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A FIRE-PRONE WORLD

Abstract

Wildfires have been common for nearly 400 million years. They have shaped landscapes and ecosystems from the boreal regions to the tropics. Wildfires have varied in spatial extent, frequency, and intensity through time, but they are currently becoming more widespread, frequent, and intense in regions including Europe's Mediterranean region, the boreal forests of North America, and the drylands of Australia and the western interior of North America. Many of these patterns reflect changing climate. Wildfire can create immediate, direct hazards for human and biotic communities through destructive heat and combustion and air pollution from smoke and other particulates. Wildfire also creates secondary effects by changing fluxes of water, solutes, sediment, and organic matter in uplands and freshwater environments. These secondary effects can shape landscapes and alter ecosystems in ways that persist for years to decades or longer. Most of the studies synthesized in this book come from forested environments in western North America, Australia, and the Mediterranean portions of Europe, even though most wildfires occur in grassland and savanna environments. The geographic distribution of information on wildfire effects reflects the bias in English-language scientific literature on wildfires.

Landscapes on Fire: Impacts on Uplands, Rivers, and Communities, Special Publications 80,
First Edition. Ellen Wohl.

DOI: 10.1002/9781394235186.ch1

Wildfire is likely to have been more or less common since the late Devonian (Schmidt & Noack, 2000), approximately 380 million years ago. Long-term records from diverse locations indicate that the location, extent, and severity of fire have varied through time. Global atmospheric transport and deposition of the smallest particles produced by fire have created records far from the actual burned areas. Isotopic records in sediment cores from the Ross Sea off Antarctica, for example, suggest large, frequent wildfires in the grasslands of the Southern Hemisphere from circa 15,000 to 4,200 years ago (Ren et al., 2022).

In recent decades, increasing frequency, extent, and severity of wildfires have made fires the hot topic in much of the world. Regional and global summaries tell the story:

- Globally, several hundred million hectares burn each year (FAO, 2001), equating to an estimated 8 billion Mg of biomass (Levine, 2000). Increased wildfire activity is observed in diverse regions and ecosystems around the world, from Mediterranean portions of Europe (Jiménez-Morillo et al., 2020; Seidl et al., 2014; Shakesby, 2011) to tropical rainforests (Cochrane, 2003) to Australian savanna (Fairman et al., 2015).
- Grassland and forest wildfires in the United States have increased in frequency, size, and severity since the mid-1980s, especially in the western United States (Joint Fire Service Program, 2004; Paul et al., 2022).
- In Arctic tundra, wildfire is projected to increase 4- to 11-fold by 2100 (Abbott et al., 2016; Hu et al., 2015).
- Fires historically occurred during hot and/or dry seasons in fire-prone ecosystems (Miller et al., 2019). Fire season has increased by nearly 20% across Earth's vegetated surface (Jolly et al., 2015). Parts of western North America, Brazil, and East Africa now have fire seasons more than a month longer than they were 35 years ago (Abatzoglou & Williams, 2016; Jolly et al., 2015). The greatest changes in fire season have occurred where temperature, changes in humidity, length of rain-free intervals, and wind speeds are greatest (Jolly et al., 2015).
- Large and frequent fires in boreal and tropical forests have the potential to cause terrestrial carbon stores to become major sources of greenhouse gases, amplifying climate change (Bowman et al., 2020). Global mean carbon emissions from fire during the period 1997–2016 were about 22% of global annual carbon emissions from fossil fuel combustion (Van der Werf et al., 2017).

Some of these patterns of wildfire reflect changing land use. Increasing wildfire frequency and spatial extent in Portugal, for example, are influenced by land abandonment and subsequent shrub encroachment, along with afforestation of former agricultural land, both of which increase fuel accumulation (Pinto et al., 2008).

Many of the patterns of wildfire reflect the changing climate. Increasing fire in the western United States corresponds to drier conditions, earlier snowmelt, and severe droughts (Paul et al., 2022). Increased tundra fires reflect increased temperature, evapotranspiration, ignition sources, and vegetation shifts (Abbott et al., 2021). Tropical fires become more frequent in years with extended dry seasons (Van der Werf et al., 2008). The area burned annually by wildfires is expected to continue to increase globally due to climate change (Sankey et al., 2017).

Charcoal records indicate a global monotonic increase in wildfire since the last glacial maximum 21,000 years ago, with increased spatial heterogeneity in the last 12,000 years (Power et al., 2008). Fire suppression and changing land use during the first half of the 20th century caused the global average area burned to decrease from 535 to 500 Mha per year (Mouillot & Field, 2005), but global burned area increased to an estimated 608 Mha per year during the second half of the 20th century (Flannigan et al., 2009). This latter change includes increasing savanna and grassland fires in the tropics and temperate regions, with an exponential increase in tropical forest fires driven by deforestation and agricultural development (Carmona-Moreno et al., 2005; Flannigan et al., 2009). During the period 2001-2019, burned area increased by 50% or more in some extratropical forest regions including the Pacific U.S. and high-latitude forests, but decreased by 27% globally because of declines in burned area in African savannas (Jones et al., 2022).

Beyond the immediate hazards of the fire itself—destructive heat and combustion, air pollution from smoke, and other particulates—the secondary effects from wildfire can substantially alter landscapes and ecosystems in ways that persist for years to decades. Burned areas increase rates of runoff and soil erosion, as well as downstream sedimentation in rivers and reservoirs. Fluxes of nutrients such as nitrogen and phosphorus can increase to levels at which they cause harmful algal blooms in receiving waters. Increased water and sediment inputs to river corridors change channel and floodplain form and function, influencing processes such as flood attenuation, surface-subsurface water exchange, biogeochemical cycling, and aquatic and riparian biotic communities.

Some species are resistant to fire, especially lower intensity fires, surviving underground or within thick protective layers such as tree bark. Others are resilient, using cues from heat and smoke to germinate, or moving into a burned area quickly to take advantage of specific resources created by fire. When the frequency and intensity of fire increase beyond levels to which species can adapt, however, or when fires start to occur in ecosystems without an evolutionary history of adaptation to fire, individual species can undergo local extinction and the community of species present can change.

As fires increase in frequency, extent, and severity, these secondary effects also increase: Modeling conditions in the western United States in 2050, for example, Sankey et al. (2017) predict that post-fire sedimentation will increase by >10% for nearly 90% of watersheds and by >100% for one third of the watersheds, which will stress the aquatic ecosystems that are on the receiving end of extra sediment. Increased fire frequency in Mediterranean drylands can be responsible for accelerated soil erosion and reduced soil nutrient content, which then causes a transition from conifer forests to shrublands (Caon et al., 2014). The persistent changes in the geographic range of individual species and in the associations of species that constitute a biotic community and ecosystem are increasingly being documented in ecosystems with a history of fire, as well as those without such a history, creating examples of what have been called novel ecosystems (Jones et al., 2015).

A global map of the fire weather index, a key indicator of extreme fire behavior potential, shows that fire hazards are more common in the western United States, Australia, the southern and central parts of Africa, the southern and northeastern portions of South America, and central Asia (Figure 1.1). Fires are generally absent poleward of 70 °N and 70 °S in regions characterized by tundra and ice, progressively more frequent toward the tropics, and then drop sharply at the equator (Mouillot & Field, 2005). To some extent, the literature reviewed in this book represents this geographic distribution. The great majority of the studies synthesized here come from western North America, Australia, and the Mediterranean portions of Europe. The portions of Africa, South America, and central Asia prone to wildfires have been poorly represented in English-language peer-reviewed scientific literature, although the number of published studies focused on these regions is increasing rapidly.

The majority of studies synthesized in this book also represent forested environments, even though the majority of wildfires occur in grassland and savanna environments (Flannigan et al., 2009). Again, this reflects a bias in the proportion of published studies examining forests versus other biomes. (Biomes are ecosystems with the same dominant plant lifeforms; Grimm et al., 2013.) This may reflect the greater severity and duration of forest wildfires relative to the relatively brief duration of grassland and savanna fires. Or perhaps the imbalance reflects the obvious changes in a forest following intense wildfire and the decades required for a mature forest to re-grow. Grasslands, in contrast, survive fire by concentrating plant resources underground and grasses can typically re-sprout rapidly after fire (e.g., Vilà et al., 2001). Whatever the causes underlying the disproportionate focus on forests in wildfire literature, I have sought to include relevant references addressing wildfire in grasslands, savannas, and Arctic and tropical peatlands wherever possible throughout this book.

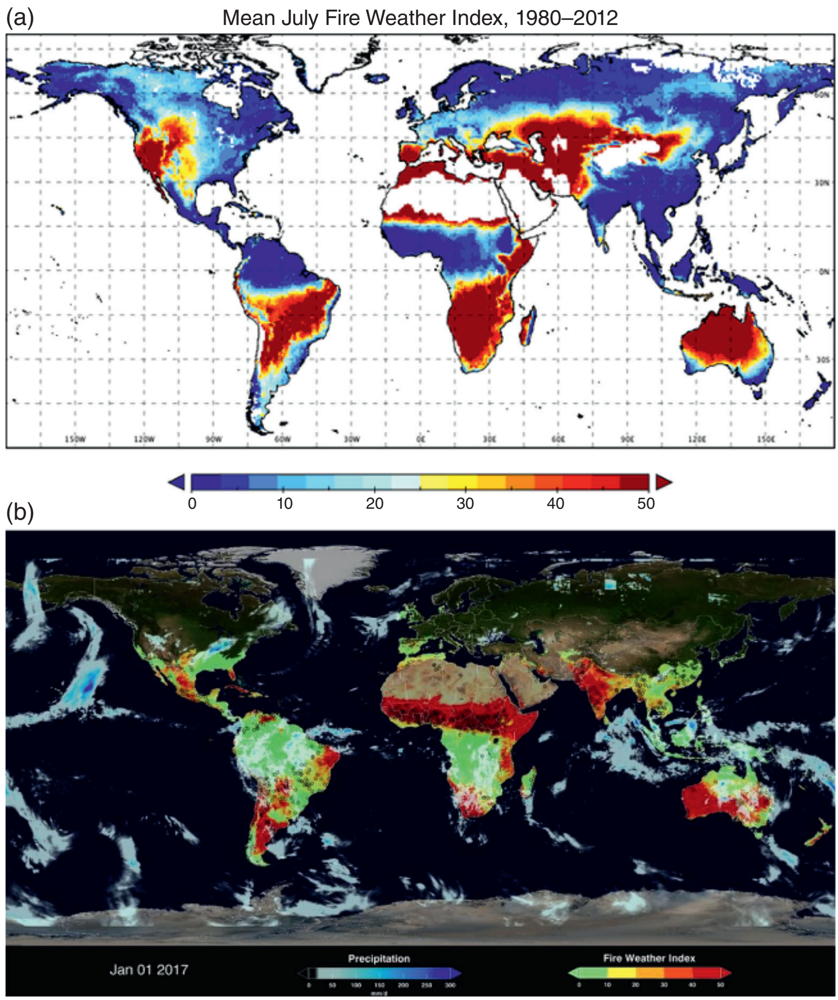

Figure 1.1 (a) Global map of fire weather index based on mean July conditions—summer in the northern hemisphere. (b) A contrasting map during summer in the southern hemisphere, here for 1 January 2017. (NASA / Public domain.)

This book focuses on wildfires. Wildfires here include fires outside of human-built environments started by processes not directly associated with humans (e.g., lightning strikes) or by deliberate or accidental human-generated ignitions of fire. Unless otherwise specified, any subsequent reference to fire refers only to wildfires. This book starts by exploring the details of fire. An introduction to the characteristics of fire, including the concept of a fire regime and fire recurrence intervals, is followed by a brief review of human alteration of fires, and the consequences of different types of fire regimes.

The succeeding two chapters are organized from the viewpoint of a geomorphologist—someone who studies the physical processes that create and maintain landscapes. Gravity is the great driver of physical processes following wildfire, aided and abetted by water. Consequently, I have organized the third chapter around the effects of wildfire in uplands—the unchanneled parts of a river catchment—that most people would simply think of as the terrestrial environment. This chapter proceeds from discussion of fire-induced changes in upland fluxes of water, solutes, sediment, and organic matter, to a review of how these changed fluxes influence landforms and biotic communities. It is worth emphasizing that the description of upland fluxes in this chapter is heavily biased toward the effects of severe wildfires in moderate- to high-relief environments. This bias mirrors the scientific literature, which primarily describes these scenarios. I presume this reflects the tendency to write about substantial change: it is more difficult to have a paper on the effects of wildfire accepted by peer reviewers if the primary conclusion is along the lines of 'nothing much happened.'

The fourth chapter focuses on post-fire changes in fluxes, morphology, and biotic communities within freshwater environments. The great majority of studies examining fire effects in freshwater environments focus on river networks, as reflected in the emphasis in the third chapter. This chapter starts with headwater streams and then moves downstream to higher-order streams, discusses stratigraphic records of long-term fire history in depositional environments such as alluvial fans and lakes, and concludes with a broader discussion of lake ecosystems.

Again, chapters three and four include a disproportionate focus on high-severity wildfires in moderate- to high-relief environments. As with the literature on forest rather than grassland fires, this coverage of severely burned, steep landscapes reflects the preponderance of literature discussing the effects of wildfire on fluxes and landscape forms. Low-relief landscapes also burn in wildfires and low-severity wildfires occur, but neither of these scenarios creates the dramatic landscape changes and post-fire hazards of floods and debris flows that attract scientists to investigate and publish their findings.

The fifth chapter addresses wildfire and human communities, with an emphasis on predicting and mitigating diverse types of fire-related hazards. The book concludes with an overview of fires in the future, including changing fire regimes, shifts in species and biomes, and human responses.

Several important compilations of fire-related research have been published within the past few years and I have used these compilations in developing the summary presented in this book. Important references include *Fire Phenomena and the Earth System: An Interdisciplinary Guide to Fire Science* (Belcher, 2013); *Fire Science: From Chemistry to Landscape Management* (Rego et al., 2021); *Spreading Like Wildfire: The Rising Threat of Extraordinary Landscape Fires* (Sullivan et al., 2022); and *Fire in the Earth System*, a special collection spanning 10 journals of the American Geophysical Union and including more than 100 individual papers (East et al., 2023).

In addition to a wealth of disciplinary and interdisciplinary studies of diverse aspects of wildfire, a specialized vocabulary related to wildfire has developed. Nearly any word can have *pyro*, from the Greek word for fire, added as a prefix to indicate that the word is being used in the context of wildfires. Text Box 1.1 defines some of the pyro vocabulary that I encountered most frequently while writing this book.

Text Box 1.1 Pyro Vocabulary: Examples of Words Incorporating *Pyro* (Fire in Greek) as a Prefix

Pyrogenic carbon: created by fire, includes charred fine residue & woody charcoal
Pyrocene: a time when humanity's firepower could interact in ways that promoted conditions that favored further fire
Pyroconvection: convection caused or intensified by fire
Pyrocumulonimbus: smoke-infused clouds & thunderstorms started or augmented by fires
Pyrodiversity: fire-derived heterogeneity of habitats
Pyrogeography: the study of human-fire relationships across space & through time
Pyrolysis: the thermal degradation of solid fuel into gases under the influence of heat
Pyrophilous: fire-loving (e.g., applied to types of fungi that appear after fire)
Pyrophytes: fire-resistant species (e.g., plants)
Pyroregions: areas with similar temporal patterns of fire activity

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