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Fire Ecology

ORIGINAL RESEARCH

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Assessing changes in global fire regimes

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Abstract

Background The global human footprint has fundamentally altered wildfire regimes, creating serious consequences for human health, biodiversity, and climate. However, it remains difficult to project how long-term interactions among land use, management, and climate change will affect fire behavior, representing a key knowledge gap for sustainable management. We used expert assessment to combine opinions about past and future fire regimes from 99 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.

Results Respondents indicated some direct human influence on wildfire since at least ~ 12,000 years BP, though natural climate variability remained the dominant driver of fire regime change until around 5,000 years BP, for most study regions. Responses suggested a ten-fold increase in the frequency of fire regime change during the last 250

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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 frequency, severity, and size in all biomes except grassland ecosystems. Fire regimes showed different climate sensitivities across biomes, but the likelihood of fire regime change increased with higher warming 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, while recognizing that management options are constrained under higher emission scenarios.

Conclusion The influence of humans on wildfire regimes has increased over the last two centuries. The perspective gained from past fires should be considered in land and fire management strategies, but novel fire behavior is likely given the unprecedented human disruption of plant communities, climate, and other factors. Future fire regimes are likely to degrade key ecosystem services, unless climate change is aggressively mitigated. Expert assessment complements empirical data and modeling, providing a broader perspective of fire science to inform decision making and future research priorities.

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

Resumen

Antecedentes Las huellas humanas globales han alterado fundamentalmente los regímenes de fuegos, creando serias consecuencias para la salud humana, la biodiversidad y el clima. Sin embargo, resulta difícil proyectar cómo las interacciones a largo plazo entre el uso de la tierra, la gestión, y el Cambio Climático van a afectar el comportamiento del fuego, lo que representa un vacío clave en el conocimiento para la gestión sostenible. Usamos las apreciaciones de expertos para combinar opiniones sobre regímenes de fuegos pasados y futuros de 99 investigadores en el tema de fuegos de vegetación. Preguntamos por determinaciones cualitativas y cuantitativas de la frecuencia, tipo, e implicaciones de los cambios en los regímenes de fuegos desde el inicio del Holoceno hasta el año 2300.

Resultados Quienes respondieron indicaron alguna influencia humana directa en los fuegos de vegetación desde al menos ~ 12.000 años atrás, en los que la variabilidad climática perduró como la conductora dominante de los cambios en los regímenes de fuego hasta hace aproximadamente unos 5.000 años, para la mayoría de las regiones en estudio. Las respuestas sugirieron que hubo un incremento de 10 veces en la frecuencia de cambios en los regímenes de fuego durante los últimos 250 años comparado con el resto del Holoceno, correspondiendo en primer lugar con la intensificación y expansión del uso de la tierra y luego con el Cambio Climático antropogénico. Mirando al futuro, predicen que los cambios en los regímenes de fuego se intensificarán, con incrementos en la frecuencia, severidad, y tamaño en todos los biomas con excepción de los ecosistemas de pastizales. Los regímenes de fuego muestran diferente sensibilidad climática a través de los biomas, aunque la probabilidad de cambio en el régimen de fuego se incrementa con mayores escenarios de calentamiento en todos los biomas. Predicen asimismo que la biodiversidad, el almacenamiento de Carbono, y otros servicios ecosistémicos, van a decrecer para la mayoría de los biomas bajo escenarios de mayores emisiones. Presentamos recomendaciones para la adaptación y mitigación bajo regímenes de fuego emergentes, mientras que reconocemos que las opciones de manejo están condicionadas bajo escenarios de mayores emisiones.

Conclusiones La influencia de los humanos en los regímenes de fuego se ha incrementado en las últimas dos centurias. Las perspectivas ganadas sobre incendios pasados deben ser consideradas en las estrategias de manejo de tierras y de fuego, aunque un nuevo comportamiento del fuego es probable, dado que la disrupción humana en las comunidades vegetales, en el clima, y en otros factores no tiene precedentes. Los regímenes de fuegos futuros probablemente degraden algunos servicios ecosistémicos clave, al menos que el Cambio Climático sea agresivamente mitigado. Las apreciaciones de los expertos complementan los datos empíricos y modelados, proveyendo una perspectiva más amplia de la ciencia del fuego para informar a los decisores y priorizar futuras investigaciones.

Background

Human alteration of land cover and climate is reshaping wildfire on Earth (Andela et al. 2017; Bowman et al. 2020; Davis 2021; Pereira et al. 2022; Ellis 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*; Fig. 1a), they can harm biodiversity (Kelly et al. 2020; Feng et al. 2021), climate (IPCC 2021), and societies (Doerr and Santín 2016; Johnston et al. 2021; Jones 2017). In some regions, recent state changes in fire regimes have reduced ecosystem services, including air quality, water availability, habitat, and ecosystem carbon storage (McClure and Jaffe 2018; Pausas and Keeley 2019; Collins et al. 2021; Xie et al. 2022). Such changes in fire regime 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 regimes has been the interaction between climate and vegetation (Girardin et al. 2013; Abbott et al. 2016; Harris et al. 2016; McDowell et al. 2020; Molinari et al. 2020). All aspects of climate, but especially patterns of precipitation and temperature influence plant community 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; Scholten et al. 2021; Chen et al. 2021a).

As humans modified global patterns of vegetation, ignition, and climate over the past several millennia (Watson et al. 2018; Abbott et al. 2019; McDowell et al. 2020; Ellis et al. 2021), fire disturbance became progressively more anthropogenically influenced at local to global scales (Hantson et al. 2015; Nowacki and Abrams 2015; Lestienne et al. 2020; Hagmann et al. 2021) (Fig. 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 (Marlon et al. 2008; Bowman et al. 2011; Balch et al. 2017; Watson et al. 2018; Słowiński et al. 2022). Likewise, climate disruption has influenced all of the Earth's ecosystems, supercharging wildfire in some regions (Turco et al. 2017, 2018; Wasserman and Mueller 2023).

Understanding the characteristics and sensitivity of fire regime change is necessary for sustainable land management as well as climate change mitigation, adaptation, and planning (Cochrane and Bowman 2021; Moritz et al. 2014). However, our understanding is incomplete for relationships linking climate, land use, and fire regimes in the past, present, and future. In this context, we combined scientific opinions 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). We intended these assessments to address the current needs of decision makers and ecosystem managers to better understand and apply the consensus view from the research community.

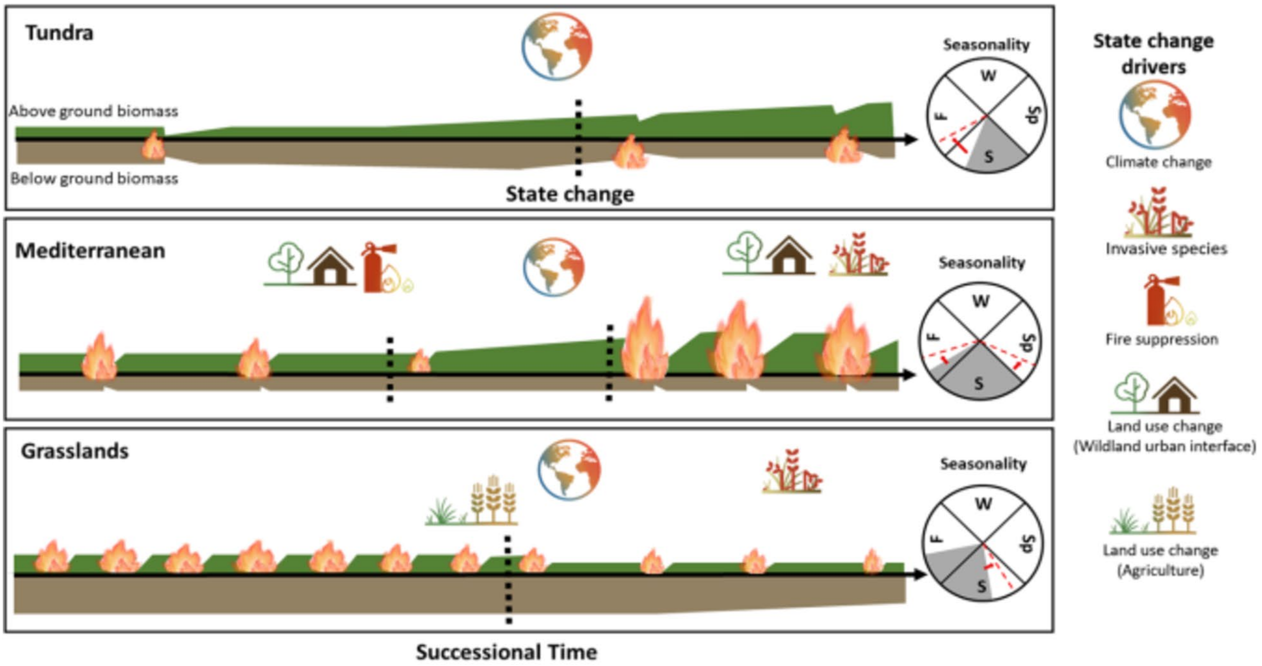
Using the collected informed opinion from experts, we evaluated centennial to millennial-scale state changes (Fig. 1a) in past, present, and future fire regimes at both regional scales and biome levels. We were motivated by four topic questions: How have fire regimes varied during the Holocene (the last ~ 11,700 years)? How likely are fire regime state changes under different future climate change scenarios? What component of ecosystems will be affected by potential future fire regimes? and What types of human activities could be the most effective for mitigation and adaptation under future fire regimes? We used a questionnaire to collect quantitative and qualitative assessments from experts for specific biogeographic realms and biomes from around the world (Fig. 1b; Supplementary Information).

Methods

We used expert assessment to evaluate the risk of fire regime change and its consequences in the future. The concept and initial preparation for this study emerged from a September 2016 paleofire workshop held in Beguey, France, supported by the PAGES (Past Global Changes) Global Paleofire Working Group 2. At that meeting and through 2020, we completed a literature review of both scientific and policy related documents about wildfires and fire regime change. Following best practices from expert assessment and expert elicitation (Bamber and Aspinall 2013; Morgan 2014; Sutherland and Burgman 2015; Sayedi et al. 2020), we designed a structured questionnaire to gather scientific opinion on changes in fire regimes and their effects on ecosystems, climate, and societies (Supplementary Information). We focused on centennial-to-millennial changes in past, present, and future fire regimes across the globe (seven biogeographic realms and 11 biomes) to consider long-term processes beyond observational and instrumental records. After two testing rounds, we distributed the final questionnaire containing 15 questions to 430 scientists with fire related expertise. To include both academic and applied wildfire experts, we invited coauthors from the papers in the background review as well as referrals from workshop participants and all respondents who filled out the questionnaire.

Of the 430 invitees, we collected 124 filled questionnaires from 99 respondents (included here as coauthors), with some respondents completing the questionnaire for more than one fire region, which explains the higher number of filled surveys. Respondents were from 23 countries (Fig. S24) and were 46% female, 45% male, and

a) Fire regime state change



b) Respondents per fire region

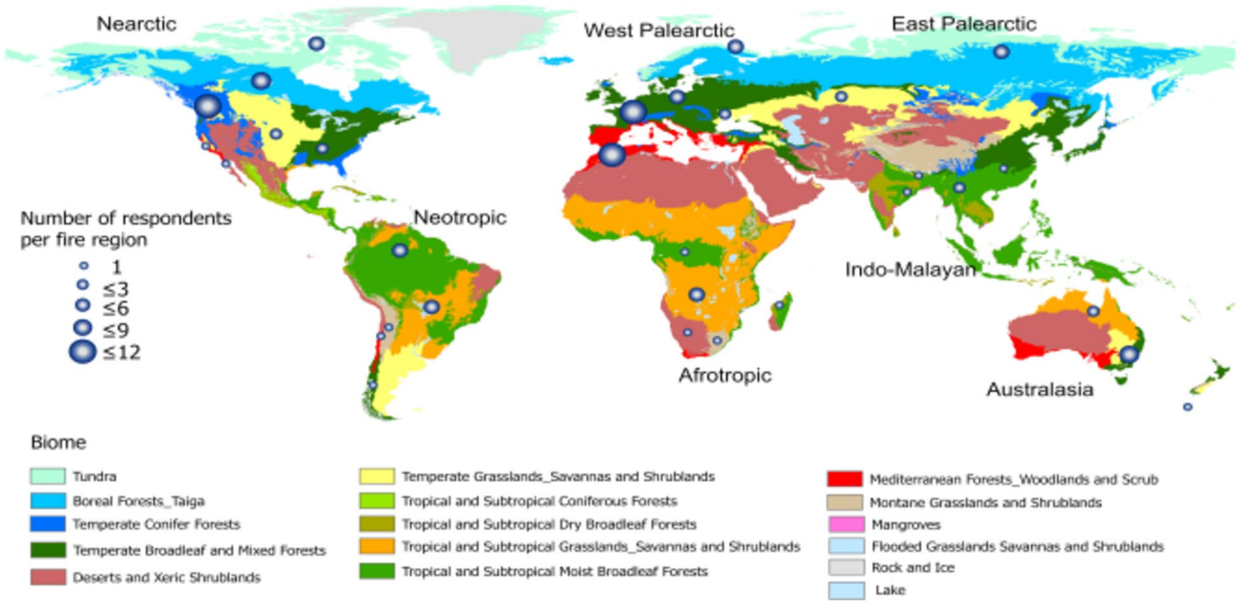


Fig. 1 **a** Conceptual diagram of fire regime characteristics and state changes for three example biomes. Fire regime is defined in terms of spatial (e.g., extent, type, patchiness), temporal (e.g., frequency, interval, seasonality), and physical (e.g., intensity, severity) fire characteristics. The 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

9% unspecified (Table S2). The primary research disciplines, as identified by the respondents themselves, were paleoecology (55%), ecology (17%), and other fields, such as geography or geosciences (28%). Each response was specific to one biogeographic realm-biome combination, which we defined as "a *fire region*" (Fig. 1). We received responses for 70% of flammable land area worldwide (total land surface excluding rock, ice, and lakes; Fig. 1b and S1, Table S2), reflecting diverse global bioclimatic, socioeconomic, and fire regime characteristics (Olson et al. 2001).

The questionnaire included detailed background information and instructions to reduce the effects of availability bias and increase the likelihood of commensurate responses across experts from different realms (Morgan 2014; Sayedi et al. 2020). The questionnaire included a description of representative concentration pathways (RCP) scenarios (Moss et al. 2008) and predicted temperature and precipitation (Supplementary Information). We also provided detailed definitions and references on the concepts of fire regime and state change (details in Supplementary Information-questionnaire). Briefly, we defined state change as a large and sustained departure from a set of specific system behaviors. Fire regime state changes can be triggered by disturbances of varying duration and intensity, including internal and external drivers such as climate change, vegetation shifts, and human activities (Fig. 1a). These disturbances can result in reversible or permanent changes to the fire regime. For example, a state change in a fire regime may be expressed as a shift in the central tendency, such as a decrease in mean annual area burned, a change in overall variance, such as an increase in interannual variability of area burned, or in the frequency of events that exceed an ecological threshold, such as a change in the return interval of crown fires (Scheffer et al. 2009).

The questionnaire focused on four topics: (1) past fire regimes, (2) current fire regime states, (3) future fire projections, and (4) interventions and management. For each section, respondents provided self-reported expertise, confidence level, sources used to generate estimates (e.g., published or unpublished empirical data, professional opinion; Table S3), along with a list of sources of uncertainty (Table 1). For future fire behavior, we asked experts to provide estimates for short (2050), medium (2100), and long (2300) time frames. We included the 2300-timestep to account for lags in the response of fire regime to disturbance, as it can take several decades or centuries to fully manifest. Although climate projections and estimates of system response become increasingly uncertain for distant time frames, we asked respondents to think conceptually about the eventual fire regime state if the described climate conditions persisted. We compared estimates for all three time-steps with current fire regime.

For most of the quantitative questions, we asked for three quantiles (5% lower, 50% central, and 95% upper) to build a credible range of 90%. We primarily discuss the distribution of central estimates for the main article, though full ranges are shown in the Supplementary Information. The qualitative questions included both open-ended and numerical responses. The open-ended questions were analyzed using a thematic analysis method, where we applied coded categories to each response. We calculated descriptive statistics in R version 3.6.1 (R Core Team 2019). We used ArcGIS Pro 3.0 for spatial analyses and visualizations.

In the following sections, we present estimates and suggestions based on experts' responses, which we compare with relevant literature. Because not all fire regions have the same number of respondents, we focus on identifying general patterns and trends rather than providing specific results for individual regions with limited representation (though the comprehensive results by fire region are included in the Supplementary Information). Consequently, we focus on general patterns and trends among biomes and biogeographic realms to create a more comprehensive and nuanced understanding of the global patterns of fire regimes.

Results

Past and present drivers of fire regime

The median estimated number of fire regime state changes during the Holocene varied across biomes, ranging from two (Tundra) to seven (Temperate grasslands, savannas, and shrublands) (Fig. S2). Respondents identified the timing of the three largest fire regime state changes in the Holocene, with 16% of responses suggesting 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). Survey responses indicated an increase in fire regime changes after the Industrial Revolution in 1760 AD, with 20% of identified fire regime changes occurring since that time (Fig. S3). This suggests a ~ 10-fold increase in the frequency of fire regime changes over the last 250 years compared with the rest of the Holocene. The Nearctic and Australasia regions may have experienced even larger 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 of changes (32%). The onset of strong human influence on fire regimes varied among regions (Fig. 2), but direct human influence was the greatest during the Late Holocene. For the post-industrial period (1950 AD-present), climate change and direct human activity were mentioned equally often as drivers (40% and 46%, respectively). Vegetation and fuel were mentioned the least for each time interval (Fig. S4), possibly because these factors respond to climate on centennial timescales, emphasizing the importance of temporal scale when considering drivers.

Respondents identified several dimensions of altered fire regimes over the past 250 years, including changes in fire frequency, extent, and severity (Fig. S5). There was a wide range of human-wildfire interactions identified that were specific to fire regions. For example, in Indo-Malayan Tropical forests, deforestation due to economic development has modified the fuel structure and ignition sources, potentially increasing fire activity in an ecosystem where it was historically rare. In multiple regions, other fire management strategies such as increased fire suppression and exclusion of Indigenous or traditional prescribed burning practices were recognized as potential drivers of increasing fuel loads and ultimately increased fire severity, especially when coupled with recent temperature increases. In seven out of eleven biomes, respondents identified a change in fire regime since the Industrial Revolution (Fig. S3), with the median estimate of current fire regime duration lasting less than 200 years (Fig. S6). The duration of the current fire regime was less than 70 years for Tundra; Mediterranean forests, woodlands, and scrub; Tropical and subtropical moist broadleaf forests; and Tropical and subtropical grasslands, savannas, and shrubs (Fig. 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 RCPs 2.6, 4.5, and 8.5, representing increasingly severe greenhouse gas emission scenarios. Most respondents predicted that the likelihood of fire regime change would increase with time and climate change severity (Figs. S9-10). For example, under RCP8.5, nine biomes were predicted to have ≥50% chance of experiencing a fire regime change by 2050, compared to one biome for RCP2.6. However, by 2100 and 2300, five biomes were predicted to have a ≥50% likelihood of fire regime change under RCP2.6 (Fig. 3a and S9-10). The climate sensitivity—which we defined as the amount of increase in the likelihood of a fire regime change across RCP scenarios—varied substantially among biomes. For example, RCP2.6 was predicted to be enough to initiate a fire regime change for Tundra, whereas the predicted likelihood of fire regime change was much lower under RCP2.6 than RCP8.5 for Boreal forest (Fig. 3b and S11-12). Results from all scales, years, and scenarios are presented in the Supplementary Information.

The climate sensitivity estimates from this study agreed with many model-based studies projecting future changes in fire activity (Bowman et al. 2020). Climate drivers such as fire weather and fire danger days are projected 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 projected in many regions such as the Amazon, western USA, Mediterranean and southern Australia (Turco et al. 2018; Bowman et al. 2020). Substantial intensification of fire behavior is projected for higher latitudes through the end of the 21st century (Flannigan et al. 2013; Bergeron et al. 2010; Abbott et al. 2021; Talucci et al. 2022), though local fire patterns are expected to be heterogeneous (McCarty et al. 2021).

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

Contrary to most regions, less burning was predicted by experts for some parts of Africa under warmer scenarios. This is consistent with observations (Moritz et al. 2012; Andela and van der Werf 2014) that reveal a more intense fire regime under cooler and wetter climates that favor fuel build-up in these dry regions (Daniau et al. 2013; Moritz et al. 2012). More generally, fire frequency

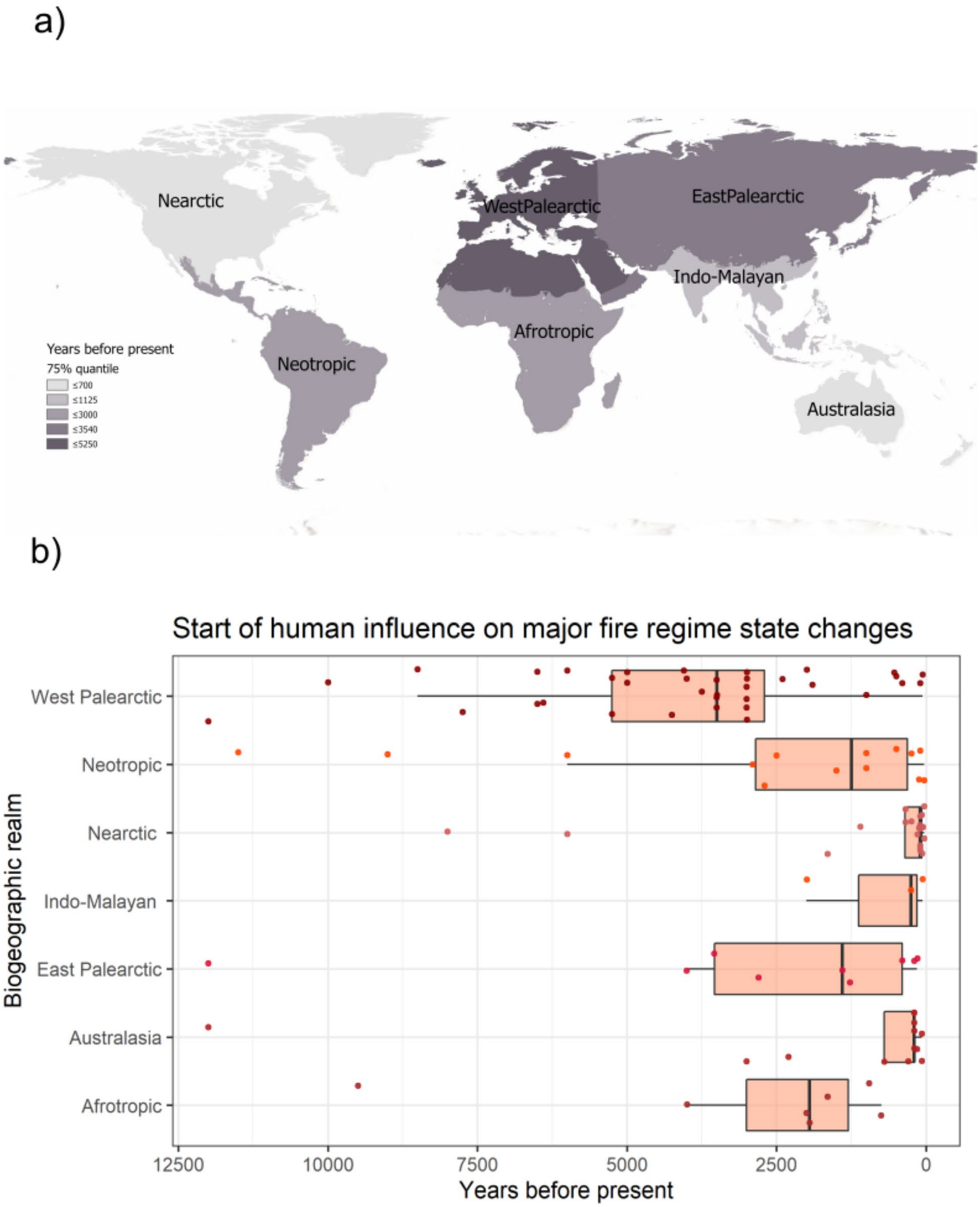
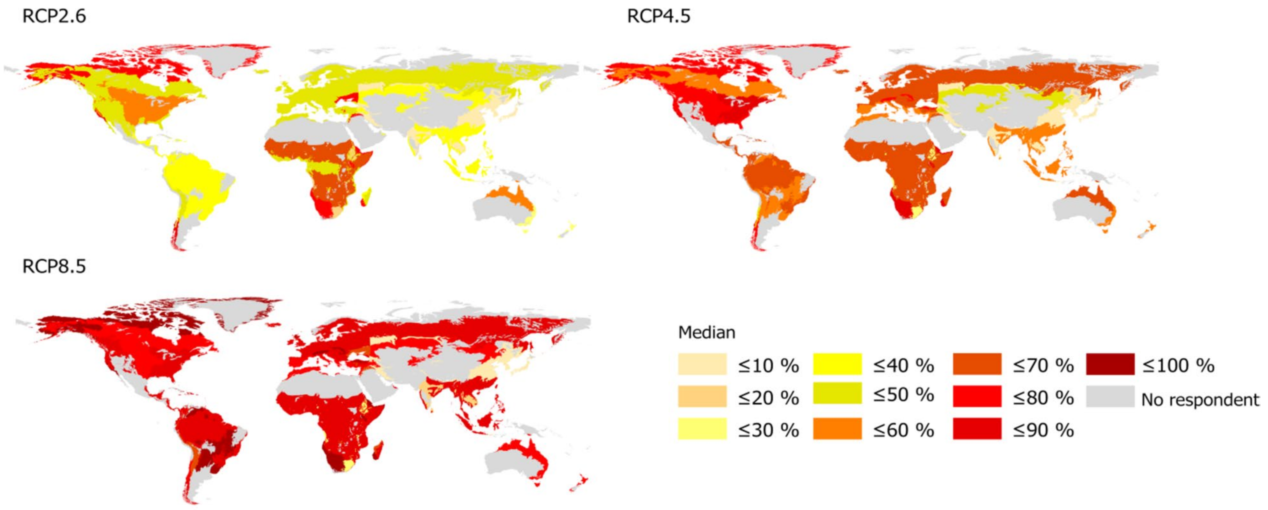


Fig. 2 Estimates of when the earliest human-driven fire regime state changes occurred during the Holocene as estimated by respondents. **a** 75th percentile values of the earliest time humans were identified as a major driver of fire regime change by respondents. **b** Points represent individual responses;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

a) Likelihood of fire regime change by 2100



b) Climate sensitivity of fire regime by 2100

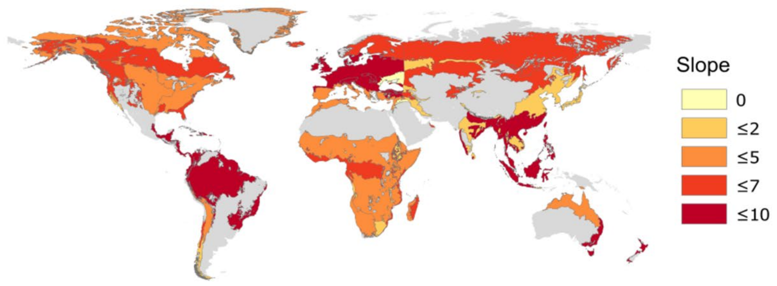


Fig. 3 Estimated likelihood of fire regime change under different RCP scenarios **a** Median of central values of the likelihood of fire regime change for year 2100 under three RCP scenarios. **b** Climate sensitivity of fire regime change for each biome based on the slope between the estimated likelihood of a fire regime change (%) and the amount of radiative forcing across the three RCP scenarios (Wm^{-2}). The higher values represent a greater climate sensitivity and increased fire regime likelihood moving from RCP2.6 to RCP8.5

and severity are expected to decrease in fuel-limited ecosystems under drier conditions, whereas they are likely to increase in wetter ecosystems where fuel humidity currently limits fire (Rogers et al. 2020).

Many respondents from most fire regions mentioned the importance of recognizing that within a single fire region, different ecological communities may experience divergent future fire trajectories (Moritz et al. 2012). For example, the risk of fire-climate interactions can vary in different types of conifer forests in western North America (moist-dry-subalpine) based on their elevation (Halofsky et al. 2020). Likewise, substantial differences exist between eastern and western Boreal forests of the Nearctic, with the latter experiencing increasing annual area burned (Chavardès et al. 2022). However, projected climate change could create similar increases for eastern and western Boreal forests of the Nearctic during the mid- to late-21st century (Chavardès et al. 2022).

Consequences of fire regime change

Respondents estimated that biodiversity (habitat extent, diversity and quality), carbon stocks (soil and vegetation), and ecosystem services (other benefits for societies living in the region) would decrease with future fire regime change. The magnitude of change was predicted to increase for more extreme warming scenarios and longer timeframes in most biomes, similar to the patterns for other questions (Fig. 5 and S17-20). The estimates of fire consequences were highly spatially variable (Fig. 5). Negative impacts estimated for biodiversity were greatest

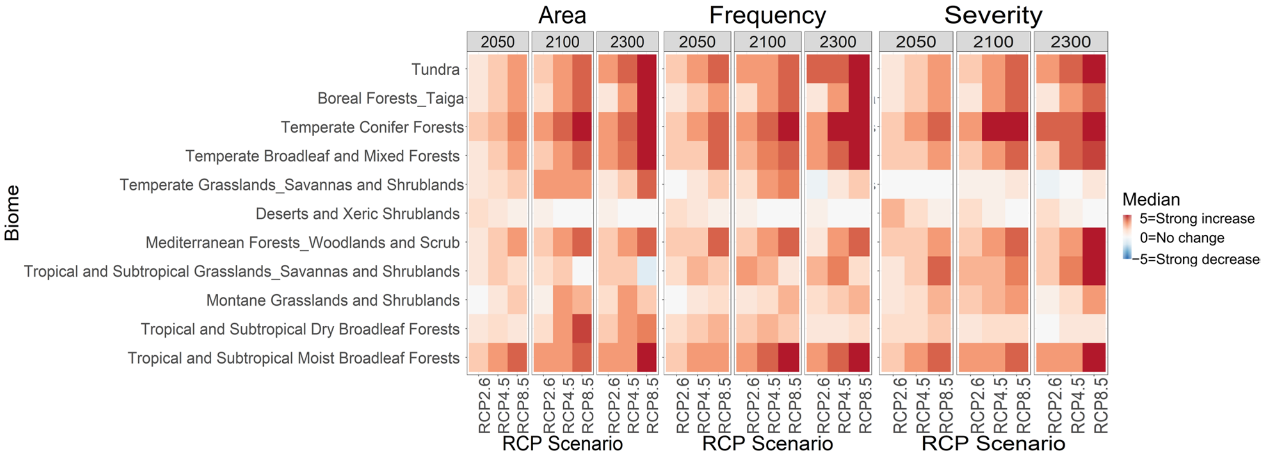


Fig. 4 Direction and magnitude of change of fire regime characteristics as estimated by respondents. Median estimates of changes in fire extent (area), frequency, and severity for global greenhouse gas emission scenarios RCP2.6, RCP4.5 and RCP8.5 in 2050, 2100, and 2300

in tropical, semiarid, and arid ecosystems, whereas decreases in carbon stocks were more uniform across biomes. The large projected decrease in carbon stocks for Boreal forests and Tropical and subtropical moist broadleaf forests was particularly concerning, given how these ecosystems contain much of global terrestrial carbon (McDowell et al. 2020; Pan et al. 2011; Schuur et al. 2022). Similarly, the strong projected loss of ecosystem services, including air, water, and soil quality in Africa, South America, and southern Europe could further burden areas already experiencing disproportionate climate impacts (Ogunbode 2022).

The projected response of albedo displayed significant temporal complexity, representing a dimension of ecosystem response that was generally expected to improve with fire regime changes (Fig. 5 and S21). It is important to note that the relationship between fire emissions and albedo is multifaceted, varying depending on factors such as the region and land surface type. These factors can lead to different effects on albedo. For example, while aerosols from fire emissions may initially reduce albedo by promoting snowpack melting, it is worth considering the net negative radiative impact of such emissions, as demonstrated in (Tian et al. 2022), which can result in a mid-term cooling effect.

Our survey respondents estimated a general increase in albedo from 2050 to 2100 as fire regimes increased. However, it is noteworthy that this trend reversed for some biomes beyond 2300, indicating a transient stabilizing effect on climate (Fig. 5 and S21). The intricate analysis encompassing various scales, scenarios, and years can be found in the Supplementary Information.

This discussion underscores the complexity of fire emissions and their impact on albedo, with outcomes varying depending on regional factors and land surface characteristics. Furthermore, the influence of fires on albedo evolves over time, making it a dynamic and intricate phenomenon.

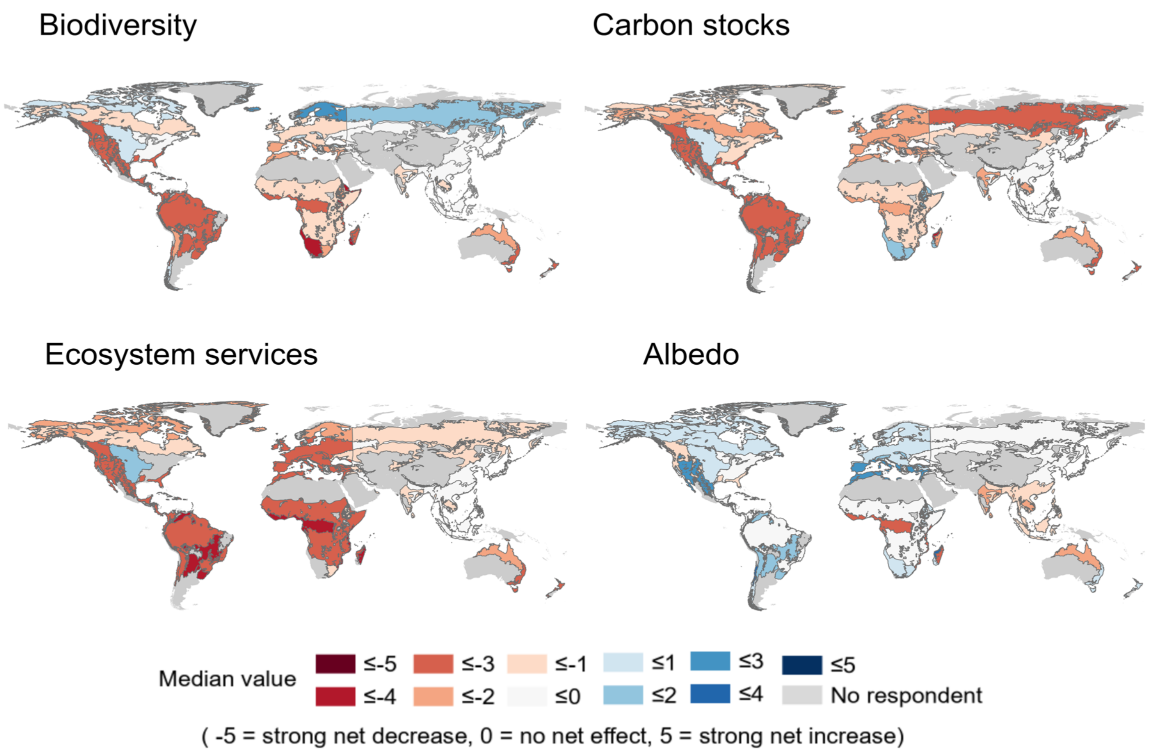
Drivers of fire regime change and management options

The identified fire regime drivers varied substantially by both warming scenario and fire region. Under higher emissions (i.e., RCP4.5 and RCP8.5), most experts suggested that climatic factors would be the dominant driver of fire regime change. Conversely, under RCP2.6, only about half of the responses indicated that climatic factors would be the most important driver. For Australasia and Nearctic fire regimes, climatic factors were identified as the most important driver for all scenarios. In the Neotropic, Afrotropic, and Indo-Malayan biogeographic realms, human activities were identified as the most important fire driver, with an average of 18% of responses across all scenarios. Although vegetation and fuel were also frequently mentioned, accounting for 22% of total responses, these factors were never suggested as the most important driver of future fire regime changes

(See figure on next page.)

Fig. 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 expert estimates under RCP4.5, year 2100 (see Figs 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 Fig. 1b 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)

a) Median values for RCP4.5 in the year 2100, per fire region



b) Summary values for all RCP scenarios in the year 2100, per biome

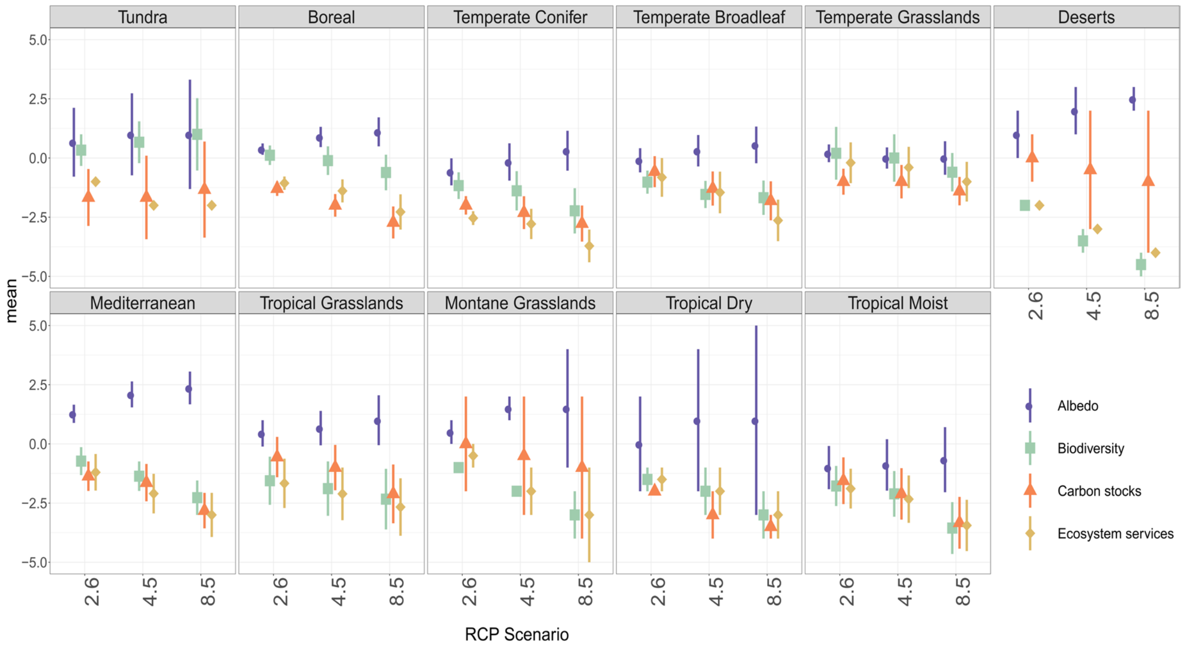


Fig. 5 (See legend on previous page.)

(representing approximately 1% of the responses (Fig. S22)), highlighting the complex interplay amongst climate, fuel, and fire, especially on centennial timescales.

While we have summarized and combined the management suggestions from respondents below, we emphasize that suitable management applications vary substantially between and within biomes. The detailed responses for each fire region can be found in the Supplementary Information. Responses suggested that human actions for the next 20–50 years will be highly influential in determining how different ecosystem values (e.g., biodiversity, carbon stocks) are likely to change. Only 14% of the respondents indicated that human actions have no effect, mainly limited to albedo (Table S1). Only 10% of responses recommended non-intervention, which instead was rated as a negative or unhelpful approach, though there were mixed opinions across and within fire regions.

About half of the respondents considered direct land management as an important approach for mitigating impacts of changing fire regime. 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-fire interface was a common recommendation, as certain levels of population (housing) density, wildland-urban interface, and landscape connectivity can affect the characteristics and societal consequences of fire (Syphard et al. 2007; Archibald et al. 2012; Moritz et al. 2014; Kelley et al. 2019). Fuel treatment, vegetation management, urban/suburban development design, and sustainable agriculture (cropland optimization, savanna conversion management, integrated grazing, traditional agroforestry, etc.) were identified as potentially useful mitigation approaches.

There was a high level of agreement that prescribed burning would help biodiversity and ecosystem services, but there were mixed opinions about its effect on carbon stocks, potentially because of successional complexities and the fact that 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 (Lindenmayer et al. 2009, 2020; Maxwell et al. 2019; Stephens et al. 2020; Baker and Hanson 2022). Conversely, traditional or Indigenous practices—such as cultural burning—were suggested as beneficial in reinforcing fire regime resilience, protecting biodiversity, and mitigating damage by preventing extreme wildfire events (Christianson 2015; Fletcher et al. 2021; Hoffman et al. 2021). However, respondents also noted that many current burning practices—such as slash-and-burn techniques—no longer resemble traditional cultural burning practices as they existed before industrialization.

There was a high level of agreement among experts who mentioned restoring vegetation (i.e., native habitat conservation and restoration; establishment of climate-adaptable vegetation communities) 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.

Direct fire management was recommended in 17% of responses. In the case of fire suppression as a direct fire management strategy, there was less agreement about the direction of effects on different factors. Fire suppression can have a negative impact on fire-dependent ecosystems, and aggressive suppression policies have led to fuel accumulation and increased flammability that have contributed to today's extreme wildfire events (Marlon et al. 2012; Valese et al. 2014; Schoennagel et al. 2017; Parisien et al. 2020). A greater proportion of responses (23%) indicated the importance of social or political awareness and action. These initiatives include climate mitigation, public education on fire risks and their ecological roles, direct (e.g., controlled burns, firebreak establishment) and indirect (e.g., illegal logging regulations, land-use policies) conservation policies, and the incorporation of Indigenous and traditional knowledge. (Table S1).

For most biogeographic realms—though notably not the Afrotropic and the Indo-Malayan—respondents projected that under RCP8.5, humans would have a decreasing capacity to control wildfires. This was most obvious for the Neotropic, Nearctic, and Australasia for both 2100 and 2300. Respondents for the Neotropic and Nearctic fire regimes indicated that this same decreased capacity was likely to apply under RCP4.5. For RCP2.6, 70% of respondents indicated that humans would maintain some effectiveness in managing fire-impacts (Fig. S23).

Sources of uncertainty

For each question, respondents identified their main sources of uncertainty (Table 1). The most common responses were limited observational data, inadequate modeling frameworks, and system complexity, particularly social dimensions. Respondents emphasized that

Table 1 Sources of Uncertainty in Survey Estimates

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[b]	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[a]	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		

This table presents the major sources of uncertainty identified by respondents for each section of the survey. The percentages represent the proportion of responses within each category for the respective sections. Note that the table includes only the significant sources of uncertainty, and the columns may not sum up to 100% due to the omission of less prominent factors

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

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

the impact of different human activities is not completely understood for the past or present, and that untangling different fire drivers can be difficult due to multiple interactions and feedbacks, which are often not represented in coupled models. Respondents also mentioned that the unprecedented rate of ongoing climate change and heterogeneity of human activities made estimations of fire return intervals and other dimensions of fire regime uncertain. Respondents had uncertainties about emergent economic and policy direction, cultural beliefs, and available technologies as tools to combat changing fire regime. Additional sources of uncertainty included the spatial variability and a lack of information about fire severity impacting ecological succession, albedo, and carbon-climate feedbacks.

Discussion

This expert assessment synthesized global fire expertise to explore the possible magnitude, type, and consequences of human-wildfire interactions in the Holocene and Anthropocene. The results confirmed the growing consensus in the literature that we have entered a new epoch of fire behavior dominated by climate change and direct human activity (Bowman et al. 2020; Mottl et al. 2021). The geographic diversity of past and future fire regimes also emphasized the importance of local factors, especially human culture and plant community. In the following section, we compare our survey results with the broader literature and summarize potential management and policy implications.

Fire regime change as an indicator of the Anthropocene

This study adds to the consensus that human activity dominates vegetation disturbance and distribution globally (Harris et al. 2016; Watson et al. 2018; Abbott et al. 2019; Bowman et al. 2020; Mottl et al. 2021; Słowiński et al. 2022). The ten-fold acceleration of fire regime change over the past two centuries aligns directly with recent paleoecological evidence showing vegetation shifts unprecedented in the last 18,000 years (Mottl et al. 2021). Although there are still debates about the formal start of the Anthropocene (Witze 2023), our survey results provide evidence that we have entered a new epoch where fire is no longer solely influenced by natural factors but is increasingly shaped by human activities, both intentional and inadvertent (Fig. S1). After approximately 500 million years of natural wildfire regulation driven by climate and vegetation interactions (Glasspool et al. 2004), our findings indicate that fire dynamics in the Earth system are now significantly controlled by direct and indirect human actions. Notably, the quadruple combination of invasive species, fire ignition and suppression practices, land use changes, and climate change has substantially reshaped nearly every dimension of fire behavior in the Anthropocene (Fig. 1).

One of the paradoxes highlighted by our study and much previous work is that knowledge of past fire behavior is both crucial and rapidly becoming outdated. Past fire regimes provide perspective on how climate, vegetation, and human actions interacted to shape fire dynamics in the Earth system (Marlon et al. 2008; Pechony and

Shindell 2010; Molinari et al. 2018). For example, paleoecological knowledge about vegetation community and historical amplitude of fire regime change in a given biome can provide estimates of historical thresholds and optimal vegetation structure for management purposes (Hennebelle et al. 2018). Likewise, fire histories show human-vegetation-climate linkages, such as decreasing tree cover creating microclimates favorable to the encroachment of flammable vegetation in the understory (Feurdean et al. 2020). However, we have exceeded the envelope of global fire behavior observed in the Holocene, meaning that human-fire interactions could have extreme and unexpected outcomes (Bova et al. 2021; Hammond et al. 2022). We should not assume that historical management practices will suffice (Pyne 2007; Crandall et al. 2021; Ellis et al. 2021) given accelerated rates of vegetation change (Mottl et al. 2021; Słowiński et al. 2022; Talucci et al. 2022), climate destabilization (Armstrong McKay et al. 2022; Breyer et al. 2023), the emergence of novel biotic and abiotic conditions (Ordonez et al. 2016; Finsinger et al. 2017; Burke et al. 2019), and increasing human population and affluence. 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. 2017).

Climate and culture control native and invasive vegetation

Ecosystem response to changing fire disturbance can take centuries to millennia (Carcaillet et al. 2010, 2020). In the Anthropocene, which is characterized by overlapping and interacting human disturbances, the emergence of stable fire regimes depends on synergies among fire, vegetation changes, and climate within a region.

The combination of climate and species change can shift the balance between native and invasive taxa. New fire-adapted species have altered vegetation structure in many fire-prone regions, including cheatgrass (*Bromus tectorum*) in some desert environments of the USA, tussock grass (*Poa flabellata*) and pampas grass (*Cortaderia selloana*) in Spain, guinea grass (*Megathyrsus maximus*) and fountain grass (*Cenchrus setaceus*) in Hawaii, and black locust *(Robinia pseudoacacia)* and tree-of-heaven (*Ailanthus altissima*) in southern Europe (Maringer et al. 2012; Trauernicht et al. 2015). These species exploit and create novel disturbance niches to outcompete native vegetation during post-fire recovery. These direct and indirect effects of fire regime change can alter plant community structure and composition, often amplifying aspects of the fire regime, including fire frequency and extent (Wan et al. 2014; Bishop et al. 2020; Mirzaei et al. 2023).

As the vegetation-climate interaction evolves in the Anthropocene, many or even most communities around the world will need to develop new cultural norms around fire (Dickinson et al. 2015; Trauernicht et al. 2015; Chapin et al. 2022). Given how controversial fire management can be, even under the best of conditions (Crandall et al. 2021; Dale and Barrett 2023), it will be crucial to establish two-way communication that prepares policymakers, managers, and the public for adaptive changes in policy and practice, including the loss of cultural and ecosystem services provided by disappearing historical fire regimes (Cassidy et al. 2022; Bowman and Sharples 2023).

Uncertain services

One of the clear conclusions from our study is that the novel fire regimes of the Anthropocene threaten multiple ecosystem services ranging from carbon sequestration to air quality. The erosion of these ecosystem services has already been observed in many regions (Balch et al. 2017; Canadell et al. 2021; Hammond et al. 2022; Hampton et al. 2022). Novel climatic conditions in peatlands can limit their recovery from disturbances, decreasing carbon stocks (Loisel et al. 2021). More severe and frequent fires can threaten carbon storage in Boreal forests (Walker et al. 2019), though changes to successional trajectories may offset or negate these losses in some cases (Girardin et al. 2013; Mack et al. 2021). Ozone produced during combustion can damage plant tissues, potentially doubling carbon losses by reducing post-fire photosynthesis (Lasslop et al. 2019). Because human land use and fire regimes are so closely linked, human actions such as deforestation coupled with cropland development can decrease carbon stocks at the same time as they modify the fire regime (Bowman et al. 2011; Cochrane and Bowman 2021).

The local impacts of changing fire regimes are both unequal and increasing (Bytnerowicz et al. 2016; Errigo et al. 2020; Burke et al. 2021; Chen et al. 2021b). From the negative health consequences of air pollution to threatened drinking water from post-fire floods and erosion (Marki and Stilianakis 2008; Tessum et al. 2019; Crandall et al. 2021; Xie et al. 2022; Bowman and Sharples 2023), we need to prepare for the socioecological consequences of fire regime change. These local changes are of course linked to additional global feedbacks. For example, enhanced black carbon and soot deposition associated with increased fire disturbance contributes to decreased albedo and accelerated ice melting (McCarty et al. 2021; Aubry-Wake et al. 2022). Likewise, in Indian tropical dry forests, an increase in fire activity may negatively alter forest potential for water regulation by changing soil characteristics (Schmerbeck and Fiener 2015) and atmospheric moisture recycling (Abbott et al. 2019).

The limits of control: prevention versus treatment

Although our global-scale study may have limited application in many specific management contexts, there were some general patterns that could be informative for policymakers, managers, and researchers. Despite the substantial uncertainties associated with fire regime changes, 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 (Moritz et al. 2014; Harris et al. 2016; Radeloff et al. 2018; Mietkiewicz et al. 2020). Likewise, the conservation of large, contiguous ecosystems (e.g., Kruger National Park, South Africa) allows the use of more effective wildfire management tools such as prescribed burning and increases resilience when unexpected wildfire behavior emerges (Driscoll et al. 2016; Bentley and Penman 2017; Miller 2020).

However, there was a high level of agreement across fire regions that the risk of extreme fire behavior overwhelming the capacity of these fire management tools increases under higher greenhouse gas emissions. Although the specific consequences vary by fire region and habitat type, the overall message is clear: rapid reduction of greenhouse gas emissions is needed to restore Holocene-like climate conditions (Cyr et al. 2009; Abbott et al. 2022; Breyer et al. 2023; Burton et al. 2023). This would reduce the difference between natural and managed environments and ensure long-term conservation of ecosystem functions and services, thereby preserving socioeconomic benefits (Führer 2000; Gauthier et al. 2009). Otherwise, the emergence of novel climates, vegetation communities, and fire regimes outside of the range of Holocene variability will complicate or compromise our ability to conserve habitats, ensure healthy communities, and preserve terrestrial carbon uptake and storage.

For example, without a reduction in greenhouse gas emissions, changes in fire regimes could undermine climate mitigation policies such as negative emissions through reforestation and afforestation (Anderegg et al. 2020; Veldman et al. 2019). Any carbon uptake from recovered or cultivated forests could be negated by the increased fire frequency or intensity projected for many regions (Hammond et al. 2022; Smith et al. 2020). Likewise, the available tools for fire management will likely be reduced as extreme fire weather narrows the periods when prescribed burning can safely take place (Pyne 2007; Abatzoglou et al. 2021; Bowman et al. 2017). These risks are not hypothetical. Indeed, climate-fire interactions are already eroding climate mitigation efforts in many regions by altering forest, grassland, and peatland carbon structure (Bowman et al. 2020; Carcaillet et al. 2020; Loisel et al. 2021; Dahl et al. 2023). For example, in tropical biomes where fires have been historically rare, an increase in extreme wildfires is augmenting tree mortality leading to habitat loss, decreasing biodiversity and carbon storage (Trauernicht et al. 2015; Silveira et al. 2016; Deb et al. 2018).

Expert assessment utility and limitations in adaptive fire management

Although this study brought together a diverse group of fire researchers, it is important to recognize that our group is not geographically balanced. Despite invitations to several hundred researchers, we received only a few responses for some fire regions (Fig. 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 (Moerman and Estabrook 2006), and wildfire research specifically (Bradstock et al. 2002; Hantson et al. 2016; Metcalfe et al. 2018), highlighting the need for more spatially diverse research networks. It is essential for readers to consider the limitations arising from the smaller number of participants in certain fire regions when interpreting our results, as well as research from other "global" fire studies. Furthermore, it is important to recognize that a similar expert assessment with a different group of experts, such as fire managers or policymakers, could yield different results. The perspectives and opinions shared by our participants were influenced by their background, knowledge, and expertise, constituting both the value and limitation of this exercise.

Thinking more generally about our goal of establishing effective, two-way communication among researchers, managers, and policymakers, is expert assessment a useful tool? Decision-making in landscape and fire management requires a nuanced, multi-scale understanding of human and natural systems. Currently, policymakers and managers working on fire issues are operating in an evolving environment with sometimes conflicting traditional, scientific, societal, and political information and priorities. As the physical, biological, and human factors controlling wildfire behavior change rapidly, how can we improve the rigor and breadth of the knowledge available to those facing changing fire regimes? The decisions and beliefs of resource managers and citizens are often based on news coverage, anecdotal accounts, agency tradition, or single-expert advice.

As several respondents mentioned in this study, quantitative models cannot capture all the factors influencing the evolution of fire behavior (Harris et al. 2016; Abbott et al. 2016; Hantson et al. 2016). We believe that 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 management plans or 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).

We are not proposing a new role for experts in policymaking and management. Rather we suggest that local expert knowledge be integrated 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 (Dickinson et al. 2015; Boag et al. 2018; Hertel-Fernandez et al. 2019). In the dynamic and dangerous environment of the Anthropocene, we cannot afford to dismiss knowledge or exclude stakeholders. For example, local expertise such as Indigenous knowledge remains insufficiently represented in scientific publications and fire management policies (Christianson 2015). Therefore, we invite those in positions of influence at any level to consider how to better share information and challenges.

Conclusion

This study investigated the past and future changes in global fire regimes using expert assessment. We identified the main drivers of fire regime change during the Holocene and explored the potential trajectories and impacts of future fire regimes on different ecosystem services. Our findings aligned with other studies that fire regimes have experienced an increase in state changes, and that fire regimes are likely to degrade ecosystem services, particularly under higher greenhouse gas emissions scenarios. We caution that carbon sequestration policies should be carefully evaluated in light of the expected increase in fire activity for a warmer planet. Although our study primarily focuses on general global patterns, the results offer a foundation for hypothesis testing in future research at smaller scales. By integrating our findings with other studies exploring aspects such as the likelihood of fire regime changes and their effects, we can gather more detailed information to address regional-specific needs.

Synthesis activities that focus on addressing decision-making needs are vital, bridging the gap between science and policy. Governments should implement systematic approaches to involve larger groups of experts in decision-making processes promptly and efficiently, encouraging participation from diverse backgrounds, including the scientific community, local managers, and traditional knowledge holders and practitioners. Given the complexity and multi-factor nature of fires, we propose conducting similar expert assessment activities involving fire and land managers and other types of expertise. These endeavors will provide new insights and perspectives on pressing issues related to fire.

Supplementary Information

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Additional file 1.

Additional file 2.

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Authors' contributions

BWA and ALD conceived the study. ALD and BWA secured funding for the project. SSS, BWA, BV, BL, DC, GGR, MS, JCA, OB, AF, CM and DR performed the initial literature review, designed the questionnaire, and generated the initial list of invitees. SSS managed expert invitations. AND, AK, ALD, AC, CT, CGA, CCR, CMM, CY, CU, CK, CC, CCM, CL, DC, DM, DH, DMG, DH, DHU, EC, ED, EB, EC, ER, EM, EUF, EJB, EMG, FXC, GBP, GGR, GM, HC, HS, IO, JM, JRS, JR, JM, JE, JALS, JMP, JA, JI, KAH, KM, KA, KB, KH, LB, LM, LS, MA, MG, MPL, MC, MH, MPG, MN, MC, MM, NP, NR, NL, NK, OB, PM, PK, PFH, PF, RG, RC, RH, RB, RV, RP, SYM, SOB, SM, SC, SB, SH, SGAF, TA, TL, TB, TA, TW, VC, VR, WF, WD, WTS, YR and YB responded to the questionnaire. SSS and BWA conducted the data analysis and wrote the manuscript with input from all co-authors.

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Availability of data and materials

The datasets used and/or analyzed during the current study are attached as supplementary data.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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