkages, such as decreasing tree cover
348 creating microclimates favorable to the encroachment of flammable vegetation in the understory
349 (Feurdean et al., 2020). An overarching lesson learned from looking at Holocene fire histories is that
350 projected conditions are generally unprecedented, meaning that human-fire interactions could have
351 extreme and unexpected consequences (Bova et al., 2021). We should not assume that historical

management practices will suffice (Crandall et al., 2021; E. C. Ellis et al., 2021; Pyne, 2007) given accelerated rates of vegetation change since c. 4000 BP (Mottl et al., 2021), the emergence of novel biotic and abiotic conditions (Burke et al., 2019; Finsinger et al., 2017; Ordonez et al., 2016), and increasing populations. For example, the expansion of human development in fire prone areas in the western US is increasing both wildfire incidence and cost of suppression (Balch et al., 2017a, 2017b).

Third, despite the substantial uncertainties associated with fire regimes, mitigation efforts such as allowing some fires to burn to reduce fuel loads, prescribed burning, and fuel treatments will help limit fire impacts and cost (Harris et al., 2016; Mietkiewicz et al., 2020; Moritz et al., 2014; Radeloff et al., 2018). Likewise, the conservation of large, contiguous ecosystems allows the use of more effective wildfire management tools such as prescribed burning and increases resilience when unexpected wildfire behavior emerges (Bentley & Penman, 2017; Driscoll et al., 2016; Miller, 2020).

While this study brought together a diverse group of paleo and present fire researchers, we point out that our group is not geographically balanced. Despite invitations to several hundred researchers, we only received a few responses for some fire regions (Figure. 1b), including the African subtropical and tropical grassland region, which accounts for a large portion of global area burned (Ramo et al., 2021). This reflects the broader geographical and cultural bias in ecological research generally and wildfire research specifically (Bradstock et al., 2002; Hantson et al., 2016; Metcalfe et al., 2018), highlighting the need for more diverse research networks.

We also point out a potential bias in climate scenarios. Low emissions scenarios such as RCP2.6 or SSP1 are sometimes omitted from model inter-comparisons because they are often deemed unfeasible (McGuire et al., 2018). In reality, it is the more extreme warming scenarios that are becoming less likely (Hausfather & Peters, 2020; Lovins et al., 2019). We found substantial differences in fire regimes between RCP2.6 and higher emission scenarios. Given the current rate of the global transition to renewable

energies (Breyer et al., 2022; Hausfather & Peters, 2020; O'Neill et al., 2020), it is important to understand both the "low " as well as the "high range" of climate change futures.

Expert assessment application in fire management

Decision-making in landscape and fire management requires a great understanding of complex human and natural systems and their interactions with fire. Currently, policymakers and managers working on fire issues are operating in a complex environment with sometimes conflicting traditional, scientific, and political information and priorities. As the physical, biological, and human factors controlling wildfire behavior change rapidly in the Anthropocene, improving science-policy-management integration would be highly beneficial for human wellbeing and ecosystem function. The primary scientific knowledge that is used by decision-makers regarding the future is based on models or single expert advice. As several respondents mentioned in this study, quantitative models cannot capture all the factors influencing the evolution of fire behavior. Various types of expert elicitations can complement quantitative models to generate more robust and reliable guidance that allows adaptive management. This could range from informal interpretation of model outputs by expert panels to iterative combinations, such as expert input on supervised and unsupervised machine learning models. These approaches should be (and already are in some cases) used in various aspects of fire management, from detecting fires to planning and policy, by providing a benchmark or improving the initial parameters and weights (Jain et al., 2020).

At some level, we are not proposing a new role for experts in policymaking and management, but we are suggesting that the integration of local expert knowledge be done in a more rigorous and robust way. Policymakers and managers are making decisions based on available information that is often filtered through informal information networks, especially trusted relationships and professional networks. By involving more independent experts to inform policy, it is possible to limit the "one-expert syndrome", where the opinions or a single knowledge holder dominate the decision-making process, whether that view represents the broader consensus.

Our study shows that experts have different views about different aspects of wildfires (i.e., there is not strong consensus on several dimensions of current and future fire behavior). These biases come from various sources, including scientific background and study methodology (Oppenheimer et al., 2019). Therefore, developing methods to transfer group expertise to decision-makers is critical. Even though our study has been done on a global scale to identify large patterns, this method can be beneficial for local management by bringing local expertise (that in many regions is not represented in scientific publications that are mostly produced in developed countries), such as indigenous knowledge, into the decision-making process (Christianson, 2015).

Acknowledgements

This study emerged during the PAGES-supported Global Paleofire Working Group 2 workshop "Fire history baselines by biome" held in September 2016 at Château de la Tour, Beguey (Bordeaux, France) led by A.-L. D. and Tim Brücher. PAGES, Past Global Changes, is funded by the Swiss Academy of Sciences and the Chinese Academy of Sciences and supported in kind by the University of Bern, Switzerland. Financial support was provided by the U.S. National Science Foundation award numbers 1916565, EAR-2011439, and EAR-2012123. Additional support was provided by the Utah Department of Natural Resources Watershed Restoration Initiative. SSS was supported by Brigham Young University Graduate Studies. MS was supported by National Science Centre, Poland (grant no. 2018/31/B/ST10/02498). JCA was supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101026211. A.-L.D acknowledge PAGES, PICS CNRS 06484 project, CNRS-INSU, Région Nouvelle-Aquitaine, University of Bordeaux DRI and INQUA for workshop support. We dedicate this manuscript to our late colleague Dr. Daniele Colombaroli.

References

Abatzoglou, J. T., Battisti, D. S., Williams, A. P., Hansen, W. D., Harvey, B. J., & Kolden, C. A. (2021). Projected increases in western US forest fire despite growing fuel constraints. *Communications Earth & Environment*, *2*(1), Article 1. https://doi.org/10.1038/s43247-021-00299-0

Abbott, B. W., Bishop, K., Zarnetske, J. P., Minaudo, C., Chapin, F. S., Krause, S., Hannah, D. M., Conner, L., Ellison, D., Godsey, S. E., Plont, S., Marçais, J., Kolbe, T., Huebner, A., Frei, R. J., Hampton, T., Gu, S., Buhman, M., Sara Sayedi, S., … Pinay, G. (2019). Human domination of the global water cycle absent from depictions and perceptions. *Nature Geoscience*, *12*(7), Article 7. https://doi.org/10.1038/s41561-019-0374-y

Abbott, B. W., Jones, J. B., Schuur, E. A. G., III, F. S. C., Bowden, W. B., Bret-Harte, M. S., Epstein, H. E., Flannigan, M. D., Harms, T. K., Hollingsworth, T. N., Mack, M. C., McGuire, A. D., Natali, S. M., Rocha, A. V., Tank, S. E., Turetsky, M. R., Vonk, J. E., Wickland, K. P., Aiken, G. R., … Zimov, S. (2016). Biomass offsets little or none of permafrost carbon release

from soils, streams, and wildfire: An expert assessment. *Environmental Research Letters*, *11*(3), 034014. https://doi.org/10.1088/1748-9326/11/3/034014

Abbott, B. W., Rocha, A. V., Shogren, A., Zarnetske, J. P., Iannucci, F., Bowden, W. B., Bratsman, S. P., Patch, L., Watts, R., Fulweber, R., Frei, R. J., Huebner, A. M., Ludwig, S. M., Carling, G. T., & O'Donnell, J. A. (2021). Tundra wildfire triggers sustained lateral nutrient loss in Alaskan Arctic. *Global Change Biology*, *27*(7), 1408–1430. https://doi.org/10.1111/gcb.15507

Andela, N., & Van Der Werf, G. R. (2014). Recent trends in African fires driven by cropland expansion and El Niño to La Niña transition. *Nature Climate Change*, *4*(9), 791–795.

Anderegg, W. R. L., Trugman, A. T., Badgley, G., Anderson, C. M., Bartuska, A., Ciais, P., Cullenward, D., Field, C. B., Freeman, J., Goetz, S. J., Hicke, J. A., Huntzinger, D., Jackson, R. B., Nickerson, J., Pacala, S., & Randerson, J. T. (2020). Climate-driven risks to the climate mitigation potential of forests. *Science*, *368*(6497). https://doi.org/10.1126/science.aaz7005

Archibald, S., Staver, A. C., & Levin, S. A. (2012). Evolution of human-driven fire regimes in Africa. *Proceedings of the National Academy of Sciences*, *109*(3), 847–852. https://doi.org/10.1073/pnas.1118648109

Aubry-Wake, C., Bertoncini, A., & Pomeroy, J. W. (2022). Fire and Ice: The Impact of Wildfire-Affected Albedo and Irradiance on Glacier Melt. *Earth's Future*, *10*(4), e2022EF002685. https://doi.org/10.1029/2022EF002685

Balch, J. K., Bradley, B. A., Abatzoglou, J. T., Nagy, R. C., Fusco, E. J., & Mahood, A. L. (2017a). Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences*, *114*(11), 2946–2951. https://doi.org/10.1073/pnas.1617394114

Balch, J. K., Bradley, B. A., Abatzoglou, J. T., Nagy, R. C., Fusco, E. J., & Mahood, A. L. (2017b). Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences*, *114*(11), 2946–2951. https://doi.org/10.1073/pnas.1617394114

Balch, J. K., Iglesias, V., Braswell, A. E., Rossi, M. W., Joseph, M. B., Mahood, A. L., Shrum, T. R., White, C. T., Scholl, V. M., McGuire, B., Karban, C., Buckland, M., & Travis, W. R. (2020). Social-Environmental Extremes: Rethinking Extraordinary Events as Outcomes of Interacting Biophysical and Social Systems. *Earth's Future*, *8*(7), e2019EF001319. https://doi.org/10.1029/2019EF001319

Barredo, J., Brailescu, C., Teller, A., Sabatini, F., Mauri, A., & Janouskova, K. (2021). *Mapping and assessment of primary and old-growth forests in Europe*. https://doi.org/10.2760/797591

Bentley, P. D., & Penman, T. D. (2017). Is there an inherent conflict in managing fire for people and conservation? *International Journal of Wildland Fire*, *26*(6), 455. https://doi.org/10.1071/WF16150

Bergeron, Y., Cyr, D., Girardin, M. P., Carcaillet, C., Bergeron, Y., Cyr, D., Girardin, M. P., & Carcaillet, C. (2010). Will climate change drive 21st century burn rates in Canadian boreal forest outside of its natural variability: Collating global climate model experiments with sedimentary charcoal data. *International Journal of Wildland Fire*, *19*(8), 1127–1139. https://doi.org/10.1071/WF09092

Bishop, T. B. B., Gill, R. A., McMillan, B. R., & St. Clair, S. B. (2020). Fire, rodent herbivory, and plant competition: Implications for invasion and altered fire regimes in the Mojave Desert. *Oecologia*, *192*(1), 155–167. https://doi.org/10.1007/s00442-019-04562-2

Bond, W. J., Woodward, F. I., & Midgley, G. F. (2005). The global distribution of ecosystems in a world without fire. *New Phytologist*, *165*(2), 525–538. https://doi.org/10.1111/j.1469-8137.2004.01252.x

Bova, S., Rosenthal, Y., Liu, Z., Godad, S. P., & Yan, M. (2021). Seasonal origin of the thermal maxima at the Holocene and the last interglacial. *Nature*, *589*(7843), 548–553. https://doi.org/10.1038/s41586-020-03155-x

Bowman, D. M. J. S., Balch, J., Artaxo, P., Bond, W. J., Cochrane, M. A., D'Antonio, C. M., DeFries, R., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Mack, M., Moritz, M. A., Pyne, S., Roos, C. I., Scott, A. C., Sodhi, N. S., & Swetnam, T. W. (2011). The human dimension of fire regimes on Earth. *Journal of Biogeography*, *38*(12), 2223–2236. https://doi.org/10.1111/j.1365-2699.2011.02595.x

Bowman, D. M. J. S., Balch, J. K., Artaxo, P., Bond, W. J., Carlson, J. M., Cochrane, M. A., D'Antonio, C. M., DeFries, R. S., Doyle, J. C., Harrison, S. P., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Marston, J. B., Moritz, M. A., Prentice, I. C., Roos, C. I., Scott, A. C., … Pyne, S. J. (2009). Fire in the Earth System. *Science*, *324*(5926), 481–484. https://doi.org/10.1126/science.1163886

Bowman, D. M. J. S., Kolden, C. A., Abatzoglou, J. T., Johnston, F. H., van der Werf, G. R., & Flannigan, M. (2020). Vegetation fires in the Anthropocene. *Nature Reviews Earth & Environment*, *1*(10), Article 10. https://doi.org/10.1038/s43017-020-0085-3

Bowman, D. M. J. S., Williamson, G. J., Abatzoglou, J. T., Kolden, C. A., Cochrane, M. A., & Smith, A. M. S. (2017). Human exposure and sensitivity to globally extreme wildfire events. *Nature Ecology & Evolution*, *1*(3), 1–6. https://doi.org/10.1038/s41559-016-0058

Bradstock, R. A., Williams, J. E., & Gill, M. A. (2002). *Flammable Australia: The Fire Regimes and Biodiversity of a Continent*. Cambridge University Press.

Breyer, C., Khalili, S., Bogdanov, D., Ram, M., Oyewo, A. S., Aghahosseini, A., Gulagi, A., Solomon, A. A., Keiner, D., Lopez, G., Østergaard, P. A., Lund, H., Mathiesen, B. V., Jacobson, M. Z., Victoria, M., Teske, S., Pregger, T., Fthenakis, V., Raugei, M., … Sovacool, B. K. (2022). On the History and Future of 100% Renewable Energy Systems Research. *IEEE Access*, *10*, 78176–78218. https://doi.org/10.1109/ACCESS.2022.3193402

Burke, K. D., Williams, J. W., Brewer, S., Finsinger, W., Giesecke, T., Lorenz, D. J., & Ordonez, A. (2019). Differing climatic mechanisms control transient and accumulated vegetation novelty in Europe and eastern North America. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *374*(1788), 20190218. https://doi.org/10.1098/rstb.2019.0218

Carcaillet, C., Desponts, M., Robin, V., & Bergeron, Y. (2020). Long-Term Steady-State Dry Boreal Forest in the Face of Disturbance. *Ecosystems*, *23*(5), 1075–1092. https://doi.org/10.1007/s10021-019-00455-w

Carcaillet, C., Richard, P. J. H., Bergeron, Y., Fréchette, B., Ali, A. A., Carcaillet, C., Richard, P. J. H., Bergeron, Y., Fréchette, B., & Ali, A. A. (2010). Resilience of the boreal forest in response to Holocene fire-frequency changes assessed by pollen diversity and population dynamics. *International Journal of Wildland Fire*, *19*(8), 1026–1039. https://doi.org/10.1071/WF09097

Chavardès, R. D., Danneyrolles, V., Portier, J., Girardin, M. P., Gaboriau, D. M., Gauthier, S., Drobyshev, I., Cyr, D., Wallenius, T., & Bergeron, Y. (2022a). Converging and diverging burn rates in North American boreal forests from the Little Ice Age to the present. *International Journal of Wildland Fire*. https://doi.org/10.1071/WF22090

Chavardès, R. D., Danneyrolles, V., Portier, J., Girardin, M. P., Gaboriau, D. M., Gauthier, S., Drobyshev, I., Cyr, D., Wallenius, T., & Bergeron, Y. (2022b). Converging and diverging burn rates in North American boreal forests from the Little Ice Age to the present. *International Journal of Wildland Fire*, *31*(12), 1184–1193. https://doi.org/10.1071/WF22090

Chen, Y., Romps, D. M., Seeley, J. T., Veraverbeke, S., Riley, W. J., Mekonnen, Z. A., & Randerson, J. T. (2021). Future increases in Arctic lightning and fire risk for permafrost carbon. *Nature Climate Change*, 1–7. https://doi.org/10.1038/s41558-021-01011-y

Christianson, A. (2015). Social science research on Indigenous wildfire management in the 21st century and future research needs. *International Journal of Wildland Fire*, *24*(2), 190–200. https://doi.org/10.1071/WF13048

Cochrane, M. A., & Bowman, D. M. J. S. (2021). Manage fire regimes, not fires. *Nature Geoscience*, *14*(7), 455–457. https://doi.org/10.1038/s41561-021-00791-4

Collins, L., Bradstock, R. A., Clarke, H., Clarke, M. F., Nolan, R. H., & Penman, T. D. (2021). The 2019/2020 mega-fires exposed Australian ecosystems to an unprecedented extent of high-severity fire. *Environmental Research Letters*, *16*(4), 044029. https://doi.org/10.1088/1748-9326/abeb9e

Connor, S. E., Vannière, B., Colombaroli, D., Anderson, R. S., Carrión, J. S., Ejarque, A., Gil Romera, G., González-Sampériz, P., Hoefer, D., Morales-Molino, C., Revelles, J., Schneider, H., van der Knaap, W. O., van Leeuwen, J. F., & Woodbridge, J. (2019). Humans take control of fire-driven diversity changes in Mediterranean Iberia's vegetation during the mid–late Holocene. *The Holocene*, *29*(5), 886–901. https://doi.org/10.1177/0959683619826652

Cook, B. I., Smerdon, J. E., Cook, E. R., Williams, A. P., Anchukaitis, K. J., Mankin, J. S., Allen, K., Andreu-Hayles, L., Ault, T. R., Belmecheri, S., Coats, S., Coulthard, B., Fosu, B., Grierson, P., Griffin, D., Herrera, D. A., Ionita, M., Lehner, F., Leland, C., … Wise, E. K. (2022). Megadroughts in the Common Era and the Anthropocene. *Nature Reviews Earth & Environment*, 1–17. https://doi.org/10.1038/s43017-022-00329-1

Crandall, T., Jones, E., Greenhalgh, M., Frei, R. J., Griffin, N., Severe, E., Maxwell, J., Patch, L., Clair, S. I. S., Bratsman, S., Merritt, M., Norris, A. J., Carling, G. T., Hansen, N., Clair, S. B. S., & Abbott, B. W. (2021). Megafire affects stream sediment flux and dissolved organic matter reactivity, but land use dominates nutrient dynamics in semiarid watersheds. *PLOS ONE*, *16*(9), e0257733. https://doi.org/10.1371/journal.pone.0257733

Cyr, D., Gauthier, S., Bergeron, Y., & Carcaillet, C. (2009). Forest management is driving the eastern North American boreal forest outside its natural range of variability. *Frontiers in Ecology and the Environment*, *7*(10), 519–524. https://doi.org/10.1890/080088

Daniau, A.-L., Goñi, M. F. S., Martinez, P., Urrego, D. H., Bout-Roumazeilles, V., Desprat, S., & Marlon, J. R. (2013). Orbital-scale climate forcing of grassland burning in southern Africa. *Proceedings of the National Academy of Sciences*, *110*(13), 5069–5073. https://doi.org/10.1073/pnas.1214292110

Davis, C. (2021). Earth, fuel and fire. *Nature Reviews Earth & Environment*, *2*(11), 742–742. https://doi.org/10.1038/s43017-021-00239-8

Deb, J., Phinn, S., Butt, N., & McAlpine, C. (2018). CLIMATE CHANGE IMPACTS ON TROPICAL FORESTS: IDENTIFYING RISKS FOR TROPICAL ASIA. *Journal of Tropical Forest Science*, *30*(2), 182–194.

Doerr, S. H., & Santín, C. (2016). Global trends in wildfire and its impacts: Perceptions versus realities in a changing world. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696), 20150345. https://doi.org/10.1098/rstb.2015.0345

Driscoll, D. A., Bode, M., Bradstock, R. A., Keith, D. A., Penman, T. D., & Price, O. F. (2016). Resolving future fire management conflicts using multicriteria decision making. *Conservation Biology*, *30*(1), 10.

Dupuy, J., Fargeon, H., Martin-StPaul, N., Pimont, F., Ruffault, J., Guijarro, M., Hernando, C., Madrigal, J., & Fernandes, P. (2020). Climate change impact on future wildfire danger and activity in southern Europe: A review. *Annals of Forest Science*, *77*(2), 35. https://doi.org/10.1007/s13595-020-00933-5

Ellis, E. C., Gauthier, N., Goldewijk, K. K., Bird, R. B., Boivin, N., Díaz, S., Fuller, D. Q., Gill, J. L., Kaplan, J. O., Kingston, N., Locke, H., McMichael, C. N. H., Ranco, D., Rick, T. C., Shaw, M. R., Stephens, L., Svenning, J.-C., & Watson, J. E. M. (2021). People have shaped most of terrestrial nature for at least 12,000 years. *Proceedings of the National Academy of Sciences*, *118*(17). https://doi.org/10.1073/pnas.2023483118

Ellis, T. M., Bowman, D. M. J. S., Jain, P., Flannigan, M. D., & Williamson, G. J. (2022). Global increase in wildfire risk due to climate driven declines in fuel moisture. *Global Change Biology*, *n/a*(n/a). https://doi.org/10.1111/gcb.16006

Feng, X., Merow, C., Liu, Z., Park, D. S., Roehrdanz, P. R., Maitner, B., Newman, E. A., Boyle, B. L., Lien, A., Burger, J. R., Pires, M. M., Brando, P. M., Bush, M. B., McMichael, C. N. H., Neves, D. M., Nikolopoulos, E. I., Saleska, S. R., Hannah, L., Breshears, D. D., … Enquist, B. J. (2021). How deregulation, drought and increasing fire impact Amazonian biodiversity. *Nature*, *597*(7877), Article 7877. https://doi.org/10.1038/s41586-021-03876-7

Fernandes, R. by P. M. (2020). Fire Country: How Indigenous Fire Management Could Help Save Australia. *International Journal of Wildland Fire*, *29*(11), 1052. https://doi.org/10.1071/WFv29n11_BR

Feurdean, A., Vanniere, B., Finsinger, W., Warren, D., Connor, S. C., Forrest, M., Liakka, J., Panait, A., Werner, C., Andric, M., Bobek, P., Carter, V. A., Davis, B., Diaconu, A.-C., Dietze, E., Feeser, I., Florescu, G., Galka, M., Giesecke, T., … Hickler, T. (2020). Fire hazard modulation by long-term dynamics in land cover and dominant forest type in eastern and central Europe. *Biogeosciences*, *17*(4), Article 4. https://doi.org/10.5194/bg-17-1213-2020

Field, C. B., Lobell, D. B., Peters, H. A., & Chiariello, N. R. (2007). Feedbacks of Terrestrial Ecosystems to Climate Change. *Annual Review of Environment and Resources*, *32*(1), 1–29. https://doi.org/10.1146/annurev.energy.32.053006.141119

Finsinger, W., Giesecke, T., Brewer, S., & Leydet, M. (2017). Emergence patterns of novelty in European vegetation assemblages over the past 15 000 years. *Ecology Letters*, *20*(3), 336–346. https://doi.org/10.1111/ele.12731

Flannigan, M., Cantin, A. S., de Groot, W. J., Wotton, M., Newbery, A., & Gowman, L. M. (2013). Global wildland fire season severity in the 21st century. *Forest Ecology and Management*, *294*, 54–61. https://doi.org/10.1016/j.foreco.2012.10.022

Fletcher, M.-S., Romano, A., Connor, S., Mariani, M., & Maezumi, S. Y. (2021). Catastrophic Bushfires, Indigenous Fire Knowledge and Reframing Science in Southeast Australia. *Fire*, *4*(3), 61. https://doi.org/10.3390/fire4030061

Fournier, T., Fèvre, J., Carcaillet, F., & Carcaillet, C. (2020). For a few years more: Reductions in plant diversity 70 years after the last fire in Mediterranean forests. *Plant Ecology*, *221*(7), 559–576. https://doi.org/10.1007/s11258-020-01034-z

Gatebe, C. K., Ichoku, C. M., Poudyal, R., Román, M. O., & Wilcox, E. (2014). Surface albedo darkening from wildfires in northern sub-Saharan Africa. *Environmental Research Letters*, *9*(6), 065003. https://doi.org/10.1088/1748-9326/9/6/065003

Girardin, M. P., Ali, A. A., Carcaillet, C., Blarquez, O., Hély, C., Terrier, A., Genries, A., & Bergeron, Y. (2013). Vegetation limits the impact of a warm climate on boreal wildfires. *New Phytologist*, *199*(4), 1001–1011. https://doi.org/10.1111/nph.12322

Hagmann, R. K., Hessburg, P. F., Prichard, S. J., Povak, N. A., Brown, P. M., Fulé, P. Z., Keane, R. E., Knapp, E. E., Lydersen, J. M., Metlen, K. L., Reilly, M. J., Sánchez Meador, A. J., Stephens, S. L., Stevens, J. T., Taylor, A. H., Yocom, L. L., Battaglia, M. A., Churchill, D. J., Daniels, L. D., … Waltz, A. E. M. (2021). Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecological Applications*, *31*(8), e02431. https://doi.org/10.1002/eap.2431

Halofsky, J. E., Peterson, D. L., & Harvey, B. J. (2020). Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, *16*(1), 4. https://doi.org/10.1186/s42408-019-0062-8

Hammond, W. M., Williams, A. P., Abatzoglou, J. T., Adams, H. D., Klein, T., López, R., Sáenz-Romero, C., Hartmann, H., Breshears, D. D., & Allen, C. D. (2022). Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. *Nature Communications*, *13*(1), Article 1. https://doi.org/10.1038/s41467-022-29289-2

Hantson, S., Arneth, A., Harrison, S. P., Kelley, D. I., Prentice, I. C., Rabin, S. S., Archibald, S., Mouillot, F., Arnold, S. R., Artaxo, P., Bachelet, D., Ciais, P., Forrest, M., Friedlingstein, P., Hickler, T., Kaplan, J. O., Kloster, S., Knorr, W., Lasslop, G., … Yue, C. (2016). The status and challenge of global fire modelling. *Biogeosciences*, *13*(11), 3359–3375. https://doi.org/10.5194/bg-13-3359-2016

Hantson, S., Pueyo, S., & Chuvieco, E. (2015). Global fire size distribution is driven by human impact and climate. *Global Ecology and Biogeography*, *24*(1), 77–86. https://doi.org/10.1111/geb.12246

Harris, R. M. B., Remenyi, T. A., Williamson, G. J., Bindoff, N. L., & Bowman, D. M. J. S. (2016). Climate–vegetation–fire interactions and feedbacks: Trivial detail or major barrier to projecting the future of the Earth system? *WIREs Climate Change*, *7*(6), 910–931. https://doi.org/10.1002/wcc.428

Hausfather, Z., & Peters, G. P. (2020). Emissions – the 'business as usual' story is misleading. *Nature*, *577*(7792), Article 7792. https://doi.org/10.1038/d41586-020-00177-3

Hennebelle, A., Grondin, P., Aleman, J. C., Ali, A. A., Bergeron, Y., Borcard, D., & Blarquez, O. (2018). Using paleoecology to improve reference conditions for ecosystem-based management in western spruce-moss subdomain of Québec. *Forest Ecology and Management*, *430*, 157–165. https://doi.org/10.1016/j.foreco.2018.08.007

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y.*

Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Jain, P., Coogan, S. C. P., Subramanian, S. G., Crowley, M., Taylor, S., & Flannigan, M. D. (2020). A review of machine learning applications in wildfire science and management. *Environmental Reviews*, *28*(4), 478–505. https://doi.org/10.1139/er-2020-0019

Johnston, F. H., Borchers-Arriagada, N., Morgan, G. G., Jalaludin, B., Palmer, A. J., Williamson, G. J., & Bowman, D. M. J. S. (2021). Unprecedented health costs of smoke-related PM2.5 from the 2019–20 Australian megafires. *Nature Sustainability*, *4*(1), 42–47. https://doi.org/10.1038/s41893-020-00610-5

Jones, B. (2017). Are We Underestimating the Economic Costs of Wildfire Smoke? An Investigation Using the Life Satisfaction Approach. *Journal of Forest Economics*, *27*. https://doi.org/10.1016/j.jfe.2017.03.004

Kelley, D. I., Bistinas, I., Whitley, R., Burton, C., Marthews, T. R., & Dong, N. (2019). How contemporary bioclimatic and human controls change global fire regimes. *Nature Climate Change*, *9*(9), Article 9. https://doi.org/10.1038/s41558-019-0540-7

Kelly, L. T., Giljohann, K. M., Duane, A., Aquilué, N., Archibald, S., Batllori, E., Bennett, A. F., Buckland, S. T., Canelles, Q., Clarke, M. F., Fortin, M.-J., Hermoso, V., Herrando, S., Keane, R. E., Lake, F. K., McCarthy, M. A., Morán-Ordóñez, A., Parr, C. L., Pausas, J. G., … Brotons, L. (2020). Fire and biodiversity in the Anthropocene. *Science*, *370*(6519). https://doi.org/10.1126/science.abb0355

Lasslop, G., Coppola, A. I., Voulgarakis, A., Yue, C., & Veraverbeke, S. (2019). Influence of Fire on the Carbon Cycle and Climate. *Current Climate Change Reports*, *5*(2), 112–123. https://doi.org/10.1007/s40641-019-00128-9

Lestienne, M., Jouffroy-Bapicot, I., Leyssenne, D., Sabatier, P., Debret, M., Albertini, P.-J., Colombaroli, D., Didier, J., Hély, C., & Vannière, B. (2020). Fires and human activities as key factors in the high diversity of Corsican vegetation. *The Holocene*, *30*(2), 244–257. https://doi.org/10.1177/0959683619883025

Lindenmayer, D. B., Hunter, M. L., Burton, P. J., & Gibbons, P. (2009). Effects of logging on fire regimes in moist forests. *Conservation Letters*, *2*(6), 271–277. https://doi.org/10.1111/j.1755-263X.2009.00080.x

Lindenmayer, D. B., Kooyman, R. M., Taylor, C., Ward, M., & Watson, J. E. M. (2020). Recent Australian wildfires made worse by logging and associated forest management. *Nature Ecology & Evolution*, *4*(7), Article 7. https://doi.org/10.1038/s41559-020-1195-5

Loisel, J., Gallego-Sala, A. V., Amesbury, M. J., Magnan, G., Anshari, G., Beilman, D. W., Benavides, J. C., Blewett, J., Camill, P., Charman, D. J., Chawchai, S., Hedgpeth, A., Kleinen, T., Korhola, A., Large, D., Mansilla, C. A., Müller, J., van Bellen, S., West, J. B., … Wu, J. (2021). Expert assessment of future vulnerability of the global peatland carbon sink. *Nature Climate Change*, *11*(1), Article 1. https://doi.org/10.1038/s41558-020-00944-0

Lovins, A. B., Ürge-Vorsatz, D., Mundaca, L., Kammen, D. M., & Glassman, J. W. (2019). Recalibrating climate prospects. *Environmental Research Letters*, *14*(12), 120201. https://doi.org/10.1088/1748-9326/ab55ab

Mack, M. C., Walker, X. J., Johnstone, J. F., Alexander, H. D., Melvin, A. M., Jean, M., & Miller, S. N. (2021). Carbon loss from boreal forest wildfires offset by increased dominance of deciduous trees. *Science*, *372*(6539), 280–283. https://doi.org/10.1126/science.abf3903

Maringer, J., Wohlgemuth, T., Neff, C., Pezzatti, G. B., & Conedera, M. (2012). Post-fire spread of alien plant species in a mixed broad-leaved forest of the Insubric region. *Flora - Morphology, Distribution, Functional Ecology of Plants*, *207*(1), 19–29. https://doi.org/10.1016/j.flora.2011.07.016

Marlon, J. R., Bartlein, P. J., Carcaillet, C., Gavin, D. G., Harrison, S. P., Higuera, P. E., Joos, F., Power, M. J., & Prentice, I. C. (2008). Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience*, *1*(10), 697–702. https://doi.org/10.1038/ngeo313

Marlon, J. R., Bartlein, P. J., Gavin, D. G., Long, C. J., Anderson, R. S., Briles, C. E., Brown, K. J., Colombaroli, D., Hallett, D. J., Power, M. J., Scharf, E. A., & Walsh, M. K. (2012). Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Sciences*, *109*(9), E535–E543. https://doi.org/10.1073/pnas.1112839109

Maxwell, J. D., Rhodes, A. C., & St Clair, S. B. (2019). Human altered disturbance patterns and forest succession: Impacts of competition and ungulate herbivory. *Oecologia*, *189*(4), 1061–1070. https://doi.org/10.1007/s00442-019-04370-8

McCarty, J. L., Aalto, J., Paunu, V.-V., Arnold, S. R., Eckhardt, S., Klimont, Z., Fain, J. J., Evangeliou, N., Venäläinen, A., Tchebakova, N. M., Parfenova, E. I., Kupiainen, K., Soja, A. J., Huang, L., & Wilson, S. (2021). Reviews & Syntheses: Arctic Fire Regimes and Emissions in the 21st Century. *Biogeosciences Discussions*, 1–59. https://doi.org/10.5194/bg-2021-83

McClure, C. D., & Jaffe, D. A. (2018). US particulate matter air quality improves except in wildfire-prone areas. *Proceedings of the National Academy of Sciences*, *115*(31), 7901–7906. https://doi.org/10.1073/pnas.1804353115

McDowell, N. G., Allen, C. D., Anderson-Teixeira, K., Aukema, B. H., Bond-Lamberty, B., Chini, L., Clark, J. S., Dietze, M., Grossiord, C., Hanbury-Brown, A., Hurtt, G. C., Jackson, R. B., Johnson, D. J., Kueppers, L., Lichstein, J. W., Ogle, K., Poulter, B., Pugh, T. A. M., Seidl, R., … Xu, C. (2020). Pervasive shifts in forest dynamics in a changing world. *Science*, *368*(6494). https://doi.org/10.1126/science.aaz9463

McGuire, A. D., Lawrence, D. M., Koven, C., Clein, J. S., Burke, E., Chen, G., Jafarov, E., MacDougall, A. H., Marchenko, S., Nicolsky, D., Peng, S., Rinke, A., Ciais, P., Gouttevin, I., Hayes, D. J., Ji, D., Krinner, G., Moore, J. C., Romanovsky, V., … Zhuang, Q. (2018). Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. *Proceedings of the National Academy of Sciences*, *115*(15), 3882–3887. https://doi.org/10.1073/pnas.1719903115

Metcalfe, D. B., Hermans, T. D. G., Ahlstrand, J., Becker, M., Berggren, M., Björk, R. G., Björkman, M. P., Blok, D., Chaudhary, N., Chisholm, C., Classen, A. T., Hasselquist, N. J., Jonsson, M., Kristensen, J. A., Kumordzi, B. B., Lee, H., Mayor, J. R., Prevéy, J., Pantazatou, K., … Abdi, A. M. (2018). Patchy field sampling biases understanding of climate change impacts across the Arctic. *Nature Ecology & Evolution*, 1. https://doi.org/10.1038/s41559-018-0612-5

Mietkiewicz, N., Balch, J. K., Schoennagel, T., Leyk, S., St. Denis, L. A., & Bradley, B. A. (2020). In the Line of Fire: Consequences of Human-Ignited Wildfires to Homes in the U.S. (1992–2015). *Fire*, *3*(3), Article 3. https://doi.org/10.3390/fire3030050

Miller, R. (2020). Prescribed Burns in California: A Historical Case Study of the Integration of Scientific Research and Policy. *Fire*, *3*(3), 44. https://doi.org/10.3390/fire3030044

Molinari, C., Carcaillet, C., Bradshaw, R. H. W., Hannon, G. E., & Lehsten, V. (2020). Fire-vegetation interactions during the last 11,000 years in boreal and cold temperate forests

of Fennoscandia. *Quaternary Science Reviews*, *241*, 106408. https://doi.org/10.1016/j.quascirev.2020.106408

Molinari, C., Lehsten, V., Blarquez, O., Carcaillet, C., Davis, B. A. S., Kaplan, J. O., Clear, J., & Bradshaw, R. H. W. (2018). The climate, the fuel and the land use: Long-term regional variability of biomass burning in boreal forests. *Global Change Biology*, *24*(10), 4929–4945. https://doi.org/10.1111/gcb.14380

Morgan, M. G. (2014). Use (and abuse) of expert elicitation in support of decision making for public policy. *Proceedings of the National Academy of Sciences*, 201319946.

Moritz, M. A., Batllori, E., Bradstock, R. A., Gill, A. M., Handmer, J., Hessburg, P. F., Leonard, J., McCaffrey, S., Odion, D. C., Schoennagel, T., & Syphard, A. D. (2014). Learning to coexist with wildfire. *Nature*, *515*(7525), Article 7525. https://doi.org/10.1038/nature13946

Moritz, M. A., Parisien, M.-A., Batllori, E., Krawchuk, M. A., Van Dorn, J., Ganz, D. J., & Hayhoe, K. (2012). Climate change and disruptions to global fire activity. *Ecosphere*, *3*(6), art49. https://doi.org/10.1890/ES11-00345.1

Mottl, O., Flantua, S. G. A., Bhatta, K. P., Felde, V. A., Giesecke, T., Goring, S., Grimm, E. C., Haberle, S., Hooghiemstra, H., Ivory, S., Kuneš, P., Wolters, S., Seddon, A. W. R., & Williams, J. W. (2021). Global acceleration in rates of vegetation change over the past 18,000 years. *Science*, *372*(6544), 860–864. https://doi.org/10.1126/science.abg1685

Nowacki, G. J., & Abrams, M. D. (2015). Is climate an important driver of post-European vegetation change in the Eastern United States? *Global Change Biology*, *21*(1), 314–334. https://doi.org/10.1111/gcb.12663

Ohkubo, S., Hirano, T., & Kusin, K. (2021). Influence of disturbances and environmental changes on albedo in tropical peat ecosystems. *Agricultural and Forest Meteorology*, *301–302*, 108348. https://doi.org/10.1016/j.agrformet.2021.108348

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P., & Kassem, K. R. (2001). Terrestrial Ecoregions of the World: A New Map of Life on EarthA new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *BioScience*, *51*(11), 933–938. https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2

O'Neill, B. C., Carter, T. R., Ebi, K., Harrison, P. A., Kemp-Benedict, E., Kok, K., Kriegler, E., Preston, B. L., Riahi, K., Sillmann, J., van Ruijven, B. J., van Vuuren, D., Carlisle, D., Conde, C., Fuglestvedt, J., Green, C., Hasegawa, T., Leininger, J., Monteith, S., & Pichs-Madruga, R. (2020). Achievements and needs for the climate change scenario framework. *Nature Climate Change*, *10*(12), Article 12. https://doi.org/10.1038/s41558-020-00952-0

Oppenheimer, M., Oreskes, N., Jamieson, D., Brysse, K., O'Reilly, J., Shindell, M., & Wazeck, M. (2019). *Discerning Experts: The Practices of Scientific Assessment for Environmental Policy*. University of Chicago Press.

Ordonez, A., Williams, J. W., & Svenning, J.-C. (2016). Mapping climatic mechanisms likely to favour the emergence of novel communities. *Nature Climate Change*, *6*(12), Article 12. https://doi.org/10.1038/nclimate3127

Parisien, M.-A., Barber, Q. E., Hirsch, K. G., Stockdale, C. A., Erni, S., Wang, X., Arseneault, D., & Parks, S. A. (2020). Fire deficit increases wildfire risk for many communities in the Canadian boreal forest. *Nature Communications*, *11*(1), 2121. https://doi.org/10.1038/s41467-020-15961-y

Pausas, J. G., & Keeley, J. E. (2019). Wildfires as an ecosystem service. *Frontiers in Ecology and the Environment*, *17*(5), 289–295. https://doi.org/10.1002/fee.2044

Pechony, O., & Shindell, D. T. (2010). Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences*, *107*(45), 19167–19170. https://doi.org/10.1073/pnas.1003669107

Pereira, J. M. C., Oom, D., Silva, P. C., & Benali, A. (2022). Wild, tamed, and domesticated: Three fire macroregimes for global pyrogeography in the Anthropocene. *Ecological Applications*, *32*(6), e2588. https://doi.org/10.1002/eap.2588

Pyne, S. J. (2007). The Meaning of Megafires and the Means of the Management. *Wildfire*, 7.

Radeloff, V. C., Helmers, D. P., Kramer, H. A., Mockrin, M. H., Alexandre, P. M., Bar-Massada, A., Butsic, V., Hawbaker, T. J., Martinuzzi, S., Syphard, A. D., & Stewart, S. I. (2018). Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences*, *115*(13), 3314–3319. https://doi.org/10.1073/pnas.1718850115

Ramo, R., Roteta, E., Bistinas, I., van Wees, D., Bastarrika, A., Chuvieco, E., & van der Werf, G. R. (2021). African burned area and fire carbon emissions are strongly impacted by small fires undetected by coarse resolution satellite data. *Proceedings of the National Academy of Sciences*, *118*(9), e2011160118. https://doi.org/10.1073/pnas.2011160118

Raymond, C., Horton, R. M., Zscheischler, J., Martius, O., AghaKouchak, A., Balch, J., Bowen, S. G., Camargo, S. J., Hess, J., Kornhuber, K., Oppenheimer, M., Ruane, A. C., Wahl, T., & White, K. (2020). Understanding and managing connected extreme events. *Nature Climate Change*, *10*(7), 611–621. https://doi.org/10.1038/s41558-020-0790-4

Rogers, B. M., Balch, J. K., Goetz, S. J., Lehmann, C. E. R., & Turetsky, M. (2020). Focus on changing fire regimes: Interactions with climate, ecosystems, and society. *Environmental Research Letters*, *15*(3), 030201. https://doi.org/10.1088/1748-9326/ab6d3a

Sage, R. F. (2020). Global change biology: A primer. *Global Change Biology*, *26*(1), 3–30. https://doi.org/10.1111/gcb.14893

Sayedi, S. S., Abbott, B. W., Thornton, B. F., Frederick, J. M., Vonk, J. E., Overduin, P., Schädel, C., Schuur, E. A. G., Bourbonnais, A., Demidov, N., Gavrilov, A., He, S., Hugelius, G., Jakobsson, M., Jones, M. C., Joung, D., Kraev, G., Macdonald, R. W., McGuire, A. D., … Frei, R. J. (2020). Subsea permafrost carbon stocks and climate change sensitivity estimated by expert assessment. *Environmental Research Letters*, *15*(12), 124075. https://doi.org/10.1088/1748-9326/abcc29

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., Held, H., van Nes, E. H., Rietkerk, M., & Sugihara, G. (2009). Early-warning signals for critical transitions. *Nature*, *461*(7260), Article 7260. https://doi.org/10.1038/nature08227

Schmerbeck, J., & Fiener, P. (2015). Wildfires, Ecosystem Services, and Biodiversity in Tropical Dry Forest in India. *Environmental Management*, *56*(2), 355–372. https://doi.org/10.1007/s00267-015-0502-4

Schoennagel, T., Balch, J. K., Brenkert-Smith, H., Dennison, P. E., Harvey, B. J., Krawchuk, M. A., Mietkiewicz, N., Morgan, P., Moritz, M. A., Rasker, R., Turner, M. G., & Whitlock, C. (2017). Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences*, *114*(18), 4582–4590.

Scholten, R. C., Jandt, R., Miller, E. A., Rogers, B. M., & Veraverbeke, S. (2021). Overwintering fires in boreal forests. *Nature*, *593*(7859), Article 7859. https://doi.org/10.1038/s41586-021-03437-y

Schuur, E. A. G., Abbott, B. W., Bowden, W. B., Brovkin, V., Camill, P., Canadell, J. G., Chanton, J. P., Chapin, F. S., Christensen, T. R., Ciais, P., Crosby, B. T., Czimczik, C. I., Grosse, G., Harden, J., Hayes, D. J., Hugelius, G., Jastrow, J. D., Jones, J. B., Kleinen, T., … Zimov, S. A. (2013). Expert assessment of vulnerability of permafrost carbon to climate change. *Climatic Change*, *119*(2), 359–374. https://doi.org/10.1007/s10584-013-0730-7

Seddon, A. W. R., Froyd, C. A., Witkowski, A., & Willis, K. J. (2014). A quantitative framework for analysis of regime shifts in a Galápagos coastal lagoon. *Ecology*, *95*(11), 3046–3055. https://doi.org/10.1890/13-1974.1

Silveira, J. M., Louzada, J., Barlow, J., Andrade, R., Mestre, L., Solar, R., Lacau, S., & Cochrane, M. A. (2016). A Multi-Taxa Assessment of Biodiversity Change After Single and Recurrent Wildfires in a Brazilian Amazon Forest. *Biotropica*, *48*(2), 170–180. https://doi.org/10.1111/btp.12267

Słowiński, M., Obremska, M., Avirmed, D., Woszczyk, M., Adiya, S., Łuców, D., Mroczkowska, A., Halaś, A., Szczuciński, W., Kruk, A., Lamentowicz, M., Stańczak, J., & Rudaya, N. (2022). Fires, vegetation, and human—The history of critical transitions during the last 1000 years in Northeastern Mongolia. *Science of The Total Environment*, *838*, 155660. https://doi.org/10.1016/j.scitotenv.2022.155660

Smith, Adam J. P., Jones, Matthew W., Abatzoglou, John T., Canadell, Josep G., & Betts, Richard A. (2020). *Climate Change Increases the Risk of Wildfires*. Zenodo. https://doi.org/10.5281/ZENODO.4570195

Stephens, S. L., Battaglia, M. A., Churchill, D. J., Collins, B. M., Coppoletta, M., Hoffman, C. M., Lydersen, J. M., North, M. P., Parsons, R. A., Ritter, S. M., & Stevens, J. T. (2020). Forest Restoration and Fuels Reduction: Convergent or Divergent? *BioScience*, biaa134. https://doi.org/10.1093/biosci/biaa134

Syphard, A. D., Radeloff, V. C., Keeley, J. E., Hawbaker, T. J., Clayton, M. K., Stewart, S. I., & Hammer, R. B. (2007). Human Influence on California Fire Regimes. *Ecological Applications*, *17*(5), 1388–1402.

Talucci, A. C., Loranty, M. M., & Alexander, H. D. (2022). Siberian taiga and tundra fire regimes from 2001–2020. *Environmental Research Letters*, *17*(2), 025001. https://doi.org/10.1088/1748-9326/ac3f07

Valese, E., Conedera, M., Held, A. C., & Ascoli, D. (2014). Fire, humans and landscape in the European Alpine region during the Holocene. *Anthropocene*, *6*, 63–74. https://doi.org/10.1016/j.ancene.2014.06.006

Veldman, J. W., Aleman, J. C., Alvarado, S. T., Anderson, T. M., Archibald, S., Bond, W. J., Boutton, T. W., Buchmann, N., Buisson, E., Canadell, J. G., Dechoum, M. de S., Diaz-Toribio, M. H., Durigan, G., Ewel, J. J., Fernandes, G. W., Fidelis, A., Fleischman, F., Good, S. P., Griffith, D. M., … Zaloumis, N. P. (2019). Comment on "The global tree restoration potential." *Science*, *366*(6463), eaay7976. https://doi.org/10.1126/science.aay7976

Veldman, J. W., Overbeck, G. E., Negreiros, D., Mahy, G., Le Stradic, S., Fernandes, G. W., Durigan, G., Buisson, E., Putz, F. E., & Bond, W. J. (2015). Where Tree Planting and Forest Expansion are Bad for Biodiversity and Ecosystem Services. *BioScience*, *65*(10), 1011–1018. https://doi.org/10.1093/biosci/biv118

Walker, X. J., Baltzer, J. L., Cumming, S. G., Day, N. J., Ebert, C., Goetz, S., Johnstone, J. F., Potter, S., Rogers, B. M., Schuur, E. A. G., Turetsky, M. R., & Mack, M. C. (2019). Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature*, *572*(7770), Article 7770. https://doi.org/10.1038/s41586-019-1474-y

Wan, H. Y., Olson, A. C., Muncey, K. D., & St. Clair, S. B. (2014). Legacy effects of fire size and severity on forest regeneration, recruitment, and wildlife activity in aspen forests. *Forest Ecology and Management*, *329*, 59–68. https://doi.org/10.1016/j.foreco.2014.06.006

Watson, J. E. M., Venter, O., Lee, J., Jones, K. R., Robinson, J. G., Possingham, H. P., & Allan, J. R. (2018). Protect the last of the wild. *Nature*, *563*(7729), 27. https://doi.org/10.1038/d41586-018-07183-6

Wu, M., Knorr, W., Thonicke, K., Schurgers, G., Camia, A., & Arneth, A. (2015). Sensitivity of burned area in Europe to climate change, atmospheric CO2 levels, and demography: A comparison of two fire-vegetation models. *Journal of Geophysical Research: Biogeosciences*, *120*(11), 2256–2272. https://doi.org/10.1002/2015JG003036

Xie, Y., Lin, M., Decharme, B., Delire, C., Horowitz, L. W., Lawrence, D. M., Li, F., & Séférian, R. (2022). Tripling of western US particulate pollution from wildfires in a warming climate. *Proceedings of the National Academy of Sciences*, *119*(14), e2111372119. https://doi.org/10.1073/pnas.2111372119

Zong, X., Tian, X., & Yin, Y. (2020). Impacts of Climate Change on Wildfires in Central Asia. *Forests*, *11*(8), Article 8. https://doi.org/10.3390/f11080802

Figure and Table

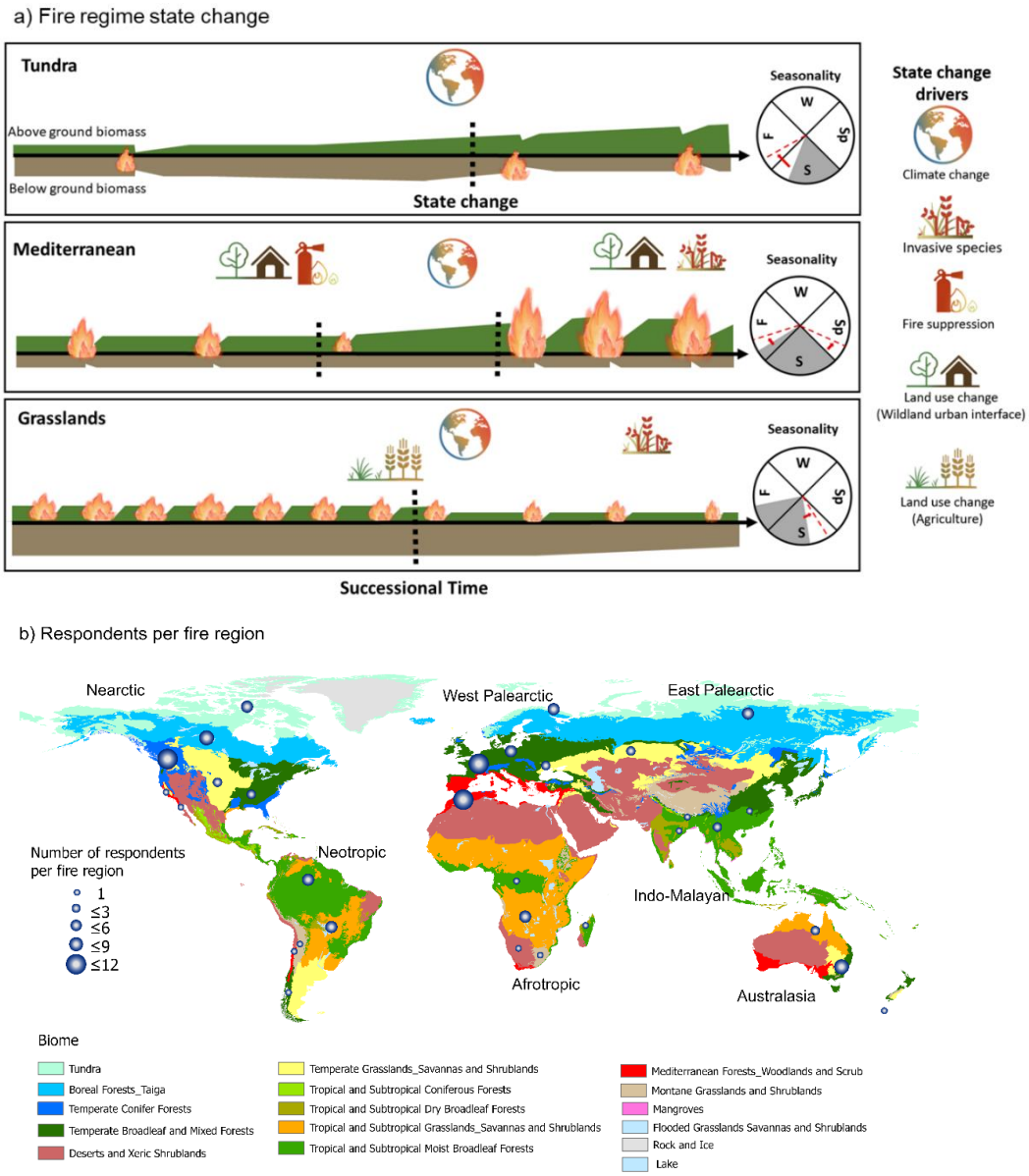
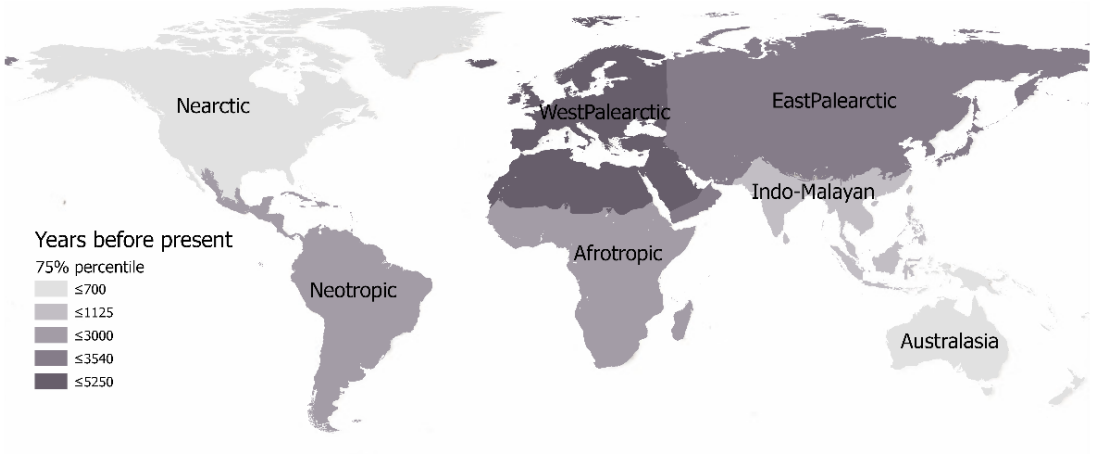


Figure1. a) Conceptual diagram of fire regime characteristics and state changes for three example biomes. Fire regime is defined in terms of spatial (e.g., extent, type, patchiness), temporal (e.g., frequency, interval, seasonality), and physical (e.g., intensity, severity) fire characteristics. The size of flame in the Figure represents fire extent, and the vertical placement of the flame represents fire type (e.g., surface vs. crown). The green and brown bands represent above- and below-ground biomass, respectively. The vertical black dashed lines represent fire regime state change. The gray wedges represent fire seasonality before fire regime change: W: winter, Sp: Spring, S: summer and F: fall/autumn. Red dashed lines inside wedges represent new fire regime seasonality after state change **b) The location of the fire regions used in this study** (Olson 2001) with the number of respondents per fire region.

a)



b)

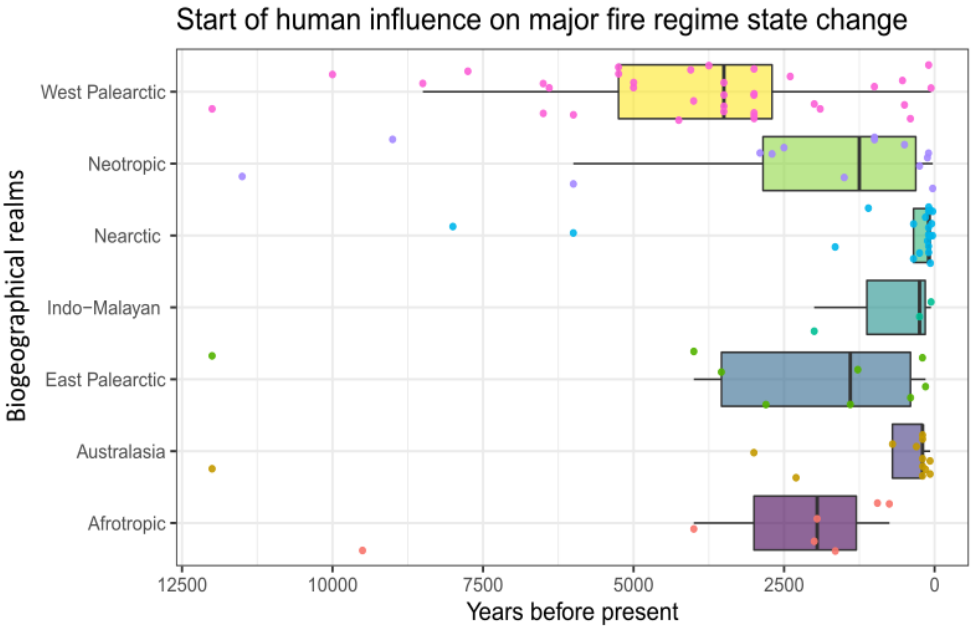
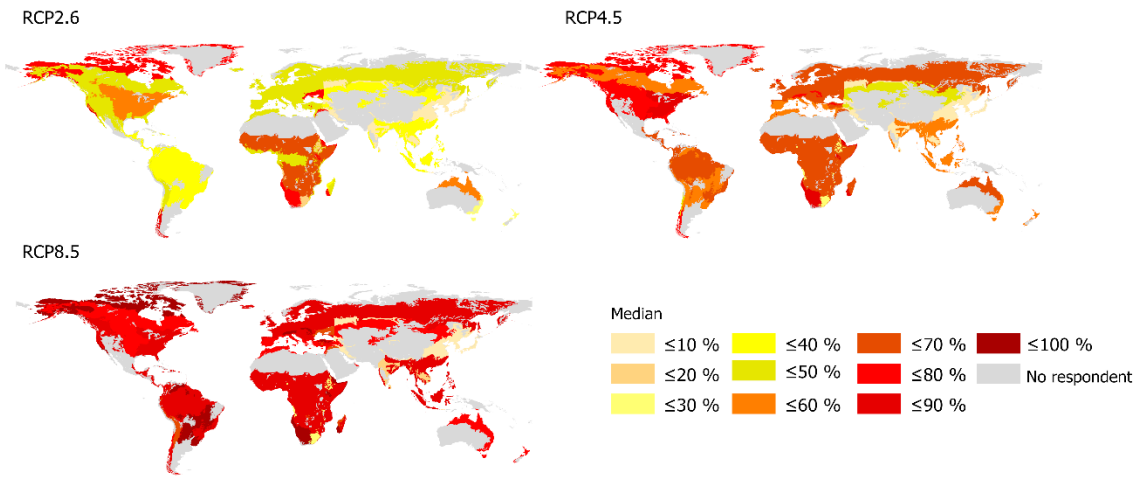


Figure 2. Estimates of when the earliest human-driven fire regime state changes occurred during the Holocene as estimated by respondents. a) 75th percentile values of the earliest time humans were identified as a major driver of fire regime change by respondents. b) Points represent individual responses, while box plots represent the median, quartiles, most extreme points within 1.5-times the interquartile range (IQR), and points beyond 1.5times the IQR.

a) Likelihood of fire regime change by 2100



b) Magnitude of fire regime change by 2100 for Representative Concentration Pathway scenarios

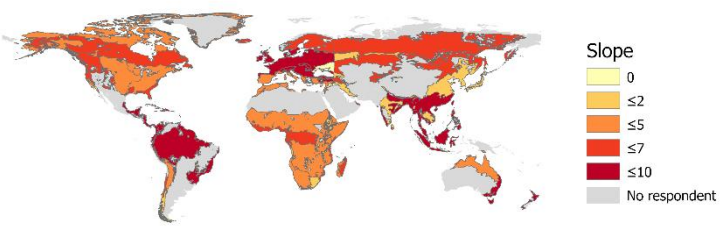


Figure 3. Likelihood of fire regime change under different RCP scenarios as estimated by respondents a) Median of central values of the likelihood of fire regime change for year 2100 under three RCP scenarios. **b)** Magnitude of fire regime change for each biome was based on the slope between the estimated likelihood of a fire regime change (%) and the amount of radiative forcing for the three RCP scenarios ($W.m^{-2}$). The higher values represent a higher magnitude of fire regime likelihood change moving from RCP2.6 to RCP8.5.

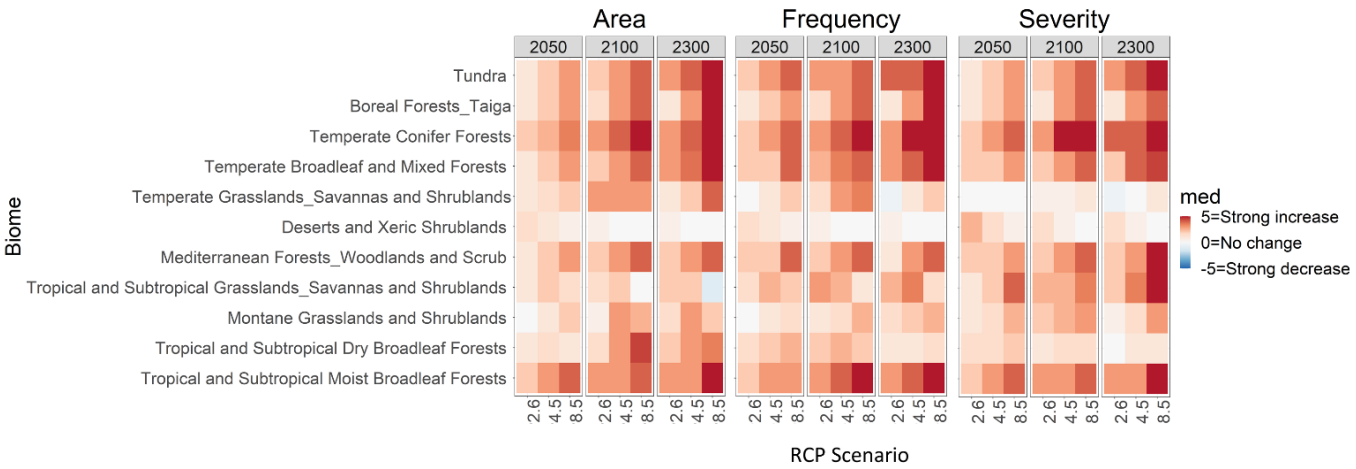


Figure 4. Direction and magnitude of change of fire regime characteristics as estimated by respondents. Median estimates of changes in fire extent (area), frequency, and severity for global warming scenarios RCP2.6, RCP4.5 and RCP8.5 in 2050, 2100, and 2300.

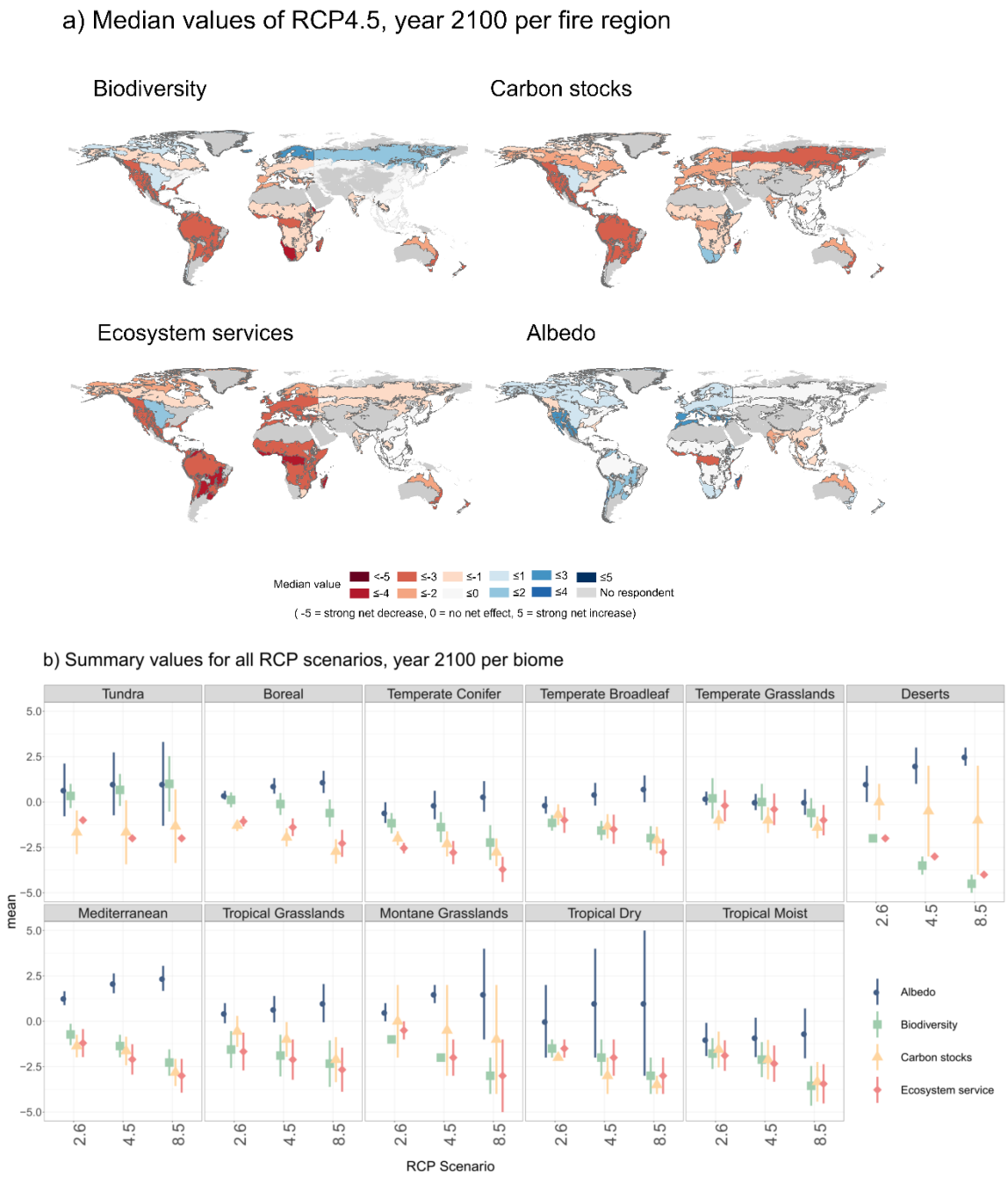


Figure 5. The net effect of predicted fire regime changes on ecosystem values in the future as estimated by respondents. a) The maps show the median value of experts estimate under RCP4.5, year 2100 (see Figures S18-21 for changes in RCP2.6 and RCP8.5). b) Average values and standard error for year 2100 under three RCP scenarios. The full names of the biomes can be seen in Figure1-b. Experts responded on a -5 to 5 scale for how strongly the future fire regime of the three RCP scenarios would affect the indicated parameters in the year 2100 (-5 = strong net decrease, 0 = no net effect, 5= strong net increase).

Table 1. Sources of uncertainty identified by respondents

Past		Current		Future		Management	
Sources of uncertainty	%	Sources of uncertainty	%	Sources of uncertainty	%	Sources of uncertainty	%
Limited proxy-paleo data	23	Spatial variability	31	Vegetation shift	12	Political and socio-economic	22
Spatial variability	17	Limited data	17	Ecosystem interactions and feedbacks[2]	12	Capacity and effectiveness of management and intervention	13
Proxy resolution	15	Combustion/severity	8	Climate change	10	Climate change	11
Model limitation	11	Small fire detection/remote sensing	7	Political and socio-economic	8	Ecosystem interactions and feedbacks	10
Human influence[1]	11	Human activity	8	Model limitation	7	Technology developments	6
Proxy reliability	8	Recent changes	4	Fire management and intervention	7	Science and management connection	4
Temporal variability	6			Land use change	6	Vegetation state	4
Chronological	5			Precipitation	6		

[1]E.g., Fire management history, land use history, etc.

[2]E.g., Climate-vegetation dynamics, albedo and new vegetation, vegetation-fire interaction, fuel-ignition relationships, climate-human intervention, climate-vegetation feedbacks.

947

Affiliations:
[1]Brigham Young University, Department of Plant and Wildlife Sciences. Provo, Utah, USA
[2]Chrono-environnement, UMR 6249 CNRS, Université Bourgogne Franche-Comté, Besançon, France;
[3]MSHE, UAR 3124 CNRS, Université Bourgogne Franche-Comté, Besançon, France;
[4]Institute of Plant Sciences and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[5]Aix Marseille Univ, Avignon Univ, CNRS, IRD, IMBE, Aix-en-Provence, France
[6]Centre for Quaternary Research (CQR), Department of Geography, Royal Holloway University of London (RHUL), Egham, Surrey , UK
[7]Dept. of Ecology Philipps-Marburg University, Marburg, Germany.
[8]Past Landscape Dynamics Laboratory, Institute of Geography and Spatial Organization, Polish Academy of Sciences, Warsaw, Poland
[9]Département de Géographie,Université de Montréal
[10]Department of Physical Geography, Goethe University, Altenhöferallee 1, 60438 Frankfurt am Main, Germany
[11]STAR-UBB Institute Babeș-Bolyai University, Kogălniceanu 1, 400084, Cluj-Napoca, România
[12]Natural Resources Canada, Canadian Forest Service, Canada
[13]University of British Columbia, Department of Earth, Environmental and Geographic Sciences, Kelowna, Canada
[14]Department of Forest Sciences, University of Eastern Finland, Joensuu, Finland
[15]Department of Archaeology, Turku Institute for Advaned Studies (TIAS), University of Turku, 20014 Turku, Finland
[16]Geography, Planning, and Spatial Sciences, University of Tasmania, Hobart, Australia;
[17]School of Ecosystem and Forest Sciences, University of Melbourne, Richmond, Australia;
[18]ARC Centre of Excellence for Australian Biodiversity and Heritage
[19]ZRC SAZU, Institute of Archaeology, Ljubljana, Slovenia
[20]Institut de recherche sur les forêts, Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, QC J9X 5E4, Canada
[21]Département des sciences biologiques, Université du Québec à Montréal, Montréal, QC H2X 1Y4, Canada
[22]Albrecht-von-Haller Institute, Department of Palynology and Climate Dynamics, University of Goettingen
[23]School of Environmental Sciences, University of Liverpool, Liverpool, UK
[24]The Institute of Evolutionary Science of Montpellier
[25]Department of Geography & Planning, School of Environmental Sciences, University of Liverpool, L69 7ZT Liverpool, UK
[26]Department of Environmental Sciences, University of Basel, Switzerland
[27]Department of Geography, University of Oregon, Eugene, Oregon, USA
[28]ARC Centre of Excellence for Australian Biodiversity and Heritage, School of Earth and Atmospheric Sciences, University of Wollonong, NSW, Australia
[29]University of Padova, Department of Land, Environment, Agriculture and Forestry (TESAF), Italy;
[30]ISEM, University of Montpellier, CNRS, IRD, EPHE, Montpellier, France
[31]EPHE-PSL University
[32]UMR LEHNA, Université Claude Bernard Lyon, Villeurbanne, France
[33]Department of Botany, Faculty of Science, Charles University, Prague, Czech Republic
[34]CEABN/InBIO – Centre for Applied Ecology / Research Network in Biodiversity and Evolutionary Biology, School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017 Lisboa, Portugal
[35]ARC Centre of Excellence for Australian Biodiversity and Heritage, Global Ecology, College of Science and Engineering, Flinders University, Adelaide, SA, Australia
[36]Eco&Sols, Univ Montpellier, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France
[37]CIRAD, UMR Eco&Sols, Montpellier, France

[38]Laurentian Forestry Centre, Canadian Forest Service, Natural Resources Canada, Quebec City, QC, G1V 4C7, Canada;
[39]Atlantic Forestry Centre, Canadian Forest Service, Natural Resources Canada, Fredericton, NB, E3B 5P7, Canada
[40]Syracuse University, Department of Earth and Environmental Sciences, Syracuse, NY, USA
[41]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Insubric Ecosystems Research Group, A Ramél 18, CH-6593 Cadenazzo, Switzerland
[42]School of Culture, History & Language, and ARC Centre of Excellence for Australian Biodiversity and Heritage, Australian National University, Canberra ACT-2601, Australia
[43]University of New South Wales, School of Biological, Earth and Environmental Sciences, Sydney, Australia
[44]Geoecology, Department of Environmental Sciences, University of Basel, Klingelbergstrasse 27, 4056 Basel, Switzerland;
[45]Center for Water Infrastructure and Sustainable Energy (WISE) Futures, Nelson Mandela African Institution of Science & Technology, P.O. Box 9124 Nelson Mandela, Tengeru, Arusha, Tanzania
[46]York Institute for Tropical Ecosystems, Department of Environment and Geography, University of York, Wentworth Way, York, YO10 5DD, United Kingdom
[47]School of Animal, Plant & Environmental Sciences, University of the Witwatersrand, Braamfontein, 2000, South Africa
[48]University of Massachusetts Amherst. Department of Geosciences. Amherst, Massachusetts, USA
[49]Departmento de Estratigrafía y Paleontología, Facultad de Ciencias, Universidad de Granada, Granada, Spain
[50]Polar Terrestrial Environmental Systems, Alfred Wegener Institute Helmholtz Center for Polar and Marine Research, Potsdam, Germany;
[51]Institute of Geography, Georg-August-University Göttingen, Goldschmidtstr. 5, 37077 Göttingen, Germany
[52]Mediterranean Ecogeomorphological and Hydrological Connectivity Research Team (http://medhycon.uib.cat), Department of Geography, Universitat de les Illes Balears, Carretera de Valldemossa km 7.5, 07122 Palma, Balearic Islands, Spain;
[53]Institute of Agro-Environmental and Water Economy Research –INAGEA (http://inagea.com), Universitat de les Illes Balears, Carretera de Valldemossa km 7.5, 07122, Palma, Balearic Islands, Spain
[54]University of Trás-os-Montes and Alto Douro, Centre for the Research and Technology of Agro-Environmental and Biological Sciences, Vila Real, Portugal
[55]ISEM, University of Montpellier, CNRS, EPHE, IRD, Montpellier, France
[56]Department of Biological Sciences, University of Bergen, PO Box 7803, 5020 Bergen, Norway
[57]Australian Bureau of Meteorology: Hobart, Tasmania, Tas, AU
[58]Center for Climate and Resilience Research (CR)2 & Institute of Ecology and Biodiversity (IEB), Chile
[59]Laurentian Forestry Centre, Canadian Forest Service, Natural Resources Canada, Quebec City, QC, G1V 4C7, Canada;
[60]Brigham Young University, Department of Public Health, Provo, UT, USA
[61]Departamento de Ciencias Biológicas, Universidad de los Andes, Bogotá-Colombia
[62]Weber State University, Department of Geography, Environment, and Sustainability, Ogden, UT, USA
[63]Max Planck Institute for the Science of Human History, Jena, Germany
[64]Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC, 27695, USA
[65]Earth System Science Program, Faculty of Natural Sciences, Universidad del Rosario, Colombia
[66]School of the Environment, Geography and Geosciences, University of Portsmouth, Buckingham Building, Lion Terrace, Portsmouth, PO1 3HE, UK
[67]School of Geography and Sustainable Development, Irvine Building, University of St Andrews, St Andrews, Scotland, UK (ROW 57)
[68]Department of Forest and Conservation Sciences, University of British Columbia, Vancouver, British Columbia, Canada

[69]Earth Lab (CIRES), University of Colorado, Boulder, CO, USA
[70]Department of Gesciences, Osaka Metropolitan University, Osaka, Japan
[71]Department of Ecology and Evolutionary Biology, Yale University, New Haven, CT, USA
[72] Independent Researcher, Chennai, India.
[73]Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland
[74]Department of Biology and Centre for Forest Biology, University of Victoria, Victoria, BC, Canada
[75]Institut of Evolution Sciences, University of Montpellier CNRS IRD EPHE, Montpellier, France
[76]Univ. Rennes 1, CNRS, ECOBIO UMR 6553, Rennes, France
[77]Department of Geography, University of Wisconsin Oshkosh, Oshkosh WI, USA
[78]Environmental Archaeology Research Group, Institute of History, CSIC, Albasanz 26-28, 28037 Madrid, Spain
[79]Department of Geography and Environmental Sciences, Northumbria University Newcastle, Newcastle upon Tyne, United Kingdom
[80]Biology Department, Luther College, Decorah, IA 55102, USA
[81]Swedish University of Agricultural Sciences, Sweden
[82]Forestry Science Institute (ICIFOR), INIA, CSIC, Madrid, Spain/University Polithechnic of Madrid, Spain
[83]Department of Archaeology, Max Planck Institute for Geoanthropology, Jena, Germany
[84]Climate Change Ecology Research Unit, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Poznań, Poland
[85]Dept. of Earth & Planetary Sciences, University of New Mexico,Albuquerque NM
[86]School of Geography, University of Nottingham, NG7 2RD, Nottingham, UK
[87]Department of Earth Sciences, Montana State University, Bozeman, Montana, 59717 USA
[88]Department of Earth, Environment and Life Sciences (DISTAV), University of Genoa, Italy
[89]Geosciences Barcelona (GEO3BCN) CSIC, c/ Lluis Sole i Sabaris s/n, 08028 Barcelona, Spain
[90]School of Biological, Earth and Environmental Sciences, UNSW Sydney, NSW Australia
[91]Institute of Plant Sciences and Oeschger Centre for Climate Change Research, University of Bern, Altenbergrain 21, CH-3013, Bern, Switzerland
[92]Grupo de Ecología y Restauración Forestal, Departamento de Ciencias de la Vida, Facultad de Ciencias, Universidad de Alcalá, Alcalá de Henares, Spain
[93]Department of Geography, University of Utah, Salt Lake City, Utah, 84112 USA
[94]School of Earth and Environmental Sciences, The University of Queensland, Brisbane, Queensland 4072, Australia
[95]Environmental Change Institute, School of Geography and the Environment, University of Oxford, OX13QY Oxford, United Kingdom
[96]Forest Research Centre, School of Agriculture, University of Lisbon
[97]Institute of Geology and Palaeoontology, University of Münster, Germany
[98]CNR - Institute of Environmental Geology and Geoengineering (IGAG), Lab. of Palynology and Palaeoecology, Piazza della Scienza 1, 20126 Milano, Italy
[99]Interdisciplinary Laboratory for Continental Environments, CNRS, University of Lorraine, Campus Bridoux, 8 rue du Général Delestraint, 57070 Metz, France
[100]ARC Centre of Excellence for Australian Biodiversity and Heritage, College of Arts, Society and Education, James Cook University, Cairns, Australia
[101]Institute of Geography, Augsburg University, Augsburg, Germany
[102]NESSC - Netherlands Earth System Science Centre
[103]PaleoData Lab, Institute of Archaeology and Ethnography SB RAS, Novosibirsk, Russia
[104]Biological Institute, Tomsk State University, Tomsk, Russia
[105]Darwin Centre for Bushfire Research, Charles Darwin University, Darwin, Northern Territory, Australia
[106]Department of Palynology and Climate Dynamics, Georg-August-University of Göttingen, Wilhelm-Weber-Str. 2a, 37073 Göttingen, Germany
[107]Global Environment and Natural Resources Institute (GENRI)
[108]Department of Geography and Geoinformation Science, George Mason University

[109]Division of Ecology, Department of Biology, Hacettepe University, Beytepe 06800 Ankara, Turkey
[110]Departments of Biology and Environmental Studies, St Olaf College, Northfield, Minnesota, 55057 USA
[111]Department of Systematic and Evolutionary Botany, University of Zurich, Zollikerstrasse 107, CH-8008 Zurich, Switzerland.
[112]Herbario Vargas CUZ, Universidad Nacional de San Antonio Abad del Cusco, Av. de La Cultura 773, Cusco, Perú.
[113]Geography, Faculty of Environment, Science and Economy, University of Exeter, United Kingdom
[114]Department of Geosciences, Auburn University, Auburn, USA
[115]Faculty of Biological and Environmental Sciences, University of Helsinki, Finland
[116]Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China; Chongqing University, Chongqing, 400044, China
[117]Univ. Bordeaux, CNRS, Bordeaux INP, EPOC, UMR 5805, F-33600 Pessac, France