SPECIAL PUBLICATIONS SERIES

AGU
ADVANCING EARTH
AND SPACE SCIENCES

Landscapes on Fire

Impacts on Uplands, Rivers, and Communities

Ellen Wohl

WILEY

Landscapes on Fire

Special Publications 80

LANDSCAPES ON FIRE

Impacts on Uplands, Rivers, and Communities

Ellen Wohl

This Work is a co-publication of the American Geophysical Union and John Wiley and Sons, Inc.

AGU
ADVANCING EARTH AND SPACE SCIENCES

WILEY

This edition first published 2025

Published under the aegis of the AGU Publications Committee

Matthew Giampoala, Vice President, Publications
Steven A. Hauck, II, Chair, Publications Committee

For details about the American Geophysical Union visit us at www.agu.org.

Registered Office
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

Editorial Office
111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data Applied for:
Hardback: 978-1-394-23513-1

Cover Image: © Vladimir Melnikov
Adobe Stock Photos
Cover Design: Wiley

Set in 10/12pt TimesNewRomanMTStd by Straive, Pondicherry, India

CONTENTS

Preface vii

Glossary ix

1 **A Fire-Prone World** 1

2 **Fires: What, When, Where, and How** 11

3 **Fires and Terrestrial Environments** 47

4 **Fires and Freshwater Environments** 143

5 **Fires and Human Communities** 211

6 **Fires in the Future** 245

Index 277

PREFACE

I live in Colorado at the base of the Southern Rockies, where gently undulating terrain of the Great Plains abruptly meets the dramatic topography of the mountains. The plains are semiarid steppe, and the mountains are nearly as dry. Annual precipitation increases gradually with elevation, falling mostly as snow in the upper mountains.

This is a landscape of wildfires. I have lived here for more than 30 years, and those years have been punctuated by large fires: Buffalo Creek in 1996, Bobcat Gulch in 2000, Hayman in 2002, Hewlett Gulch in 2012, High Park in 2012, Waldo Canyon in 2012, Fern Lake in 2012, Cameron Peak in 2020, and East Troublesome in 2020. The most recent large fires in my immediate area—High Park and Cameron Peak—directly affected my life for weeks as smoke hazed the air, leaving my eyes stinging and my throat scratchy. I swept ash from the sidewalks around my home and anxiously scanned the online map of the fire perimeter. These fires continue to influence my research on streams in the burned areas—as well as my quality of life. Most of the areas in which I hike and snowshoe are burned and will never again during my lifetime appear as they did before the fires.

Wildfire affects your life also, even if you live in a wet climate and have never directly witnessed a wildfire. The global scope of wildfire smoke creates far-reaching impacts that may be visible when orange or brown haze smudges the skyline or invisible as fire pumps more carbon into the global atmosphere.

I wrote this book to generate a more inclusive understanding of fires. My research focuses on how water and sediment move from hillslopes into and through stream corridors after fire and how these fluxes then affect the distribution of large wood, channel and floodplain morphology, hyporheic exchange, nitrate uptake, and so on. The focus of my research keeps expanding, and I keep adding more collaborators because fire and its aftereffects do not stop at traditional scholarly boundaries. Like wind-borne firebrands that cause a fire to dance across the most rugged terrain and drainage divides, comprehending fire requires moving across disciplinary divides and synthesizing the expertise of diverse scholars. That is my objective in writing this book. I think about fire and write as a geomorphologist, but I strive to draw on knowledge from other disciplines as a means to greater insight.

With that context, I stress that this book is written by a geomorphologist. I have tried to distill relevant information from other disciplines, but readers seeking a detailed discussion of the mechanics of wildfire, the interactions between weather and fire, or the effects of fire on biotic or human communities can find more detailed discussions in other sources. Given my disciplinary background, the book focuses on the movements of water, solutes, sediment, and organic material across uplands and into and through river networks. I review the effects of wildfire on process and form in upland and freshwater environments, as well as the interactions between living organisms, wildfire, and physical environments. Because the book spans multiple disciplines, I have included a glossary of terms.

The discussion of all topics covered in this book benefited greatly by thorough reviews from Stefan Doerr, Amy East, Joan Florsheim, Francis Rengers, and two anonymous reviewers. I very much appreciate their time and efforts.

Ellen Wohl
Colorado State University, USA

GLOSSARY

active layer: within permafrost regions, describes the upper layer of the ground that thaws each summer and freezes in the winter

aerosol: a colloidal suspension of particles dispersed in air

albedo: the proportion of incident sunlight or solar radiation that is reflected by a surface

alluvial fan: a fan-shaped (in planform) alluvial deposit, typically at the junction of a smaller river with a larger river or at the exit of a river from a mountain front

anthropogenic: human-caused

beaver meadow: a beaver-modified portion of river corridor that includes multiple dams and ponds of varying age; despite the name, typically includes abundant woody vegetation such as willows (*Salix* spp.)

benthic macroinvertebrates: live on or within the stream bed for at least some portion of their lifecycle and are visible to the naked eye (e.g., mussels, clams, worms, crayfish, snails, and a diverse array of insects)

biofilm: a matrix-enclosed and surface-attached microbial community

biomass: the total quantity or weight of living organisms in a given area or volume

biome: a major ecological community type, such as desert or grassland

bioturbation: the physical disturbance of sediment deposits by living organisms (e.g., by burrowing)

boreal: an ecosystem or river catchment in the northern hemisphere, between approximately 50 and 70° N latitude

channel head: the upstream boundary of concentrated water flow and sediment transport between definable banks

coarse woody debris: downed, dead wood outside of stream corridors

colluvial deposits: sediment deposited after transport by processes other than eolian or fluvial (e.g., rockfall, dry ravel, debris flow)

colluvial hollows: concave or convergent areas of uplands

conduction: transfer of heat via physical contact between a heat source and fuel or mineral body

connectivity: the movement of materials and organisms between components in a system (e.g., between uplands and river corridor, between active channel and floodplain, or between surface and subsurface)

convection: heat transfer by mixing of air masses

crown fire: a wildfire that burns within the forest canopy

debris flow: mass of poorly sorted, saturated sediment that moves downslope; typically has 40–77% sediment concentration by volume

drylands: designated based on the scarcity of water; defined by the United Nations Environment Program (UNEP) as tropical and temperate areas with an aridity index of less than 0.65; numerous aridity indices have been proposed – UNEP uses an index equal to ($100 \times R/LP$), where R is mean annual net radiation, P is mean annual precipitation, and L is latent heat of vaporization for water

dry ravel: involves rapid, dry, particle-to-particle rolling, sliding, and bouncing of sediment and some organic matter under the force of gravity and without the presence of water

dust: silt and clay-sized particles transported by wind

ecoregions: areas where ecosystems are generally similar

ENSO atmospheric circulation pattern: the El Niño-Southern Oscillation, a recurring climate pattern involving changes in the temperature of waters in the central and eastern tropical Pacific Ocean

fallout radionuclides: residual radioactive material propelled into the upper atmosphere following a nuclear blast and subsequently deposited on Earth's surface

fire-dependent ecosystems: those in which most species have evolved in the presence of fire

fire-independent ecosystems: naturally lack sufficient fuel or ignition sources to support fire as an evolutionary force; examples include desert and tundra

fire-sensitive ecosystems: those in which most species have not evolved in the presence of fire

fire hazard: in the context of wildfire, hazard typically refers to the state of the fuel and is quantified with respect to the likelihood and intensity of wildfire

fire intensity: rate of heat energy release

fire risk: in the context of technical risk assessments, risk includes the probability of an event, as well as values and expected losses; i.e., the probability of an event with harmful consequences, which can be thought of as the combination of hazard and vulnerability; in the context of fire, however, *risk* may refer only to the probability of natural or human-caused ignition, or it may be used to refer to hazard and the susceptibility of values-at-risk

fire severity: the effects of the fire on plant communities, or the loss of or change in above- and below-ground organic matter

fire vulnerability: vulnerability typically describes exposure and susceptibility, which can be differentiated as asset vulnerability and human vulnerability

flammability: reflects multiple metrics that quantify the ease of ignition and the behavior of the fire once ignited

floodplain: a low-relief sedimentary surface adjacent to the active channel that is constructed by fluvial processes and frequently inundated

forest canopy: the upper layer of forest formed by mature tree crowns

forest duff: the layer of organic soil below litter but above the mineral soil; composed of partly decomposed organic material

forest litter: the upper, organic soil layer of dead, fallen plant material; includes recognizable plant parts

forest understory: plant life growing beneath the forest canopy without penetrating the canopy to any great extent, but above the forest floor

fuel bed: a generic description of the complex of fuels occupying a given area

fuel component: subdivides the fuel type as a function of size (e.g., fine woody fuels) or physiological condition (e.g., dead wood)

fuel layer: vertical stratification of the fuel bed into ground, surface, and canopy fuels

fuel load: mass per unit area

fuel moisture: measured as the ratio between the mass of water in the fuel and the mass of dry fuel

fuel particle: individual fuel elements (e.g., twig, needle) that form the fuel complex at coarser scales

fuel type: the dominant fuels in the fuel bed (e.g., forest litter or grass)

gelisols: soils formed in very cold climates that contain permafrost within 2 m of the surface

grassland: an area in which the vegetation is dominated by grasses

ground cover: the lowest layer of aboveground vegetation (living and dead) and biological crusts that are in contact with the soil surface

headcut: a vertical down-step in the streambed that is migrating upstream over time

headwaters: first- and second-order streams

heat-induced spalling: wildfire heat results in lensoid-shaped rock flakes up to a few mm in thickness detaching from the surface of boulders or bedrock outcrops

herbaceous plants: vascular plants that have no persistent woody stem above ground

histosols: soils that are dominantly organic, commonly associated with bogs, moors, or peatlands

Hortonian overland flow: runoff that remains on the ground surface without infiltrating

hydrophobic soils: water-repellent soils that can form during wildfire

hyperconcentrated flow: a flowing mixture of water and sediment in a channel, with properties intermediate between fluvial flow and debris flow

hyporheic zone: subsurface areas in a river corridor containing water that originates from and returns to the channel

ignition: the initiation of combustion

indigenous: people inhabiting a region from the earliest times or before the arrival of European colonists

infiltration capacity: the maximum rate at which soil or regolith is capable of absorbing water under given conditions

landslide: mass movement with relatively rigid motion and deformation localized along persistent slip surfaces or shear zones

large wood: downed, dead wood with dimensions ≥ 10 cm in diameter and 1 m in length

machine learning: computer systems that are able to learn and adapt without following explicit instructions; these systems use algorithms and statistical models to analyze and draw inferences from patterns in data

mass movements: downslope movements of multiple grains simultaneously; types include debris flow, landslide, and soil creep

natural range of variability: the range of specified ecosystem or physical system properties (e.g., river discharge) over a particular time period in the absence of human alteration

nutrients: substances used by organisms to survive, grow, and reproduce

organic matter: remains of formerly living organisms, primarily plants; subdivided into fine particulate organic matter (>0.45 μm–1 mm), coarse particulate organic matter (>1 mm), and small wood (<10 cm in diameter and 1 m in length)

overland flow: water flowing across the surface as either diffuse sheet flow or concentrated flow in rills and gullies

peatlands: terrestrial wetland ecosystems in which waterlogged conditions prevent plant material from fully decomposing

periphyton: synonymous with biofilm

permafrost: permanently frozen ground; found at high altitudes or high latitudes

prescribed burns: fires deliberately set to reduce fuel load or to create desired ecological effects (also known as *controlled burns*)

$PM_{2.5}$: fine particulate matter with an aerodynamic diameter $\leq 2.5\,\mu m$

polycyclic aromatic hydrocarbons (PAHs): a class of chemicals composed of multiple aromatic rings; they occur naturally in coal, crude oil, and gasoline and result from burning coal, oil, gas, wood, garbage, and tobacco; they are carcinogens

Pyrocene: a time when humanity's firepower could interact in ways that promoted conditions favoring further fire

pyroconvection: convection caused or intensified by fire

pyrocumulonimbus: smoke-infused clouds and thunderstorms started or augmented by fires

pyrodiversity: fire-derived heterogeneity of habitats

pyrogenic carbon: a high-C and low-N byproduct of the incomplete combustion of organic matter; includes charred fine residue, but mostly takes the form of woody charcoal

pyrogeography: the study of human-fire relationships across space and 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

pyrotornadogenesis: when fires generate atmospheric vortices and tornadoes

radiation: transfer of heat via electromagnetic wave motion

rainsplash: occurs when the force of falling raindrops dislodges individual particles up to sand size

recalcitrant humic substances: humic substances that result from the decomposition of plant and animal residues and are composed of complex heterogeneous mixtures of organic compounds; they tend to be recalcitrant or resistant to biodegradation

regolith: loose, unconsolidated sediment; can include soil

resilience: describes the ability of a system (e.g., ecosystem, river corridor, human community) to return to a state or conditions similar to those before the disturbance

rills: small, linear erosional features on hillslopes, sometimes distinguished from gullies as being $\leq 0.3\,m$ deep; may be transient or persistent features

riparian zone: encompasses the stream channel between low- and high-water marks and that portion of the terrestrial landscape from the high-water mark toward the uplands where vegetation may be influenced by elevated water tables or flooding and by the ability of the soils to hold water

river/stream: although a river is generally understood to be larger than a stream, there is no formal definition of the difference in size, and I use both words interchangeably in this book

river corridor: includes the active channel(s), the floodplain and riparian zone, and the underlying hyporheic zone

saturation overland flow: surface runoff that infiltrates to shallow depths and then returns to the surface

savanna: a grassy woodland in which trees are sufficiently widely spaced that the canopy does not close

sediment cascade: describes the sequential transport of sediment through the landscape or some portion of the landscape (e.g., uplands to river network); the most comprehensive version covers sediment movement from source (weathering of bedrock to regolith) through to sink (e.g., oceanic depositional environments)

sheetwash/sheetflow: surface runoff that forms a continuous layer across the ground surface, submerging small irregularities such as pebbles

shrubland: areas with vegetation dominated by shrubs or short-statured trees, generally <5 m tall, and commonly in a single canopy layer

snag: in a forest context, standing dead wood

soil creep: a slow, seasonal downslope movement of sediment facilitated by freezing and thawing or wetting and drying

solastalgia: psychological distress from losing a valued landscape, as occurs after wildfire

solutes: materials dissolved in water

spotting: the mass transport of solid hot particles carried by winds ahead of the fire front

stream order: a numbering system that reflects spatial position within a river network; first-order streams have no tributaries, second-order streams have two or more first-order streams tributary to them, third-order streams have two or more second-order streams tributary to them, and so on

subcritical cracking: fractures in rock that grow slowly and steadily at stresses much lower than critical stresses

supply-limited sediment: the amount of sediment moved is limited by the supply of weathered material

taiga: a type of forest of cold, subarctic regions; mostly consists of pines, spruces, and larches

talik: unfrozen patches within permafrost terrain

thermokarst: subsidence and slope failure caused by melting of ice disseminated through or concentrated within permafrost

throughflow: water moving below the ground surface but above the groundwater table; can move as diffuse matrix flow or within concentrated zones such as pipes

transpiration (within plants): a plant's loss of water, mainly through the stomata (minute pores) of leaves

transport-limited sediment: the amount of sediment moved is limited by the energy of the transport mechanism

tropical: areas within the tropics of Cancer and Capricorn, or within 23°26' north and south of the equator

tundra: type of biome where tree growth is hindered by cold temperatures and short growing seasons

vapor pressure deficit: the difference between the amount of moisture in the air and the amount that air could hold at saturation

WHI: wildland–human interface

WUI: wildland–urban interface

1

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.

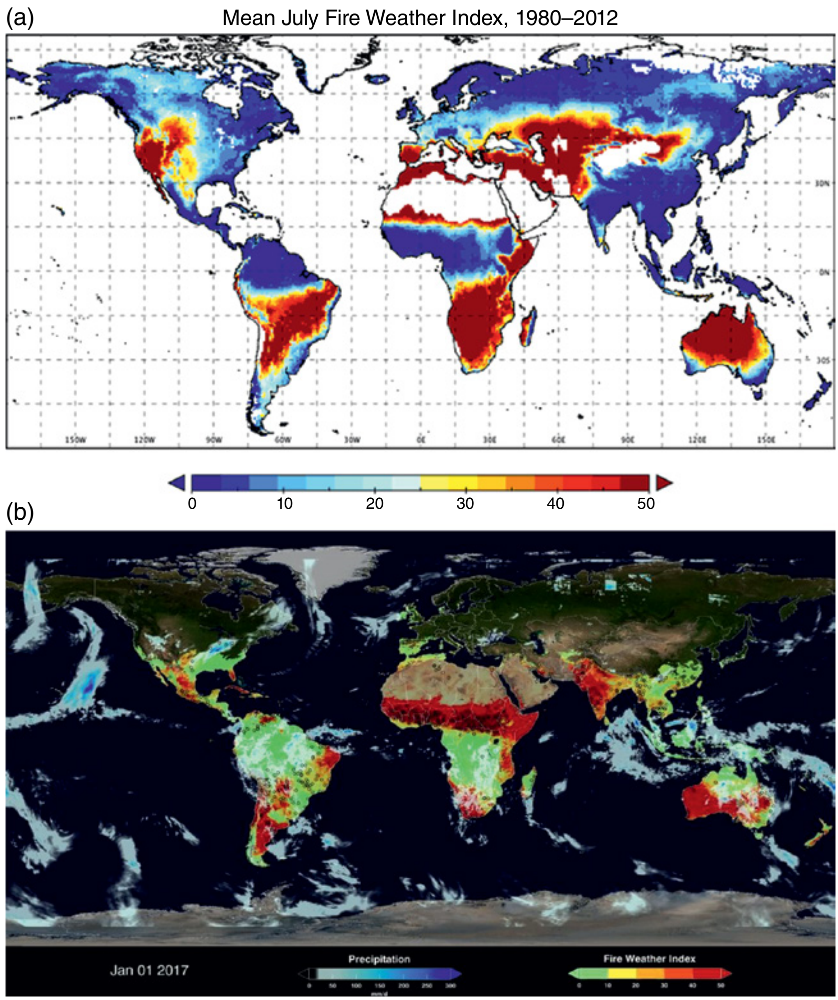

Figure 1.1 (a) Global map of fire weather index based on mean July conditions—summer in the northern hemisphere. (b) A contrasting map during summer in the southern hemisphere, here for 1 January 2017. (NASA / Public domain.)

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

References

Abatzoglou, J. T., & Williams, A. P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Science*, *113*, 11770–11775.

Abbott, B. W., Jones, J. B., Schuur, E. A. G., Chapin, F. S., Bowden, W. B., Bret-Harte, M. S., et al. (2016). Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: An expert assessment. *Environmental Research Letters*, *11*, 034014.

Abbott, B. W., Rocha, A. V., Shogren, A., Zarnetske, J. P., Iannucci, F., Bowden, W. B., et al. (2021). Tundra wildfire triggers sustained lateral nutrient loss in Alaskan Arctic. *Global Change Biology*, *27*, 1408–1430.

Belcher, C. M. (Ed.) (2013). *Fire phenomena and the earth system: An interdisciplinary guide to fire science*. Chichester, UK: Wiley-Blackwell.

Bowman, D. M. J. S., Kolden, C. A., Abatzoglou, J. T., Johnstons, F. H., van der Werf, G. R., & Flannigan, M. (2020). Vegetation fires in the Anthropocene. *Nature Reviews Earth and Environment*, *1*, 500–515.

Caon, L., Vallejo, V. R., Ritsema, C. J., & Geissen, V. (2014). Effects of wildfire on soil nutrients in Mediterranean ecosystems. *Earth-Science Reviews*, *139*, 47–58. http://dx.doi.org/10.1016/j.earscirev.2014.09.001

Carmona-Moreno, C., Belward, A., Malingreau, J.-P., Hartley, A., Garcia-Alegre, M., Antonovskiy, M., et al. (2005). Characterizing interannual variations in global fire calendar using data from Earth observing satellites. *Global Change Biology*, *11*, 1537–1555. http://dx.doi.org/10.1111/J.1365-2486.2005.01003.X

Cochrane, M. (2003). Fire science for rainforests. *Nature*, *421*, 913–919.

East, A., AghaKouchak, A., Caprarelli, G., Filipetti, G., Florindo, F., Luce, C., et al. (2023). Fire in the Earth system: Introduction to the special collection. *Journal of Geophysical Research: Earth Surface*, *128*, e2023JF007184. http://dx.doi.org/10.1029/2023JF007184

Fairman, T. A., Nitschke, C. R., & Bennett, L. T. (2015). Too much, too soon? A review of the effects of increasing wildfire frequency on tree mortality and regeneration in temperate eucalypt forests. *International Journal of Wildland Fire*, *25*, 831–848.

FAO. (2001). Global Forest Fire Assessment 1990–2000. Food and Agriculture Organization of the United Nations, Forestry Department, Forest Resources Assessment Programme Working Paper 55, Rome.

Flannigan, M. D., Krawchuk, M. A., de Groot, W. J., Wotton, B. M., & Gowman, L. M. (2009). Implications of changing climate for global wildland fire. *International Journal of Wildland Fire*, *18*, 483–507. http://dx.doi.org/10.1071/WF08187

Grimm, N. B., Chapin, F. S., Bierwagen, B., Gonzalez, P., Groffman, P. M., Luo, Y., et al. (2013). The impacts of climate change on ecosystem structure and function. *Frontiers in Ecology and Environment*, *11*, 474–482. http://dx.doi.org/10.1890/120282

Hu, F. S., Higuera, P. E., Duffy, P., Chipman, M. L., Rocha, A. V., Young, A. M., et al. (2015). Arctic tundra fires: Natural variability and responses to climate change. *Frontiers in Ecology and Environment*, *13*, 369–377.

Jiménez-Morillo, N. T., Almendros, G., De la Rosa, J. M., Jordán, Z. L. M., Granged, A. J. P., & González-Pérez, J. A. (2020). Effect of a wildfire and of post-fire restoration actions in the organic matter structure in soil fractions. *Science of the Total Environment*, *728*, 138715.

Joint Fire Service Program. (2004). *Joint fire service program 2003 business summary*. Seattle, WA: US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Jolly, W. M., Cochrane, M. A., Freeborn, P. H., Holden, Z. A., Brown, T. J., Williamson, G. J., & Bowman, D. M. J. S. (2015). Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, *6*, 7537. https://doi.org/10.1038%2Fncomms8537

Jones, T. A., Monaco, T. A., & Rigby, C. W. (2015). The potential of novel native plant materials for the restoration of novel ecosystems. *Elementa*, *3*, 000047. https://doi.org/10.12952/journal.elementa.000047

Levine, J. S. (2000). Global biomass burning: A case study of the gaseous and particulate emissions released to the atmosphere during the 1997 fires in Kalimantan and Sumatra, Indonesia. In J. L. Innes, M. Beniston, & M. M. Verstraete (Eds.), *Biomass burning and its inter-relationships with the climate system. Advances in global change research* (Vol. 3, pp. 15–31). Dordrecht: Springer.

Miller, R. G., Tangney, R., Enright, N. J., Fontaine, J. B., Merritt, D. J., Ooi, M. K. J., et al. (2019). Mechanisms of fire seasonality effects on plant populations. *Trends in Ecology and Evolution*, *34*, 1104–1117.

Mouillot, F., & Field, C. B. (2005). Fire history and the global carbon budget: A 1°× 1° fire history reconstruction for the 20th century. *Global Change Biology*, *11*, 398–420. http://dx.doi.org/10.1111/J.1365-2486.2005.00920.X

Paul, M. J., LeDuc, S. D., Lassiter, M. G., Moorhead, L. C., Noyes, P. D., & Leibowitz, S. G. (2022). Wildfire induces changes in receiving waters: A review with considerations for water quality management. *Water Resources Research*, *58*, e2021WR030699.

Pinto, P., Vaz, P., Robinson, C., & Morais, M. (2008). Wildfire impacts on aquatic ecosystems. In L. M. G. Duarte & P. Pinto (Eds.), *Sustainable Development: Energy, Environment and Natural Disasters* (pp. 25–34). Fundação Luis de Molina.

Power, M., Marlon, J., Ortiz, N., Bartlein, P., Harrison, S., Mayle, F., et al. (2008). Changes in fire regimes since the last glacial maximum: An assessment based on a global synthesis and analysis of charcoal data. *Climate Dynamics*, *30*, 887–907. https://doi.org/10.1007/%20S00382-007-0334-X

Rego, F. C., Morgan, P., Fernandes, P., & Hoffman, C. (2021). *Fire science: From chemistry to landscape management*. Cham, Switzerland: Springer Nature Switzerland.

Ren, P., Luo, C., Zhang, H., Cui, C., Sun, S., Song, H., et al. (2022). Isotopic records of ancient wildfires in C_4 grasses preserved in the sediment of the Ross Sea, Antarctica. *Geophysical Research Letters*, *49*, e2022GL098979. http://dx.doi.org/10.1029/2022GL098979

Sankey, J. B., Kreitler, J., Hawbaker, T. J., McVay, J. L., Miller, M. E., Mueller, E. R., et al. (2017). Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds. *Geophysical Research Letters*, *44*, 8884–8892.

Schmidt, M. W., & Noack, A. G. (2000). Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. *Global Biochemical Cycles*, *14*, 777–793. https://doi.org/10.1029/1999GB001208

Seidl, R., Schelhaas, M. J., Rammer, W., & Verkerk, P. J. (2014). Increasing forest disturbances in Europe and their impact on carbon storage. *Nature Climate Change*, *4*, 806–810.

Shakesby, R. A. (2011). Post-wildfire soil erosion in the Mediterranean: Review and future research directions. *Earth-Science Reviews*, *105*, 71–100.

Sullivan, A., Baker, E., & Kurvits, T. (Eds.) (2022). *Spreading like wildfire: The rising threat of extraordinary landscape fires*. United Nations Environment Programme.

Van der Werf, G., Dempewolf, J., Trigg, S., Randerson, J., Kasibhatla, P., Giglio, L., et al. (2008). Climate regulation of fire emissions and deforestation in equatorial Asia. *Proceedings of the National Academy of Sciences*, *105*, 20,350–20,355. http://dx.doi.org/10.1073/pnas.0803375105

Van der Werf, G. R., Randerson, J. T., Giglio, L., Van Leeuwen, T. T., Chen, Y., Rogers, B. M., et al. (2017). Global fire emissions estimates during 1997-2016. *Earth System Science Data*, *9*, 697–720.

Vilà, M., Lloret, F., Ogheri, E., & Terradas, J. (2001). Positive fire-grass feedback in Mediterranean Basin woodlands. *Forest Ecology and Management*, *147*, 3–14. http://dx.doi.org/10.1016/S0378-1127(00)00435-7

2

FIRES: WHAT, WHEN, WHERE, AND HOW

Abstract

Heat is transferred from wildfires via radiation, conduction, convection, and spotting when wind transports solid hot particles ahead of the fire front. Fire intensity describes the energy release rate. Fire severity describes the effects of the fire on plant communities or the loss or change in above- and belowground organic matter. Ground fires burn the organic layer overlying mineral soil. Surface fires burn ground fuels. Crown fires burn through the forest canopy. Although most wildfires result from human activities in the coterminous United States and some other parts of the world, most natural wildfires are ignited by lightning strikes. Fire weather occurs under weather conditions conducive to the ignition and spread of wildfires, which typically means hot, dry, and windy. Fire weather indices that incorporate daily weather variables related to fuel moisture and fire behavior are used to characterize fire weather. A fire regime describes the historical sequence of fires with some stable, recurrent, or cyclic characteristics or properties affecting a specified spatial and temporal window. Human activities have forced fire regimes outside of the natural range of variability in most of the world. Fire-prone ecosystems cover 40% of Earth's land surface and include grasslands, savannas, shrublands, and boreal forests.

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

DOI: 10.1002/9781394235186.ch2