ANNUAL REVIEWS

Annual Review of Environment and Resources

Understanding Fire Regimes for a Better Anthropocene

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Annu. Rev. Environ. Resour. 2023. 48:207–35

First published as a Review in Advance on August 31, 2023

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-120220-055357

Keywords

biodiversity, climate change, Earth System, social-ecological systems, sustainability, wildfire

Abstract

Fire is an integral part of the Earth System and humans have skillfully used fire for millennia. Yet human activities are scaling up and reinforcing each other in ways that are reshaping fire patterns across the planet. We review these changes using the concept of the fire regime, which describes the timing, location, and type of fires. We then explore the consequences of fire regime changes on the biological, chemical, and physical processes that sustain life on Earth. Anthropogenic drivers such as climate change, land use, and invasive species are shifting fire regimes and creating environments unlike any humanity has previously experienced. Although human exposure to extreme wildfire events is increasing, we highlight how knowledge of fire regimes can be mobilized to achieve a wide range of goals, from reducing carbon emissions to promoting biodiversity and human well-being. A fire regime perspective is critical to navigating toward a sustainable future—a better Anthropocene.

Contents

1. INTRODUCTION

Fire is an ecological process (1) and cultural practice (2) that shapes life on Earth. Patterns of fire influence the evolution of biota (3), status of biodiversity (4), cycling of matter and energy across global spheres (5), and human health and well-being (6). People have been using fire for millennia and it is arguably one of the most important processes in the cultural evolution of humankind (7). Yet the effects of current human activities, including different types of burning and suppression, are changing patterns of fire at a planetary scale and creating environments different from any others that humanity has experienced.

Fire frequency: the number of fires in a defined time and space

Fire regime changes: changes in fire characteristics—such as the frequency, seasonality, and size of fires—compared to measures of central tendency and dispersion at defined times and spaces

Observations of fires burning in unexpected places, at unusual times, and in rarely observed ways are fast-growing. Recent fire seasons in Arctic tundra and boreal forests have started earlier and been more intense than usual (8, 9). Record-setting fires have burned large areas in temperate forests of eastern Australia (10), forests and woodlands of western United States (11, 12), and tropical wetlands of Brazil (13). At the same time, fire-dependent grasslands and savannahs across Africa and Brazil have experienced marked reductions in fire frequency (14–16). Departures of fire patterns from historical conditions are likely to have profound consequences for human society and sustainability.

In this review, we explore the causes and consequences of fire regime changes in the Anthropocene, the current period where human activity rivals biophysical forces in shaping planetary

THE ANTHROPOCENE

The Anthropocene concept highlights the prominent role of human activity in creating a hotter climate and markedly different biosphere (17). Changing patterns of fire are both a consequence of and a contributor to these planetary changes. Several starting points of the Anthropocene have been proposed, including 50,000, 10,000, 500, 200, and 70 years ago, marked by megafauna extinctions, the spread and intensity of farming, European colonization, the Industrial Revolution, and the Great Acceleration of socioeconomic and Earth System trends, respectively (18). An emerging view of the Anthropocene recognizes that human societies began modifying the Earth long ago; what is new about this period is how social and environmental changes accumulate, scale-up, and transform the Earth System (19, 20). A deep understanding of fire is essential for examining these transformative changes and achieving a sustainable future—that is, a better Anthropocene.

processes (see the sidebar titled The Anthropocene). Because fire is an ecological and social phenomenon, we engage a diverse body of research spanning natural sciences (e.g., ecology and evolution), social sciences (e.g., anthropology and archaeology), and physical sciences (e.g., climatology and meteorology). We start by introducing the concept of the fire regime—which describes the characteristics and dimensions of recurrent fire—and synthesize how fire patterns are changing across the globe. Next, we examine how human drivers are causing these changes in fire regimes. We then highlight the consequences of fire regime changes on the air, biodiversity, soils, and water that sustain life on Earth. Lastly, we explore opportunities to apply knowledge of fire to benefit people and ecosystems. Our review concludes that valuing the role of fire regimes in the Earth System will help to shape a better Anthropocene.

2. FIRE REGIMES

A central concept in fire science is the fire regime, which describes when, where, and which fires occur (21). The key idea is that landscape fire has multidimensional and repeatable properties (22), such that patterns of recurrent fire can be identified and described by the frequency, intensity, patchiness, seasonality, size, and type of fire at defined spatial and temporal scales (21). Many plant and animal species are adapted under a particular fire regime, and substantial changes to these fire characteristics can modify populations and shift ecosystems (4). In turn, modification of biota influences subsequent patterns of fire, highlighting feedback effects among plants, animals, and fire (23). In this article, we use the multidimensional fire regime concept as an organizing principle to articulate how fire activity is changing globally, to understand the causes and consequences of changing spatiotemporal fire patterns, and to aid development of actions and strategies for managing fire-prone landscapes.

Contemporary geographic patterns of fire regimes show remarkable diversity around the world (**Figure 1**). Using data from 2000 to 2021, we calculated that an average of 3.98 million km^2 of the terrestrial land surface is burned per year. In general, fire activity displays a unimodal relationship with primary productivity (24). Regions with intermediate productivity, such as tropical savannahs along the equator, experience high fire frequency, a product of rapid fuel production coupled with predictable dry seasons when fuel is available to burn (25). By contrast, arid regions with low productivity (e.g., some African, Middle Eastern, and central Asian deserts), and moist rainforest environments with high productivity (e.g., continuous areas of the Amazon basin), experience relatively low fire frequency (**Figure 1*c***). Fire size shows substantial variation, with large fires [>10,000 hectares (ha)] particularly common in the western United States, southern Africa, northern Australia, and Eurasia, often associated with areas having contiguous if intermittently

Anthropocene: the contemporary period where human activity rivals biophysical forces in shaping Earth System processes such as biodiversity, climate and nutrient cycling

Fire regime: the temporal and spatial dimensions of recurrent fires, and their characteristics

Fire science: the application of scientific methods to understand the role of fire on Earth, including the role of fire in biological, physical, and social phenomena

Landscape fire: The combustion of biomass in natural or cultural landscapes that cover a range of extents from hundreds to thousands of hectares

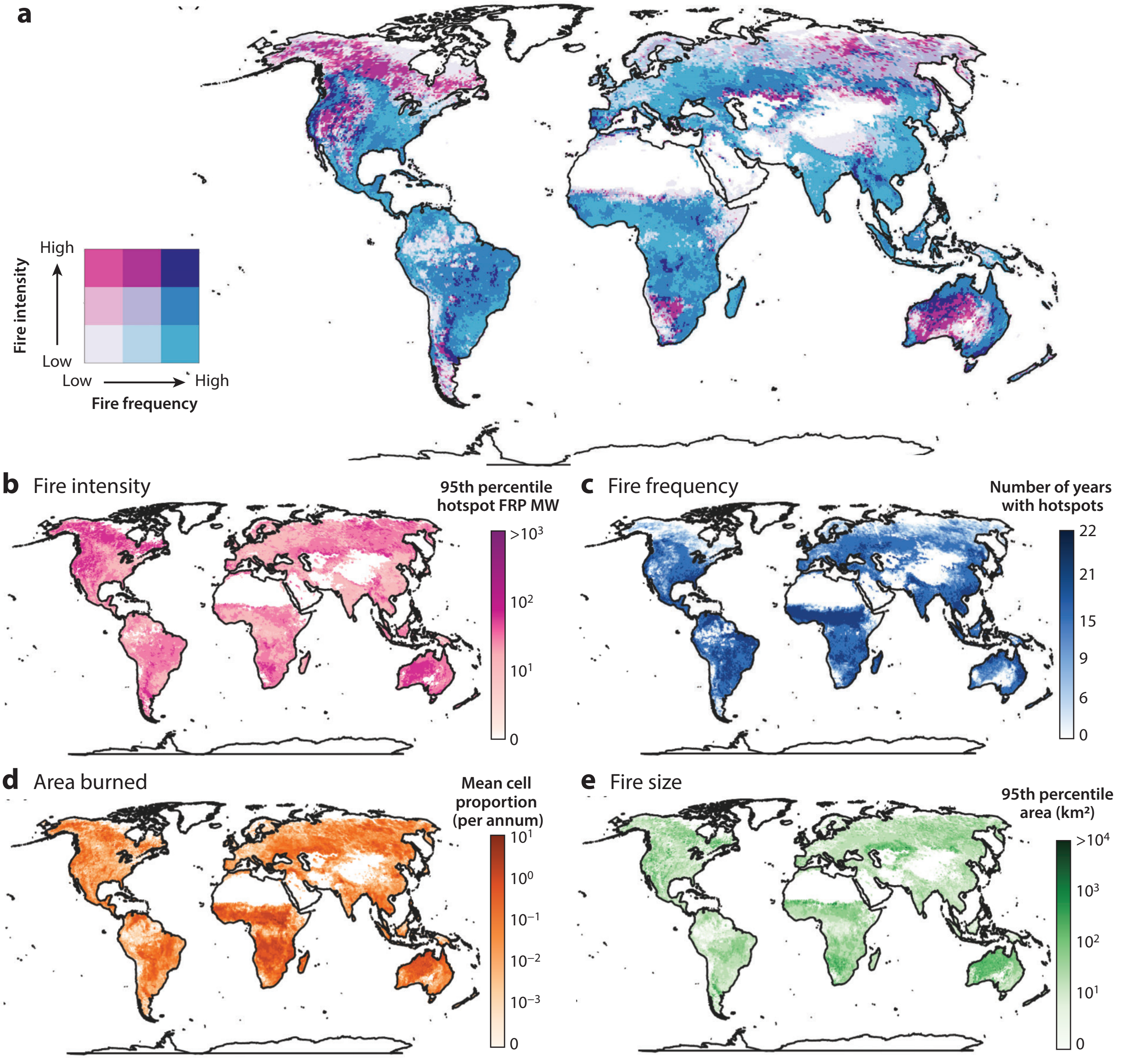

Figure 1

A global portrait of fire regimes. (*a*) A bivariate choropleth map of fire intensity (95th percentile FRP in MW) and fire frequency (count of number of years from 2000 to 2021 in which hotspots were detected in a cell). (*b*) Fire intensity (95th percentile FRP MW). (*c*) Fire frequency (count of number of years from 2000 to 2021 in which hotspots were detected in a cell). (*d*) Area burned (mean cell proportion burned per annum). (*e*) Fire size (95th percentile area km^2). All fire regime data are calculated from 2000 to 2021, displayed in a Robinson projection on equal-area cells of approximately 3,090 km^2, and sourced from active fire hotspot and burned area products collected by MODIS and VIIRS instruments on the NASA Aqua, Terra and Suomi NPP, and NOAA-20 satellites. Color classes on the bivariate choropleth map were selected manually to highlight contrasting fire regimes, with class divisions for fire intensity at 100 and 300 95th percentile FRP MW, and for fire frequency at 5 and 18 hotspots present out of the 22-year period. Abbreviations: FRP, fire radiative power; MODIS, moderate resolution imaging spectroradiometer; MW, megawatts; NASA, National Aeronautics and Space Administration; NOAA, National Oceanic and Atmospheric Administration; NPP, National Polar-orbiting Partnership; VIIRS, visible infrared imaging radiometer suite.

flammable fuels, or where remoteness from large human settlements limits suppression efforts (**Figure 1*e***).

If we looked at only one component of the fire regime, we would be missing something important about the nature of fire. This is clear when fire intensity, a measure of the energy released from fire, is visualized alongside fire frequency, in this case a measure of how often fire hotspots are detected (**Figure 1*a***). In some cases, high fire intensity corresponds with high fire frequency; for example, fire frequency and fire intensity are both relatively high in temperate western North America, the Mediterranean basin, and southeastern Australia. In other cases, the two fire regime variables differ. Regions with high fire frequency and moderate intensity typify tropical central Africa, central South America, and northern Australia; locations with low fire frequency and high intensity include arid parts of central Australia, western North America, and high-latitude boreal regions such as Alaska, northern Canada, and eastern Eurasia (**Figure 1*a***). The low-intensity, high-frequency fire combination is prevalent in areas with high human population densities and is indicative of agricultural fire use, including in the Indian subcontinent, the eastern United States, parts of Europe, eastern China, and Southeast Asia (**Figure 1*a***).

There is also considerable diversity in types of landscape fire. This includes wildfires (sometimes called bushfires) started by natural or human ignitions, as well as intentional fires used for hunting and gathering (e.g., hunting fires), agriculture and pastoralism (e.g., shifting cultivation fires), fuel reduction (e.g., hazard reduction fires), land clearing (e.g., deforestation fires), and a wide range of other social and environmental goals (e.g., cultural burning) (2, 26, 27). People have been describing patterns of fire in nuanced ways for thousands of years. For example, in Noongar, a language of Indigenous peoples in southwestern Australia, the term *karla nyidiny* describes cool fires ignited in early summer to promote new growth and *karla karlang* communicates hot fires ignited approximately every decade to maintain thick growth (28). A newer term is megafire—used to describe the rise of extremely large fires (29). All these different types of fires interact and combine to generate the fire regime of a given time and space. Areas with similar fire characteristics are sometimes called pyromes (30).

In the Anthropocene, these patterns and trends of fire can be comprehensively explained only through consideration of a broad range of biophysical and human factors (**Figure 2*a***). Biophysical drivers of fire patterns include weather and climate (31), soils and topography (1), and the vegetation types and biota that comprise and shape fuels (25). Human drivers include global climate change, land use (including application of fire and active suppression), invasion and extinction of species, and their underlying societal causes (32) (**Figure 2*b***). Complex interactions and feedbacks between biophysical and human drivers mean that global generalizations are difficult, but new data (27, 33), techniques (34, 35), collaborations (36, 37), and conceptualizations (38, 39) are helping to make exciting progress on this task.

Fire intensity: the amount of energy released through combustion per unit time

Megafire: anomalously large fires arising from single or multiple related ignition events

Earth System: the interacting physical, chemical, and biological processes that cycle material and energy across the Earth's global spheres

Pyrogeography: the holistic study of fire on Earth achieved by bringing together and creating knowledge across the sciences and humanities

3. FIRE REGIME CHANGES

Fire has been a feature of the Earth System since the rise of vascular plants approximately 420 million years ago (Mya) (40), and fire regimes have changed at geological timescales as climate, atmospheric oxygen concentrations, and vegetation fluctuated (34). Human ancestors evolved in fire-prone landscapes, with an archaeological signal of deliberate human fire use for cooking, warmth, and light clear by the Middle Pleistocene (approximately 400,000 years ago) in Africa and western Eurasia (7). Multiple lines of evidence indicate that humans have also been changing landscape patterns of fire for millennia, a foundational idea of the field of pyrogeography (41). For example, humans were present in northern Australia by 65,000 years ago (42), and oral traditions and ethnographic studies reveal sophisticated application of landscape

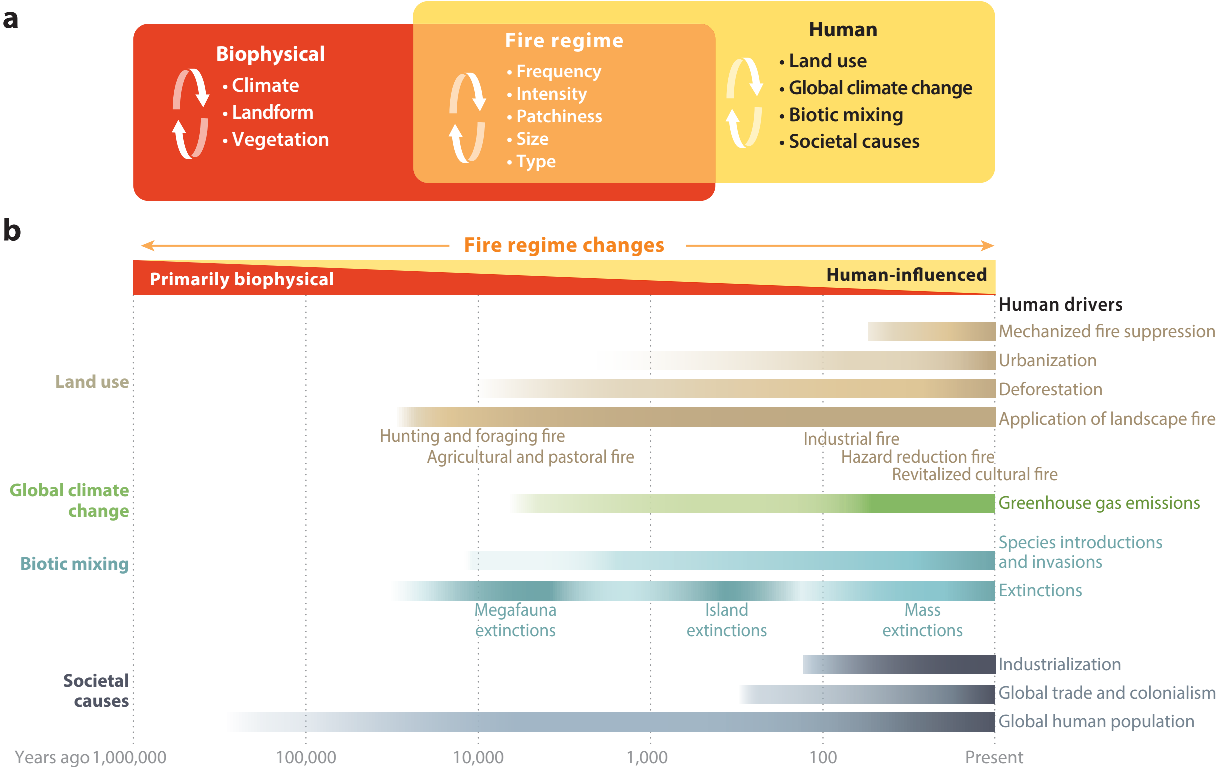

Figure 2

Fire regimes in the Anthropocene. (*a*) A conceptual model of the fire regime concept, showing that fire regimes can be understood as the nexus of biophysical and human drivers. Fire regime characteristics include—but are not limited to—fire frequency, fire intensity, fire patchiness, fire seasonality, fire size, and fire type. In the Anthropocene, these characteristics emerge from interactions and feedbacks between recurrent fire, biophysical drivers, and human actions. (*b*) A historical timeline of how people have influenced fire regimes and applied landscape fire. What is new about the Anthropocene is how social and environmental changes—including land use, global climate change, and biotic mixing—are accumulating and scaling-up to transform patterns of fire in the Earth System. The panel illustrates human drivers that have been, and continue to be, influential across the globe. Other globally important human drivers such as cessation of traditional land uses and subsequent reforestation or woody encroachment, different types and intensities of livestock grazing, and wetland degradation are discussed in the main text. The density of color within each bar of human drivers represents the intensity of changes. Panel *a* co-produced by Clare Kelly and commissioned by the authors. Panel *b* is adapted with permission from Reference 19; copyright 2016 Springer Nature. It was adapted by Clare Kelly and the authors and also informed by data from References 17, 20, and 41.

fire by Indigenous peoples to promote and produce food resources (43). From the Holocene onward, approximately 12,000 years ago, paleofire reconstructions and archaeological data indicate widespread use of fire for hunting and foraging (44) and pastoralism and agriculture (45)—skillful uses of fire that still form a continuum of practices worldwide (27) (**Figure 2*b***). More recently, combustion of fossil fuels has powered industrial application and modification of landscape fire (46), including through aerial ignition of planned fires and mechanical suppression of wildfires. In combination with a myriad of other changes powered by fossil biomass, this industrial fire has been channeled for a wide range of objectives, including fuel or hazard reduction, production of commodities, and biodiversity conservation (5, 41). In the Anthropocene, there is also growing evidence that human modification of fire patterns alters the historical range and variation of fire characteristics and generates widespread ecosystem changes.

Historical range and variation: the envelope of past fire regimes

QUANTIFYING PAST FIRE REGIMES AND THEIR RANGE AND VARIATION

Past fires provide a reference for contemporary fires (147). Identifying fire regime changes is difficult because of high spatial and temporal variation in the characteristics of fires, new and emerging conditions that are in flux or unstable, and the availability of data to define baselines and detect trends (148). Nevertheless, contemporary fire patterns and the historical distribution, range, and variation of fires can be explored using a wealth of approaches: satellite remote sensing and aerial photos (33), historical studies and written records (35), fire scars on trees (35), combustion residue in sediment and ice (34), oral traditions and Indigenous and local knowledge (36), and surface reconnaissance and excavations of the material record (37). Different approaches have different strengths and weaknesses. Satellite remote sensing has built a valuable picture of fire activity at global scales—but spans short timescales and omits small fires (33, 47). Alternatively, paleofire records from sediment and ice have illuminated decadal to millennial fire regime changes—but lack spatial and temporal precision of some other methods (34). A way forward is to combine approaches; for example, new collaborations between archaeologists and fire scientists employ a mix of simulation models, human behavior studies, and paleoecological records to understand fire regime changes (37).

3.1. Global Fire Regime Changes

Advances in imagery from Earth observation satellites have created opportunities for quantifying changes in fire activity at global scales, usually by assessing burned area over the past two decades (47; see also the sidebar titled Quantifying Past Fire Regimes and their Range and Variation). Comprehensive assessment of Earth observation data revealed that burned area reduced by 27% globally from 2001 to 2019 (33). This shift is due in large part to a decline in burned area in northern African savannahs, where a 41% decline of annual burned area was observed. This pattern of reduced fire in northern Africa is consistent with earlier remote sensing studies (14) and can be explained by human modification of fuels and ignitions (14, 33). Importantly, changes in burned area vary by region; from 2001 to 2019 increases in burned area of 49% were observed in mainland forests of the Pacific United States (33).

Global observations have also pinpointed substantial changes in fire weather and fuel moisture, which indicate potential for fire regime changes. Assessments of global meteorological data have found that the annual fire weather season lengthened by 14 days globally (from 1979 to 2019) (33), the area of the Earth's burnable surface that experiences extreme fire weather has increased from more than a quarter to almost half (from 1979 to 2020) (48), and there is a strong drying trend of fuels across most of the world's ecosystems (from 1979 to 2019) (49). Fire weather is also changing at hourly and daily scales. Global satellite observations of daytime and night-time fire detections indicate that, across burnable lands, the annual number of flammable nighttime hours increased by 110 hours, from 1979 to 2020 (50). Changes in fire weather can translate to changes in fire activity: Globally, night fires increased in intensity by 7.2% from 2003 to 2020 (50).

Burned area: summed area marked by fire per unit time and area

Fire weather: hot, dry, and windy weather conditions conducive to the ignition and spread of wildfires

3.2. Regional Fire Regime Changes

Global fire activity is largely a consequence of human and environmental changes at regional scales. Yet human-environment transformations have affected fire regimes in different places, at different times, and at different rates. This includes marked shifts in burned area (12, 51), fire frequency (15, 52), fire seasonality (53, 54), fire size (55, 56), fire type (36, 57), and the location of fires (8). We start our exploration of regional changes with two brief case studies that show how the fire regime concept can be used as an organizing principle to understand shifts at small and large temporal scales. We then develop and expand on the examples provided in **Table 1**—selected to illustrate fire regime changes in a cross section of environments globally

Table 1 Examples of human drivers changing fire regime characteristics in the Anthropocene

Location	Human drivers	Timescale	Fire regime characteristics	References
Africa				
1. Ethiopia, Bale Mountains National Park, subalpine heathlands	The number of large fires (>100 ha) increased in a national park, but not outside the park, and this coincided with a reduction in human ignitions in the early dry season (and therefore less fuel breaks) and ignitions made later in the dry season.	1968–2017	Fire size ↑	58
2. Madagascar, Ibity and Itremo National Parks, tropical grasslands	Fire frequency decreased and fire size increased after active fire suppression and livestock exclusion in protected areas.	1989–2015	Burned area ↔ Fire frequency ↓ Fire season timing ↕ Fire size ↑	53
3. Southern Kenya and northern Tanzania, Serengeti-Mara ecosystem, savannas	The number of fires and burned area were reduced by livestock grazing and subsequent reductions in fuels.	2001–2014	Burned area ↓ Fire frequency ↓	15
Asia				
4. Borneo, tropical rainforests	Initial deforestation for the plantation of palm oil increased fire frequency, but once industrial forests were established fire frequency decreased and stabilized.	1982–2010	Fire frequency ↕	59
5. Kazakhstan, Eurasian steppe, temperate grasslands	After the dissolution of the Soviet Union, widespread rural abandonment reduced livestock grazing, increasing landscape flammability, fire frequency, and total burned area.	1990–2015	Burned area ↑ Fire frequency ↑	52
6. Syrian Arab Republic, ranging from forests, shrublands, grasslands and croplands	Civil war has increased human ignitions and decreased active fire suppression. Simultaneously, economic instability has induced land conversion to cropland, likely increased flammability, and altered fire seasonality.	2002–2020	Burned area ↑ Fire season length ↑	60
Australia				
7. Northern Australia, savanna	Planned burning for the purpose of emissions reductions was linked to an increase in early dry season fire extent, a decrease in late dry season fire extent, and an increase in fire patchiness.	2000–2019	Fire patchiness ↑ Fire season timing ↕	54
8. Southern and eastern Australia, forests	In Australian forests, the burned area, fire season length, fire frequency, and the frequency of megafire years (>1 M ha burned) show a positive annual trend, associated with anthropogenic climate change.	1988–2020	Burned area ↑ Fire frequency ↑ Fire season length ↑	51
9. Tasmania, temperate grasslands and forests	British invasion and colonialism resulted in cessation of Indigenous burning regimes. Charcoal records indicate the frequency of low-intensity fires likely decreased, prompting a shift in vegetation state evidenced by pollen records.	1830–2000	Fire frequency ↓	61

(*Continued*)

Table 1 (*Continued*)

Location	Human drivers	Timescale	Fire regime characteristics	References
Europe				
10. Norway, Trillemarka-Rollagsfjell Nature Reserve	Human population growth, shifting cultivation fires, and human-ignited forest fires resulted in increased fire frequency. As the value of timber increased over time, fire frequency decreased.	1257–2009	Burned area ↕ Fire frequency ↕ Fire season timing ↕ Fire size ↕	35
11. Russia, East Europe boreal zone	Homesteads were positively associated with fire frequency and burned area from 1670 to 1810, likely via increased human ignitions, but relationships between human land use and fire frequency shifted over time and natural variation in climate was a strong driver of fire cycles.	1271–2010	Burned area ↕ Fire frequency ↕	62
12. Spain, Valencia Province, Mediterranean forest and shrubland	Rural land abandonment shifted mosaics of farmland and open forest to denser forests, increasing fuel amount and connectivity, and increasing area burned, fire frequency, and fire size.	1873–2006	Burned area ↑ Fire frequency ↑ Fire size ↑	63
North America				
13. Canada, British Columbia, montane and subalpine forests	European colonization led to cessation of Indigenous burning and active fire suppression that initially reduced fire frequency. Exclusion of fire changed fuel structure in forests and, in combination with global climate change, led to increases in burned area and fire size, particularly after 2003.	1919–2019	Burned area ↕ Fire frequency ↕ Fire size ↕	57
14. United States, Rocky Mountains, subalpine forests	Global climate change has contributed to increases in fire size, the frequency of large fires, and total burned area.	1984–2020	Burned area ↑ Fire frequency ↑	12
15. United States, southeastern grasslands and forests	Planned burning activities were canceled early during the COVID-19 pandemic, reducing the number of fires in the landscape compared to previous decades.	2003–2020	Fire frequency ↓	64
South America				
16. Brazil, Kadiwéu Indigenous Territory, tropical savanna	Indigenous-led fire suppression has reduced fire frequency, the size of fires, and area burned.	2001–2018	Burned area ↓ Fire frequency ↓ Fire size ↓	55
17. Colombia, Amazon-Macarena Special Management Area, rainforest	Fire frequency increased in the short term as a result of land-grabbing, deforestation, and livestock grazing caused by poor governance postconflict.	2017–2018	Fire frequency ↑	65
18. Chile, central Chile, forests, grasslands, plantation forests, shrublands	The conversion of subsistence plantations to industrial-scale monoculture has increased flammability and connectivity of landscapes, and in combination with anthropogenic climate change and rural abandonment, has increased the total burned area and intensity of wildfires.	1985–2017	Burned area ↑ Fire intensity ↑	66

Arrows represent the following: ↔, no change; ↑, increase; ↓, decrease; ↕, increase and decrease within the timescale of study or shift or lengthening of fire season.

and at a variety of temporal scales, through exploration of drivers (Section 4) and consequences (Section 5) of fire regime changes.

Madagascar is an island nation that contains large areas of fire-prone savannahs. The establishment of two protected areas for biodiversity conservation in Madagascar in the early 2000s enabled exploration of fire regime changes before (1989 to 2003) and after (2004 to 2015) management interventions, such as reduction of livestock herding and active fire suppression (53). Interestingly, mapping the area and timing of fires demonstrated that the burned area remained unchanged between the two periods. However, after conservation management interventions, the number of fires decreased while the size of fires increased (53). Together, these shifts in fire characteristics cancelled each other out and maintained the same burned area. Only by exploring a suite of fire regime characteristics did this more complete picture of the fire regimes emerge (53), including changes that potentially have flow-on effects for plant communities.

The boreal forests of Europe have a long history of fire. Fire scars on pines enable the dating of fires and, in southern Norway, dendrochronological and seasonal dating was used to identify and map 254 fires over 753 years (1257 to 2009) in a 74 km^2 area (35). Fire frequencies were then compared with historical climate proxies, vegetation maps, and written sources. A significant increase in fire frequency was observed from 1625 when fire counts peaked at 50–60 fires per 25 years (35). Fire frequency remained high until 1750, when it decreased to ≤5 fires per 25 years from 1800 onwards. Linking fire scars with other historical records showed that agricultural and pastoral fire was responsible for the increase in fire frequency, and the decrease in fire frequency was associated with increasing value of timber and fire suppression policies (35). Variability in climate was also an important influence on fire regimes (35). A focus solely on a single source of environmental records, at any single scale, would have masked important changes about the pace, magnitude, and direction of fire regime changes.

4. DRIVERS OF FIRE REGIME CHANGES

Interactions between human drivers such as global climate change, land use, and the introduction and extinction of species are reshaping fire regimes worldwide (4, 67). Here, we examine changes in fire regimes and how they are modified by three groups of direct drivers arising from human actions, as well as the societal drivers that propel them (**Figure 2*b***).

4.1. Global Climate Change

Increasing global temperatures and more frequent heatwaves and droughts increase the likelihood of fire by promoting hot, dry and windy conditions. Human-induced warming via greenhouse gas emissions has already led to global increases in the frequency and severity of fire weather (48), increasing the risks of wildfire. A pattern of extreme fire weather outside of natural climate variation is also emerging in regions around the world, including North America (11), southern Europe (68) and the Amazon basin (69). For example, modeled climate projections across the western United States indicate that that human-caused climate change produced more than half of the observed increases in fuel aridity from 1979 to 2015 and contributed to an additional 4.2 million ha of forest fire from 1984 to 2015 (70). There is also evidence that human-induced climate change influences fire regimes via other fire switches such as availability to burn (fuel moisture) and ignitions (see the sidebar titled The Four Fire Switches). Using satellite-derived and ground-based fire data, Canadell et al. (51) found a linear increase in the forest area burned in Australia from 1988 to 2019, and an increase in the frequency of megafire years (≥1 M ha burned) since the year 2000. These changes in fire patterns are consistent with more extreme fire weather, increased ignitions from dry lightning, and more severe droughts under climate change (51).

THE FOUR FIRE SWITCHES

A useful approach for understanding the biogeography of fire regimes is to conceptualize four "switches" that need to be activated for fire to occur (38): biomass, sufficient fuel to allow fire to propagate; availability to burn, fuel must be dry enough to burn; fire weather, weather must be suitable to allow fires to spread; and ignitions, lightning or anthropogenic sources that initiate fire. Understanding how human activity influences these four processes helps to predict when and where fires occur, and how they will burn, in ecosystems worldwide. The relative importance of fire switches varies in space and time (71). For example, some flammable ecosystems with low human populations do not burn frequently because of a lack of ignitions, whereas other ecosystems with large human populations are saturated by ignitions, and availability to burn and fire weather are what limit fire occurrence (38, 71).

4.2. Land-Use Change

Humans modify fire regimes by changing land-use for agricultural, forestry, and urban purposes, and by intentionally starting or suppressing fires to meet social, economic and ecological goals. The effect of land-use change on fire regimes varies based on the specific activity and its social-ecological context.

Until recent decades, large fires in tropical broadleaf forests were uncommon (5). But contemporary land use, including deforestation fires to clear primary forest for agriculture, often promotes more frequent and intense uncontrolled fires (72). On average, 38% of global forest loss is associated with landscape fires (73). In Borneo, fire frequency was relatively high throughout the 1990s, when land was first cleared for palm oil plantations, but fire frequency declined during the 2000s after large areas of primary tropical forests were converted to permanent plantations (59). In the Amazon basin, logging, habitat fragmentation, and climate change act synergistically to increase the risk of larger burned areas and more intense fires (74). The fragmentation of tropical forests creates more flammable forest edges and increases human ignitions (75), with potential for this feedback to convert forests to derived savannahs (72).

At the same time, fire frequency has declined in some grassland and savannah ecosystems, such as the Serengeti-Mara savannah of Tanzania, through increased livestock grazing and habitat fragmentation (15). Fire exclusion in the Brazilian Cerrado is increasing tree cover in former grasslands where fire occurrence, which limits woody encroachment, has been impeded by fire suppression policies, habitat fragmentation, and land abandonment (16). In the Kadiwéu Indigenous Territories of Brazil, situated between the Pantanal (wetland) and the Cerrado (savannah), evaluation of burn scars showed that Indigenous brigades, comprised of Indigenous residents implementing a mix of prescribed fire and fire suppression activities, reduced fire frequency by as much as 80% and reduced the size of area burned by 53% (from 2001 to 2018) (55). In other areas, such as savannahs of northern Australia, programs of deliberate planned burning have been used to introduce different timing of fire: From 2000 to 2019, areas where early season fires were applied experienced reduced late season wildfire and patchier fires (54).

Human settlements and urbanization are also key drivers of fire regime changes (35, 62, 76). In California, the contemporary spatial arrangement of human settlements can diminish the influence of climate on fire activity (77)—in general, ignitions caused by human actions are a strong influence on fire activity across the United States (78). Importantly, a mix of archaeological, paleoecological and ethnographic evidence reveals that humans have been living within and modifying urban-wildland interfaces for centuries. In the mountains of New Mexico, Native American ancestors of Jemez Pueblo harvested wood and strategically burned forests using small, patchy fires for more than 500 years. Maintenance of this cultural landscape, particularly from approximately

1340 to 1630, was linked to a higher total area burned but lower fire size and fire intensity compared to later periods impacted by Spanish colonialism (79). Human populations moving away from rural settlements to urban areas can also result in fire regime changes. Examination of a 133-year period (from 1873 to 2006) in the western Mediterranean basin showed that rural depopulation increased fuel availability and landscape connectivity, driven by the abandonment of crops and grazing pastures, reduction in forest harvesting, and afforestation (63). This caused a fire regime shift in the 1970s, characterized by increased fire frequency and total area burned (63).

4.3. Biotic Mixing

Humans have transported plants and animals across the globe, resulting in novel mixes of species that modify fuels and fire regimes. In many parts of the world, invasive grasses have increased flammability and fire activity (71). For example, the invasive buffelgrass (*Pennisetum ciliare*) in Northern Australia, cheatgrass (*Bromus tectorum*) in western United States, and molasses grass (*Melinis minutiflora*) in central Brazil have increased fuel loads and continuity in many landscapes (80). In turn, changes in grassy fuels can increase the frequency and size of fires, and alter their seasonality—especially where invasions of non-native species co-occur with human ignitions (80). Construction of new types of landscapes, such as plantations of exotic or commercial flammable trees, can also shift fuel dynamics, leading to increased fire activity, such as in Chilean forests and grasslands (66).

Disruption of biotic interactions and extinction of populations can also contribute to fire regime changes. During the late Quaternary, some of the world's largest herbivores or megafauna became extinct, starting approximately 60,000 years ago and following the expansion of humans across the globe (81). Increases in charcoal after these extinctions suggests that it is plausible that removal of megafauna increased vegetation burning in forest and woodland environments once their consumption of plant matter and moderation of fuels ceased (81). A review of International Union for the Conservation of Nature (IUCN) Red List data indicates that modification of fire activity has contributed to the recent extinction of 37 species (4), including a suite of marsupials in Australia whose digging and foraging activity may have moderated fuels and fire regimes by engineering the soil and litter later (82). Empirical evidence indicates that large grazing and browsing mammals in Europe, North America, and other parts of the world can reduce fuel loads and moderate fire frequency and intensity when herbivore preferences match local vegetation (83). However, variation in herbivore type and their population density means that some forms of grazing and browsing have no effect or even increase flammability (83).

4.4. Societal Causes

Demographic, economic, institutional, and political factors are root causes of changes in land use and other direct drivers of fire regime shifts. In the Amazon basin, increases in deforestation fires and uncontrolled fires have underlying societal causes, including deregulation, market demand for agricultural products and timber, and weak governance (74, 84). After the collapse of the Soviet Union in 1991, the abandonment of large areas of cropland and pasture in the dry steppe of Kazakhstan reduced grazing pressure and increased burned area across a region of 358,000 km^2 (52). Conflicts and epidemics are largely hidden drivers of changes in fire regimes, but new research is shedding light on their important role. A sixfold increase in fires in nominally protected areas, from 2017 compared to 2018, was observed following armed conflict and demobilization in Colombia (65); moreover, a recent increase in burned area in Syria is explained, in part, by conflict from 2011 onward and related increases in human ignitions and reductions in active fire suppression (60). In 2020, COVID-19-related shutdowns at the beginning of the prescribed fire season in the southeastern United States reduced active fires from March to December by 40% on federal lands (64).

Colonization by Europeans has had profound effects on fire regimes across the globe, in areas long managed and cared for with fire (36, 57, 61, 85, 86). Colonialism in California, United States, disrupted fire-dependent societies with cascading effects for a mixed conifer ecosystem, including an increase in forest biomass following the depopulation of ancestors of the Karuk and Yurok Tribes that applied frequent, low-severity fires (36). In forests of British Columbia, Canada, the combined effects of colonial fire suppression, which led to buildup of fuels in some ecosystems, and global climate change have been linked to recent increases in burned area and fire size (57). In southeastern Australia, cessation of Indigenous burning practices has been linked with shrub encroachment (85) and conversion of temperate grassland into rainforest (61) and, along with climate change, has been proposed as an explanation of wildfires of unprecedented extent (85). Restriction of Indigenous land-use practices, including application of fire, has also been linked to increased incidence of deforestation and wildfire across South America (86). Although prevention of traditional fire practices continues to affect fire regimes and ecosystems, the revitalization of Indigenous fire stewardship and cultural burning is taking place in many parts of the world (2).

5. CONSEQUENCES OF FIRE REGIME CHANGES

The Earth System comprises interacting biological, chemical, and physical processes (17). Next, we explore the consequences of fire regime changes on four parts of the Earth System: the atmosphere, biosphere, geosphere, and hydrosphere (**Figure 3**). These global spheres are linked, in part, through fire-related interactions and feedbacks (5).

5.1. Atmosphere

Fire links the atmosphere and biosphere by releasing heat, gases, and particulate matter (41). Landscape fires are an important source of greenhouse gases, emitting 2.1 Pg of carbon to the atmosphere per year from 2002 to 2019 (91). Most carbon emissions are recaptured by sequestration during postfire vegetation recovery. However, emissions from deforestation fires (25% of global fire emissions) and combustion of organic deposits of boreal and tropical peatlands (14% of global fire emissions) are net sources of carbon to the atmosphere (91). This is concerning because these two fire types have become more common in the Anthropocene, and there is potential for positive feedbacks whereby wildfires increase atmospheric CO_2, contributing to further global heating, which in turn amplifies the risk of more wildfires (5, 92).

There is evidence that emissions from Anthropocene fires are already modifying the atmosphere and generating feedbacks. A prime example is the historically exceptional 2019–2020 Australian wildfires, which were associated with prolonged drought amplified by climate change (93). They produced record-breaking levels of aerosols over the Southern Hemisphere (94), and carbon emissions in Australia over the 12-month period including the wildfires were approximately 1.5 times that of 2017 (95). Smoke produced by the Australian wildfires is associated with extraordinary impacts on the atmosphere, including an outbreak of 38 fire-induced storm clouds called pyrocumulonimbus (87) (**Figure 3*a***). Smoke plumes from these extreme storms emitted particles into the stratosphere that circled the globe and affected regional weather patterns (96), with conditions conducive to pyrocumulonimbus projected to increase (97). The wildfire-smoke-related health costs of the 2019–2020 fire season in Australia included an estimated 429 smoke-related premature deaths as well as 3,230 hospital admissions for cardiovascular and respiratory disorders—with smoke-related health costs totaling approximately US$1.25 billion (98).

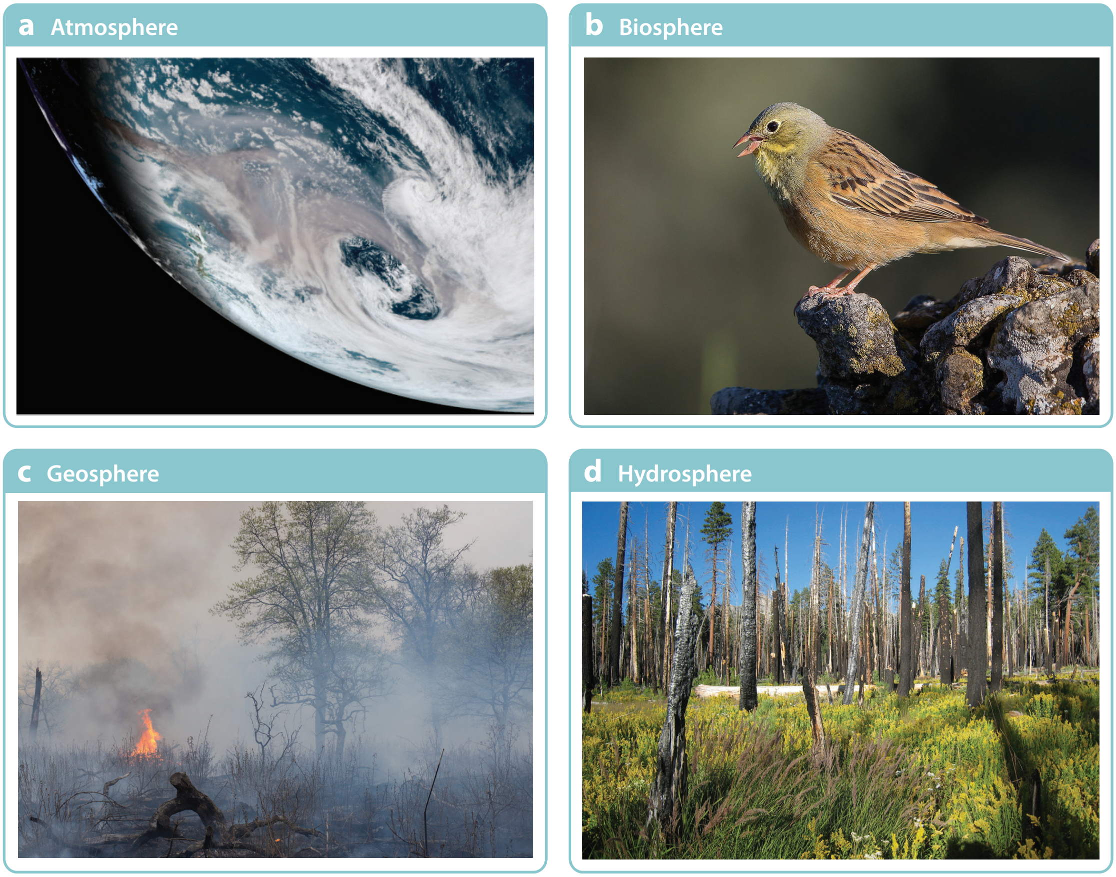

Figure 3

Fire regime changes in the Earth System. (*a*) Atmosphere: The coupling of landscape fires with the atmosphere can create pyrocumulonimbus storms that inject smoke into the stratosphere [this true color image is based on the GeoColor Algorithm from the Cooperative Institute for Research in the Atmosphere (87).] (*b*) Biosphere: The ortolan bunting (*Emberiza hortulana*) benefit from fire-created openings in forests (88). (*c*) Geosphere: Experimental fire in places such as the temperate savannah in Minnesota, at the Cedar Creek Ecosystem Science Reserve, help us learn about soils in the upper part of the geosphere (89). Hydrosphere: Letting wildfires burn when conditions are not extreme can enhance stream flow and freshwater ecosystems such as meadows and wetlands in Yosemite National Park, California (90). Panel *a* used with permission from David A. Peterson. Panel *b* used with permission from Tubifex, Public domain, via Wikimedia Commons. Pierre Dalous, CC BY-SA 3.0, via Wikimedia Commons. Panel *c* used with permission from Frank Meuschke. Panel *d* used with permission from Scott L. Stephens. Figure co-produced by Clare Kelly and commissioned by the authors.

5.2. Biosphere

Many organisms have evolved strategies that enable them to thrive under a particular fire regime, so substantial changes to fire characteristics can harm populations and alter ecosystems. A recent review of the 29,304 terrestrial and freshwater species categorized as threatened with extinction by the IUCN found that for at least 4,403 (15%) modification of fire regimes is a recorded threat (4). This includes 28% of gymnosperms, 19% of birds, 18% of monocots, 17% of dragonflies and damselflies, 16% of mammals, and 14% of reptiles that are classified as critically endangered, endangered, or vulnerable (4). Most species are threatened by an increase in fire frequency or intensity (4). For example, since 2001, as much as 190,000 km^2 of the Amazon rainforest has experienced fires, impacting the ranges of approximately 77–85% of threatened species in the region (84). However, exclusion of fire in ecosystems that need it can also be harmful (4). For instance, the ortolan bunting (*Emberiza hortulana*) is one of a suite of open-country birds in Europe that benefit from fire-created openings in forests and woodlands (88).

An advantage of a fire regime perspective is that it helps to pinpoint patterns of recurrent fire that contribute to population declines. An illustrative case study comes from Australia, where inappropriate fire regimes are pushing 88% of threatened land mammals closer to extinction (99). Frequent, intense, and large fires are the primary cause of fire-related mammalian declines, particularly through low postfire survival rates (99). For example, large and intense fires are reducing the availability and connectivity of forest habitat preferred by the greater glider (*Petauroides volans*) (99). However, several Australian mammal taxa are threatened by a lack of fire: Reduced fire frequency alters food resources and habitats preferred by the northern bettong (*Bettongia tropica*) in parts of its range in the tropics of northern Australia at higher altitudes (99).

Extreme wildfire event: characterized by exceptional fire behavior, including enormous energy release, accelerated rate of spread, and long-distance spotting, often threatening people and social-ecological values

Fire regime changes are also reshaping whole ecosystems. More frequent or more severe fires even threaten forests with a long history of landscape fire. For example, consecutive, high-severity fires that occur before trees can set seed and reproduce are reshaping the species composition of temperate forests in Australia (100, 101) and boreal and subalpine forests in the United States (102, 103). In southern California, frequent, short-interval fires are reducing woody cover of native vegetation and converting shrublands to grasslands (104).

5.3. Geosphere

Soils play a critical role in the upper surface of the geosphere, supporting carbon stocks, pools of nutrients, and biotic communities (1). A big question is how changes in fire characteristics, such as fire frequency, modify pools of carbon and nutrients held in plants and in the soil. A long-term fire experiment across a forest-grassland continuum showed the resilience of carbon and nutrients in plants can be high when vegetation is herbaceous and capable of resprouting (105). However, repeated burning at high frequencies can limit total plant biomass and shift a community to less productive species (105). Pools of soil organic matter can also increase or decrease depending on whether they are combusted by fire events and whether prevailing fire regimes increase plant growth, incorporate ash into soils, or reduce the turnover of plant litter (106). Data collected at decadal scales in several ecosystems indicate that increased fire frequency can deplete soil carbon and nitrogen—but there is substantial variation between ecosystems and fire types, with fire-driven carbon and nitrogen losses observed to be more substantial in some ecosystems (e.g., savannah grasslands) than others (e.g., temperate forests) (89). More frequent burning can even shift certain ecosystems from carbon sinks to sources of carbon to the atmosphere: Increased fire frequencies in boreal ecosystems are combusting soil organic matter before it can reaccumulate following the previous burn (92). Emerging research is also pointing to the need to better understand changes in soil microorganisms and their important role in carbon and nitrogen cycling, via decomposition, in fire-prone landscapes (106).

Fire regimes also shape erosion and geomorphology (107). Landscape fires can contribute to erosion directly by consuming large amounts of organic matter, reducing the organic horizon and soil moisture, and increasing soil water repellency (108). Fires can also intensify erosion indirectly by removing ground cover and exposing soils to wind, rain, and snow (107). Fire type is an important influence on erosion; a global analysis indicates that wildfires, which tend to be larger and more intense than controlled fires, have stronger negative effects on erosion control than prescribed fires (109). Consequently, there is a risk that fire regime changes, such as more frequent extreme wildfire events (110), will cause marked changes in soil exposure and water infiltration: Recent observations indicate that extreme fire events can amplify natural hazards such as floods and harmful debris flows (111).

5.4. Hydrosphere

Fire regime changes influence the physical, chemical, and biological components of the hydrological cycle (112). For example, climate change is driving fires upslope to higher elevations of the western United States, with strong impacts on vegetation, snowpack, and water availability (113). Snow measurements in this well-studied region indicate that wildfires will likely cause declines in peak snow accumulation and snow duration, especially in low-latitude areas where fire generally increases the amount of shortwave radiation that reaches the snow surface (114). There is already a growing impact of wildfire on water supply; among basins of the western United States that have recently experienced >20% of forest burned, streamflow has increased by approximately 30% in the first six years after fire due to fire-induced soil erosion and water repellency (115). Increased streamflow may enhance water availability but poses hazard management challenges such as reduced water quality, enhanced debris flow, and landslides (115). These challenges are shared globally: Extreme wildfires pose a risk to water catchments worldwide (112).

It is not just freshwater systems that are affected by fire regime changes—new research has revealed linkages between terrestrial and marine environments. For example, smoke plumes from the 2019–2020 Australian wildfires transported nutrients to the Southern Ocean, resulting in widespread phytoplankton blooms (116). Large wildfires over the western United States have been linked to diminishing sea ice in the Arctic; observations of this teleconnection were tested using climate modeling simulations and help to explain how sea-ice loss in summer and autumn enhance fire weather thousands of kilometers away (117). River export of black carbon (BC) produced by landscape fires is also an important linkage between global spheres: Global data on BC concentrations indicate that rivers export 43 Tg BC per year globally, and that 34% of the BC produced by landscape fires ends up in the ocean (118).

6. FIRE AND A BETTER ANTHROPOCENE

Fire regime changes are threatening human lives and livelihoods (39), as well as ecosystems and the services that they provide (109). However, viewing fires primarily as natural disaster events, or all types of fires as harmful, continues to limit progress in sustainably coexisting with fire. Here, we present an alternative perspective for thinking about fire regime changes that draws from a diversity of disciplines and pioneering applications. Using the United Nations Sustainable Development Goals (SDGs)—17 Goals at the heart of the 2030 Agenda for Sustainable Development—we reason that understanding fire regimes offers the opportunity to (*a*) better protect life on land and in the water, (*b*) promote human health and well-being, and (*c*) create transdisciplinary research and innovative partnerships. A fire regime perspective is critical to navigating toward a sustainable future—in other words, a better Anthropocene (119, 120) (**Table 2**).

6.1. Life on Land and in the Water

Variation in fire regimes within historical bounds enables many plants to complete their life cycles (3), creates habitats for a range of organisms (129), and maintains ecosystems and processes (1) that sustain life on Earth. Understanding the different components of fire regimes and how they are changing can help to promote biodiversity and healthy ecosystems in two important ways.

First, knowledge of fire regimes can help to develop approaches that involve actively managing fire to suit particular species or ecosystems. For example, knowing when plants flower and produce

Table 2 Ways that knowledge and practice of fire helps to achieve sustainability goals in the Anthropocene

United Nations Sustainable Development Goals	Insights from knowledge and practice of fire	Opportunities and actions	References
No poverty	Uncontrolled fires impact livelihoods and are a major social-environmental challenge in the tropics.	Understand farmers' burning practices to identify approaches that align with local customs and that are more equitable.	121
Zero hunger	Fire can be used to promote desirable animals, fungi, plants, and food security.	Encourage Indigenous fire stewardship and reinstatement of cultural burning in a modern context.	122
Good health and well-being	Practicing fire and related activities as a community increases social cohesion and human health and well-being.	Support community-owned solutions for more effective and sustainable fire management.	86
Quality education	Indigenous knowledge of seasonal biocultural indicators informs when, where, and how to apply fire.	Development of fire season calendars is a practical and educational activity for intergenerational transfer of knowledge and fire management.	43
Gender equality	Cultural burning is an important part of foraging for traditional foods and, in some cases, women specialize in collecting resources.	Ensure equitable support for women in practicing fire and hunting.	123
Clean water and sanitization	Managed wildfire whereby wildfires are allowed to burn naturally and are suppressed only under specific conditions can enhance ecosystem resilience.	Restored fire regimes offer an opportunity to increase the security of mountain water supplies.	90
Affordable and clean energy	Sustainable timber harvesting can provide a source of local (but not necessarily clean) energy and reduce fuel loads in some forest types.	Trial the use of sustainable harvesting to moderate fire activity, provide local sources of renewable energy and promote habitat for open-country bird species.	124
Decent work and economic growth	Fire is a necessary part of healthy savanna ecosystems around the world.	Appropriate use of fire can promote charismatic animals that benefit the tourism industry.	15
Industry, innovation, and infrastructure	Fire management at the urban-rural interface requires strategies that are economically viable, socially acceptable, and congruent with hazard mitigation standards.	Codevelop fire-resilient structures through collaborative partnerships with material scientists, community planners, and risk assessment industries.	125
Reduced inequalities	Wildfires can impact low-income communities the most, thereby exacerbating inequality.	Allocate resources before, during, and after wildfires to at-risk communities and residents.	126
Sustainable cities and communities	Fire science can be used to identify areas with high fuels and that contribute the most to fire spread.	Design green firebreaks and mixed-use areas with low fuels, strategically located in the landscape.	127
Responsible consumption and production	Fires on previously cleared lands provide many of the ignition sources for tropical forest fires.	Incentives and capacity building can encourage fire-free cattle ranching, which can also return higher yields to pasture management.	72

(*Continued*)

Table 2 (*Continued*)

United Nations Sustainable Development Goals	Insights from knowledge and practice of fire	Opportunities and actions	References
Climate action	Fire regimes have a strong influence on carbon storage in soil organic matter.	Using low-intensity fire to promote the stability of soil organic matter may be an important way to increase carbon storage.	128
Life below water	Wildfires can impact marine ecosystems thousands of kilometers away through long-range atmospheric aerosol transport.	A greater appreciation of the links between wildfires, pyrogenic aerosols, and marine photosynthesis will improve understanding of the global climate system.	116
Life on land	Variation in fire regimes can promote biodiversity.	Use of fire can be tailored to promote and restore species and ecosystems.	129
Peace, justice, and strong institutions	Valuable fire and ecological knowledge is held by many peoples and groups.	Participatory approaches can aid decision-making in postconflict regions.	130
Partnerships for the goals	Living with fire is a global challenge.	Explicitly incorporate fire into national and international sustainability initiatives.	26

seed can be used to identify when fire is needed, as well as recognize parts of the landscape where fire should be applied or suppressed (100, 102, 103). Indeed, a host of fire-related plant traits can be used to understand and navigate the feedbacks, tipping points, and regime shifts typical of the Anthropocene (**Figure 4**). Moreover, linking information about variation in fire regimes (sometimes called pyrodiversity) provides a powerful way to design more effective fire and conservation strategies (see the sidebar titled Pyrodiversity). A recent field experiment in semiarid Australia indicates that areas subject to patchy planned burns, which are applied to moderate the size of wildfires, can provide habitat for many species of reptiles when unburned refuges are retained (131). A continent-wide analysis of savannah ecosystems in Africa showed that pyrodiversity was influential in wet savannahs, where areas with large variation in fire size, intensity, and timing had 27% more mammal species and 40% more bird species compared to areas with low variation in fire regimes (132). This highlights how managers can use fire to promote animal diversity.

Pyrodiversity: variation in the spatial and temporal dimensions of fire regimes, generated by a range of ecological and social feedbacks

Second, considering fire regimes (and not just a single fire event) ensures that scientists, stakeholders, and decision-makers confront the long-term role of fire and the diverse processes that it interacts with. Fire regime changes cannot be tackled in isolation from other environmental changes such as deforestation, extinctions, invasive species, and wetland drainage. From forests to

PYRODIVERSITY

Pyrodiversity refers to spatial and temporal variation in fire regimes. This concept has encouraged the generation of diverse fire regimes under the assumption that "pyrodiversity begets biodiversity." A surge of empirical studies have explored this hypothesis (149), with much work to date asking the deceptively simple question "Does pyrodiversity promote biodiversity?" A more nuanced approach is emerging that recognizes that there are many different forms of pyrodiversity (129), and they are the outcome of feedbacks between fire regimes, ecological processes (such as dispersal, grazing, pollination, predation), and human actions (23). Connecting pyrodiversity to biodiversity means creating variation in fire regimes tailored to suit the needs of ecosystems and species.

floodplains, large-scale environmental restoration projects involving local communities and national agencies have been proposed to increase the resilience of ecosystems (137, 138). The boreal region of Canada supports diverse plant communities and species adapted to wet conditions, but draining peatlands has increased the risk of very large fires and deep smoldering fires that persist even in cold conditions (139). However, preliminary studies indicate that strategic rewetting of drained peatlands and the promotion of fire-resistant mosses can reduce smoldering potential and mitigate carbon loss (139), which will likely have positive outcomes for wetland biodiversity. In

(*Caption appears on following page*)

Figure 4 (*Figure appears on preceding page*)

Using plant traits to navigate fire regime changes in the Anthropocene. (*a*) Plant species with thinner bark are less tolerant of fire in the Cerrado, Brazil. Higher fire frequency could reduce carbon storage by thin-barked trees in tropical savannahs and forests (133). (*b*) Fire and herbivory both consume plants. Grasses with the ability to resprout from stored reserves and a bud bank are more likely to withstand fire and grazing in tropical grasslands (3). (*c*) Short-interval stand-replacing fires reduce tree regeneration in lodgepole pine (*Pinus contorta*) forests in the Rocky Mountains, United States. The time needed for pines to mature and accumulate seed sets the threshold below which decline of species populations is predicted (102). (*d*) The storage of mature seeds in a canopy seedbank (serotiny), that are released in response to fire, provides fitness benefits to Aleppo pine (*Pinus halepensis*) in the Mediterranean basin. These trees have higher levels of serotiny in areas where crown fires are more common (134). (*e*) Some eucalypts in southern Australia resprout after fire via epicormic buds along the trunk and branches, others resprout basally from underground lignotubers. Resprouting type influences how rapidly the tree layer, an important habitat for birds, regenerates—within several years with epicormic resprouting, or over decades with basal resprouting (135). (*f*) Populations of a native forb *Helenium aromaticum* from the Chilean matorral show substantial variation in seed thickness. Seed thickness is strongly associated with fire frequency and this indicates rapid evolution under recent anthropogenic changes to fire regimes (136). Panel *a* used with permission from Adam F.A. Pellegrini. Panel *b* used with permission from Peripitus, CC BY-SA 3.0, via Wikimedia Commons. Panel *c* used with permission from Design Pics Inc./Alamy Stock Photo. Panel *d* used with permission from Luke T. Kelly. Panel *e* used with permission from Thomas A. Fairman. Panel *f* used with permission from Tubifex, Public domain, via Wikimedia Commons. Figure co-produced by Clare Kelly and commissioned by the authors.

Africa, reintroducing native grazing animals such as white rhinoceros (*Ceratotherium simum*) moderates fuel loads and helps to create patchy fires that generate habitats for insects and plants (81). A strategy trialed in temperate forests is letting wildfires burn when conditions are not extreme, to promote variation in fire regime characteristics such as fire severity. In Yosemite National Park, California, a policy of not extinguishing fires started by lightning has created more diverse habitats that support a variety of plants and their pollinators—as well as enhancing stream flow and freshwater ecosystems such as meadows and wetlands (90).

6.2. Human Health and Well-Being

Actively managing fire regimes for human health and well-being means ensuring an appropriate amount, pattern, and timing of fire in landscapes. Importantly, restoring and promoting fire-prone landscapes that benefit people also creates opportunities to balance diverse human and ecosystem values in many regions of the world (**Table 2**).

More extreme wildfires (140) are causing loss of human life (67), displacing people from their homes (39), and having wide-ranging effects on human health (6). There is no silver bullet for eliminating the risk of dangerous fires to people, but managing fire regimes, not single fires, can reduce risks by helping to shape the characteristics of future fires and design strategies to coexist with them (141). For example, recent advances are pinpointing when and where hazard reduction burning is most effective (142) and helping to understand the role of different types of ignitions and their causes (78). Moreover, identifying the human communities and demographics most at risk from wildfires can help to allocate resources before, during, and after fires (126), including mental health services (6). A wealth of evidence indicates that undertaking burning and fire management activities as a community increases social cohesion and human health and well-being (86) (**Table 2**).

Fire severity: the effects of fire on plant biomass and other aspects of the environment

Applying or shaping suitable fire regimes can also benefit people by encouraging desired species and food resources (122), and providing economic (15) and education opportunities (43) (**Table 2**). Agriculture and forestry across the Mediterranean basin that promotes patchworks of low-flammability crops and oak woodlands can also reduce the risk of large, intense fires to people and simultaneously provide suitable habitat for threatened bird species (124). Across the globe, there is a long history of Indigenous peoples using fire to promote desirable animals, fungi, and plants (122). In arid Australia, for example, patchy fires can improve the availability of traditional foods and the quality of contemporary human diets (123). Skillful application of landscape fire is also used widely as part of smallholder agriculture and pastoralism (27). In Kalimantan, Indonesia, knowledge of the types of burning that align with local farming practices provides an opportunity to design more equitable fire policies that maintain customary use of fire and enhance livelihoods (121). Fire is a necessary part of healthy savannah ecosystems in Africa—and appropriate use of fire can promote charismatic animals that benefit the tourism industry and local economies (15).

Integrated fire management: a strategic and operational approach that considers the social, economic, cultural, and ecological dimensions of fire

Fire regimes have a strong influence on climate and air quality. Although fires produce gases and particulate matter that influence climate, applying specific types of fire may offer nature-based solutions that can increase carbon storage. For example, low-intensity planned burning in deciduous and mixed forests could lead to more stable carbon storages in soil organic matter by reducing fuels and wildfire severity, and therefore limiting combustion of soil organic matter (128). Different types of fires have different outcomes on smoke-related health issues, and preliminary studies are starting to explore trade-offs between wildfires and prescribed fires on human health (143). Concurrent actions are urgently required to reduce greenhouse gas emissions and limit global temperatures; otherwise, health effects of smoke will continue to rise under more extreme wildfires (6).

6.3. Opportunities for Transdisciplinary and Inclusive Science

The magnitude of sustainability challenges under emerging fire regimes are such that conventional ways of doing things will not succeed. New fire science, partnerships, and experiments are required.

Science provides abundant lenses with which to view fire and fire regime changes: as a biological phenomenon that shapes the ecology and evolution of ecosystems, as a social phenomenon that crosses human cultures and geographic boundaries, and as a physical phenomenon that links the Earth's global spheres. Fire regime changes cannot be understood through any single lens (144), and we have showcased encouraging examples of studies linking social sciences, biological sciences, physical sciences, and mathematical sciences throughout this review. A challenge now is to keep growing connections and collaborations across disciplines so that the feedbacks, tipping points, and regime shifts characteristic of the Anthropocene can be understood and predicted (144, 145).

Other forms of knowledge are important too. The maturing discipline of pyrogeography has already provided valuable syntheses of the human dimensions of fire (5, 41) and provides a focal point for bringing together and creating knowledge across not only the sciences but also the humanities. Learning from previous and current management by local and Indigenous peoples and fostering shared and integrated fire management are invaluable steps in promoting fires that benefit life on Earth (2, 79, 86).

Innovative partnerships across a range of sectors are crucial for navigating big decisions about new and changing ecosystems—whether it be consideration of fire in the context of meeting global climate targets, caring for cultural landscapes, or protecting homes and habitats. At local and regional scales, fire management at the urban-rural interface will benefit from codevelopment of fire-resilient structures through partnerships with material scientists, community planners, and risk assessment industries (125). Valuable fire and ecological knowledge is held by many peoples and groups; thus, participatory approaches that bring together a wide range of actors and stakeholders are likely to aid fire management decisions in many contexts (13, 130). At national and global scales, explicitly incorporating fire regimes into the United Nations SDGs provides an opportunity to develop innovative policies to set and achieve sustainability targets (26) (**Table 2**). Emerging international initiatives that bring together industry, government, and local communities with scientists, such as the pan-European FIRE-RES project built on the concept of integrated fire management, provide a foundation through which large-scale sustainability policies and practices could be developed and assessed.

The challenges the world faces in a new era of fire are so immense that people need to keep experimenting, testing new ideas, and trialing alternative fire management initiatives and technologies. We envisage that inclusive science and innovative partnerships will enable large-scale tests of novel initiatives such as immediate detection of ignitions and rapid suppression (8, 101), restoration of ecosystems to moderate and disconnect fuels (81, 83), and modification of ecosystems and built environments such that they are better adapted to future climate and fire (4, 138). Designing experiments that effectively influence management is important, and a large body of work on iterative learning and adaptive management provides a framework for doing this (146). Ecosystems are shaped by complex and interconnected reactions to humans and fire; as the world changes, society as a whole needs to keep learning about this interplay.

7. CONCLUSIONS

Our overarching message is directly relevant to the billions of people living in fire-affected areas: Humans are active participants in the Earth System, and there are plentiful opportunities to apply knowledge of fire to benefit people and ecosystems. Although the pace and scale of changes across global spheres represent fundamental challenges to humanity, we reason that valuing the critical role of fire regimes in the Earth System will help to achieve a better Anthropocene. Realizing this opportunity depends on understanding how interactions with anthropogenic drivers—such as global climate change, land use, and species introductions and extinctions—are transforming fire activity and its impacts on social and ecological systems. Some of these interactions are generalizable across different biomes and places but other patterns and processes are shaped by factors specific to regions and local contexts. The fire regime concept can help to disentangle the causes and consequences of these changes. Ultimately, considering the combined effects of human activities and fire regimes means that there is a greater likelihood of finding effective solutions for sustaining biodiversity and promoting human well-being.

SUMMARY POINTS

1. Fire is an integral part of the Earth System, affecting the air, land, and water that support life on Earth.
2. Humans have been modifying landscape fire for millennia, yet social and environmental changes continue to accumulate, scale up, and reshape fire patterns worldwide.
3. The fire regime concept provides a valuable framework with which to describe altered patterns of fires and understand their causes and consequences.
4. Multiple lines of evidence show that fire regimes are changing from local to global scales, including an increase in extreme fire weather and altered patterns of burned area, fire frequency, fire seasonality, and fire size.

5. Human drivers such as climate change, land use, fire use and suppression, and transportation and extinction of species are shifting fire regimes and creating environments unlike any humanity has previously experienced.
6. Some forms of fire regime changes are contributing to global heating and threatening ecosystems and human lives; other forms are the result of deliberate and skillful use of fire to achieve beneficial outcomes.
7. Knowledge of fire regimes can be mobilized to achieve a variety of goals—including reducing carbon emissions, promoting biodiversity, and enhancing human well-being—and is critical for a sustainable future.

FUTURE ISSUES

1. How can fire regimes be achieved that enhance biodiversity, climate stability, and ecosystem services while reducing the risk of extreme fires that harm people?
2. How can monitoring systems be designed that accurately track multiple dimensions of fire regimes and fire weather at large scales, at high resolution, and in real-time?
3. What is the best way to foster and expand knowledge of the social values and goals that motivate past and present fire use?
4. What transdisciplinary research initiatives should be created to explore pathways to sustainable coexistence with landscape fire?
5. How can partnerships across sectors be forged and nurtured to trial new fire management approaches and engage with local communities?
6. How can the revitalization of Indigenous fire management, and other forms of traditional and local knowledge, be supported around the world?
7. How can we quantify and understand the trade-offs between fuel management, risk of uncontrolled fires, and adverse effects on social and environmental values?
8. What strategies should be employed to collect the biological data (from genes to ecosystems), social data (from individuals to whole societies), and physical data (from local to global) that will be essential for developing models that capture the feedbacks and regime shifts characteristic of the Anthropocene?

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We thank Clare Kelly for co-designing the submitted figures. We appreciate the valuable contributions of Yuka Estrada on **Figure 2** and copyediting from Marie-Thérèse Wright.

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