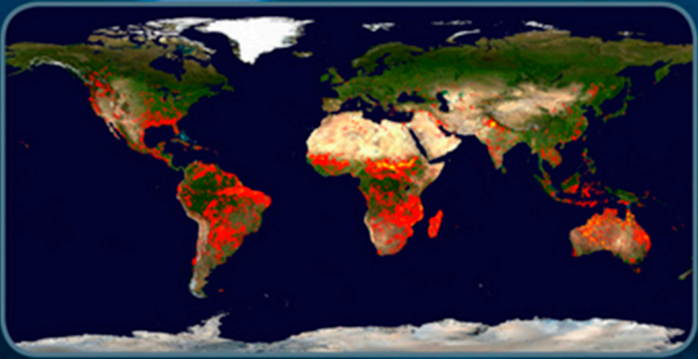
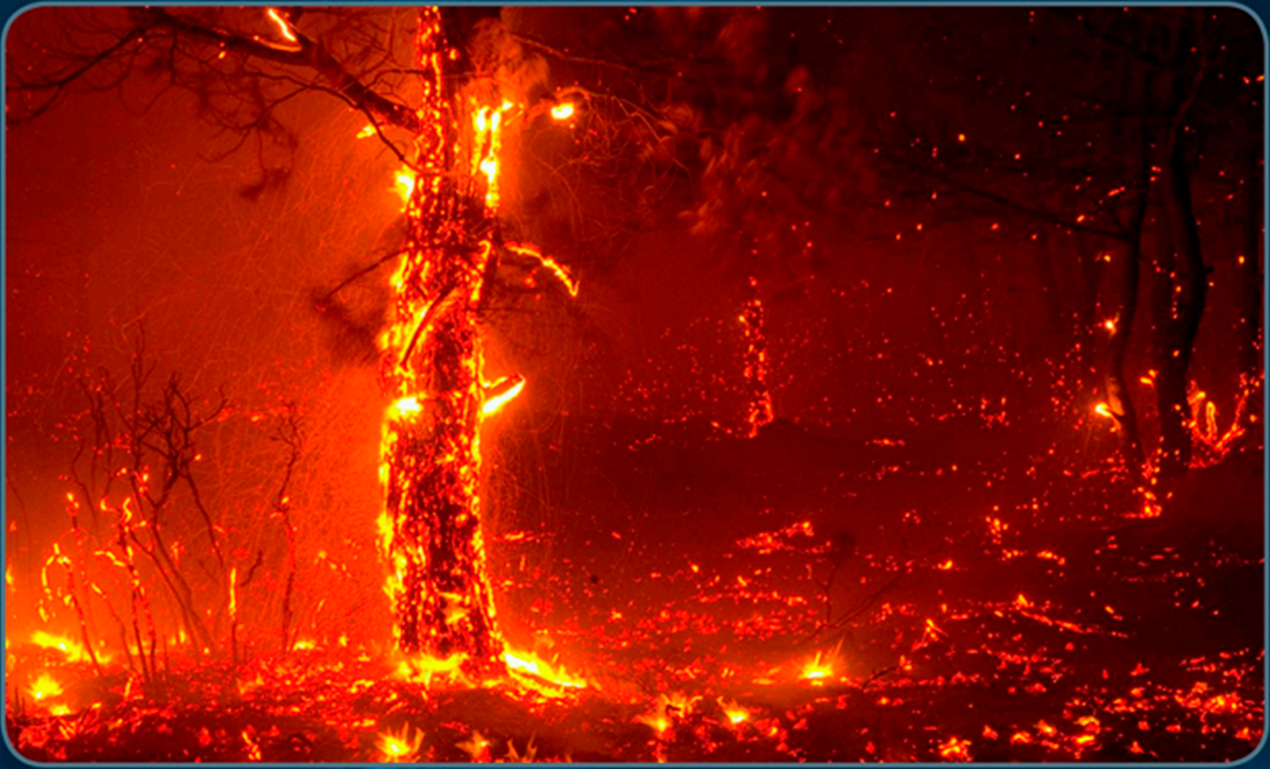


FIRE ON EARTH

An Introduction

Andrew C. Scott, David M.J.S. Bowman, William J. Bond,
Stephen J. Pyne and Martin E. Alexander



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Fire on Earth

Fire on Earth:

An Introduction

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This edition first published 2014 © 2014 by John Wiley & Sons, Ltd

Registered office: John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial offices: 9600 Garsington Road, Oxford, OX4 2DQ, UK
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Library of Congress Cataloging-in-Publication Data
Scott, Andrew C.
Fire on earth : an introduction / Andrew C. Scott, David M.J.S. Bowman, William J. Bond, Stephen J. Pyne, Martin E. Alexander.
pages cm
Includes bibliographical references and index.
ISBN 978-1-119-95357-9 (cloth) – ISBN 978-1-119-95356-2 (pbk.)
1. Fire–History. 2. Fire management. 3. Fire ecology. 4. Forest fires. 5. Wildfires. I. Bowman, D. M. J. S. II. Bond, William J., 1948- III. Pyne, Stephen J., 1949- IV. Alexander, Martin E. V. Title.
GN416.S46 2013
541'.361–dc23
2013018591

A catalogue record for this book is available from the British Library.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Cover images: Aykut ince, OGM-Turkey and NASA (http://lance-modis.eosdis.nasa.gov)

Cover design by Steve Thompson

Set in 10/12pt, Minion by Thomson Digital, Noida, India.

1 2014

For my wife Anne, my children Rob and Katrina for their love,
cheery encouragement and support and in memory of my father
John D. Scott (1917–1966)
ACS
For Fay, for her wisdom and unwavering support of my quest
to discover the meaning of fire on Earth.
DMJSB
For my wife, Winifred, for her cheerful companionship
and support over many years.
WJB
For Sonja – who didn't need a third time to be charmed
SJP
For my wife Heather and children Neal, Evan, Graeme and Wynne,
and my parents Connie and Russ, with much love.
MEA

Contents

Preface

Earth is the only planet known to have fire. The reason is both simple and profound: fire exists because Earth is the only planet to possess life as we know it. Life created both the oxygen and the hydrocarbon fuel that combustion requires, it arranges those fuels according to processes of evolutionary selection and ecological dynamics and, in the form of humanity, it supplies the most abundant source of ignition. Fire is an expression of life on Earth and an index of life's history. Few processes are as integral, unique or ancient.

Yet, while the significance of fire can hardly be doubted, it rarely enters the discourse of relevant disciplines or appears in standard texts of geology, biology, human history, physics or global chemistry. Fifty years ago, the only organized inquiries lodged in applied contexts such as combustion engineering, urban fire services and, fitfully, forestry and range science. No journal exclusively reported on it; conferences, wholly national, might be held once a decade on how better to control it; and, even when it was examined, free-burning fire, which integrates everything around it, was narrowly confined within other disciplines. The outcome was an extraordinary disconnection. While fire was ubiquitous in various forms throughout Earth, it was absent from our formal inquiries about our world. It stood outside both science and scholarship.

Today, the literature has multiplied exponentially. Dedicated journals exist. Half a dozen international conferences might be held annually. A host of formal sciences, or programmes announcing interdisciplinary intentions, are willing to consider fire. Wildfire appears routinely in media reporting. What has not happened, however, is a synthesis of contemporary thinking that can bring together the most powerful concepts and disciplinary voices that have interested themselves in fire. There is no global survey that can convey why planetary fire exists, how it works and why it looks the way it does today. This volume intends to redress the problem.

The text consists of four parts. The choice of themes is not arbitrary. We wanted to:

- establish the autonomy and longevity of fire on Earth;
- centre its dynamics in the living world;
- accent the critical presence of fire for humanity, and of humanity for pyrogeography;
- have fire's behaviour serve more as an integration of factors, and hence a summary, than as a putative foundation to everything else.

No volume can hope to summarize everything that has been published on the subject, or convey fire's endlessly ramified expressions in the field. We have selected those organizing themes that we believe best introduce the subject.

Each part is intended to stand alone, yet allow for connections to the others. Instead of creating an artificial synthesis, an intellectual equivalent of Esperanto, we elected to let each author speak in his own disciplinary tongue, in the hope that the gains from fluency will overcome any losses from translation. Yet, as in any collaborative venture, we have had an influence on what each of us has written and, hence, this volume must be considered as a book with five authors rather than an edited volume. The result is not an encyclopaedia, but a studied description and explanation of how fire appears to a prominent cadre of fire researchers. As each discipline organizes the whole through its own disciplinary prism, so each author speaks in his own voice.

Inevitably, there are lapses and overlaps in the particulars of the four parts. Each of us, for example, sees the foundational fire differently. For someone interested in deep time, fire appears as an emerging property of an evolving planet – one that leaves a geologic record. For biologists, fire appears as a product of the living world – the substrate without which fire cannot exist. For a cultural historian, it appears as an informing and defining technology for humanity – a unique signature of our agency and identity. And for someone interested in fire behaviour, fire will appear as a chemical reaction shaped by its physical surroundings.

We felt it better to let each author follow his own vision and thematic arc than try to merge them into a common cauldron. In this way, each perspective:

- will understand the increasingly dominant presence of humanity differently;
- will see it as the latest in a long chronicle of fire eras;
- will see it as perturbation along all scales of Earth's biota;
- will see it as an index of humanity's changing power; or
- will see it an arena for the application of better understanding to protect ourselves from the fires we do not want and promote those we do.

Nor have we tried to describe field operations, as previous texts by some of the authors have. The reason is simple. Other technologies, notably video, can do that job much better; 30 seconds of film can convey more accurately and vividly how to scrape fireline or run a pump than 30 pages of text. We wanted to let a book do what it can do best, which is to explore our understanding of fire and our relationship to it. We have sought to explain what principles mean through ground-truthing details, selected examples and case studies.

Inevitably, we can include only a minuscule fraction of landscapes, events, information and published (and unpublished) studies. Our choices will reflect our own judgment of what is most useful within the setting of this text, what the fashion of the times prefers and, inevitably, our own personal experiences and tastes.

We have elected to hold in-text citations to a minimum and to supplement them – again selectively – in the rosters of references and further reading attached to each of the four parts. The published literature on fire now numbers in the tens of thousands (and is expanding exponentially) and, while it is densest in the more developed world, its topics range across the planet. The authors of this text alone have a collective bibliography that includes hundreds of citations. The fire literature since the early 1960s has multiplied exponentially so, just as only a handful of examples must stand for the whole, only a tiny fraction of this literature can enter our bibliography. A master bibliography belongs online, not on printed pages.

These choices will please those members of the fire community whose work has been selected and will doubtless irk those who work has not. To the many who may feel we have slighted important sources, we plead *nolo contendere* and repeat that our purpose has not been to summarize the entire state of the literature, but to demonstrate why fire matters and how we might better understand the complex ways it intertwines with Earth and humanity. As Plutarch famously put it, the mind is not a vessel to be filled, but a fire to be kindled.

Acknowledgements

This book resulted from two circumstances. The first was the formation of the International Pyrogeography Research Group, which was funded by the Kavli Institute for Theoretical Physics and NCEAS (National Center for Ecological Analysis and Synthesis) in Santa Barbara. This was led by David Bowman and Jennifer Balch and has led to a wide interchange of ideas and experiences. The second was the persistence of Ian Francis of Blackwell (now Wiley Blackwell) to persuade two of us (ACS and SJP) to undertake a book on Fire.

We thank the many researchers for allowing us to use their photos and diagrams and, in some cases, make new versions for us.

ACS: I am indebted to Bill Chaloner for introducing me to fire in deep time, and to both him and my colleague Margaret Collinson for their constant support over the past 40 years. I thank all of my research students for continuing to stimulate me and, in particular, I thank Ian Glasspool and Claire Belcher, who have helped in my fire research in so many ways. I thank Deborah Martin for getting me to look at modern fire systems and for her constant interest in my work, and members of the International Pyrogeography Research Group for their stimulating discussions. Finally, I thank the Department of Geology and Geophysics at Yale University, who hosted my sabbatical, which directly led to the expansion of my fire research, and am grateful to the late Leo Hickey, Bob Berner and Derek Briggs for organizing my visit and to the late Karl Turekian for many hours discussing fire on earth. I thank Guido van der Werf and Mark Wooster for commenting on Chapter 1. For photographs and diagrams, I am indebted to: Sally Archibald, Jennifer Balch, Chris Baisan, Claire Belcher, Sarah Brown, John Calder, Mark Cochrane, Margaret Collinson, J.H. Dieterich, Stefan Doerr, Ian Glasspool, Rick Halsey, John Keeley, Meg Krawchuk, Colin Long, Jen Marlon, Deborah Martin, John Moody, Max Moritz, Dan Neary, Gary Nichols, Susan Page, Roy Plotnick, Mitch Power, Sue Rimmer, Dave Scott, Greg Smith, Alan Spessa, Tom Swetnam, Kirsten Thonicke, Dieter Uhl, Guido van der Werf, Cathy Whitlock.

DMJSB: I thank the National Center for Ecological Analysis and Synthesis (NCEAS) and Australian Centre for Ecological Analysis and Synthesis (ACEAS) for enabling a focused, synoptic understanding of landscape fire. I acknowledge the generosity of the numerous members of the fire community who shared their original figures and photos, thereby enhancing the book and expediting its preparation. I am indebted to all my colleagues, students and collaborators who have taught me so much about fire over the last 30 years; you are so numerous the hazard of naming some is that I will risk neglecting many others. Nonetheless, I thank my lab team including Brett Murphy, Lynda Prior, Grant Williamson, Sam Wood, Andres Holz, David Tng, Clay Trauernicht and Jess O'Brien who have been fantastic sounding boards for thinking through ideas about fire. Over the years many people have shared their knowledge of fire with me including, in Australia, Ross Bradstock, Jeremy Russell-Smith, Dick Williams, Peter Clarke, Don Franklin, Mike Crisp, Simon Haberle, Rod Fensham, Barry Brook, Owen Price, Greg Jordan, Geoff Burrows, and Fay Johnston. Thanks also to my Aboriginal friends Joshua Rostron and Rahab Redford have welcomed me on their country in Arnhem Land and taught my family how to burn the bush. I have been blessed with wonderful overseas collaborators including Jennifer Balch, Meg Krawchuk, Sarah Henderson, Jon Keeley, Tom Veblen, Cathy Whitlock, Chris Roos, Jon Lloyd, David Janos, George Perry, Brad Marston, Matt McGlone, Tom Swetnam, Johann Goldammer and Mark Cochrane. Finally, I am indebted to Stephen Pyne, William Bond and Andrew Scott—this book is a testament to their drive, wisdom and generosity.

WJB: I thank the many people from different parts of the world who have hosted visits at various times and made my life as an ecologist so rewarding. For the preparation of this book, I am particularly grateful to Dave Bowman for hosting me at the University of Tasmania, Grant Wardell-Johnson for a spectacular introduction to the world of giant eucalypts, Caroline Lehmann, Dick Williams, Garry Cook, Mahesh Sankaran, Bill Hoffmann and others for global perspectives on savannas, Jon Keeley and Ross Bradstock for continuing insights into fire in woody systems, Sally Archibald, Carla Staver, Kath Parr, Ed February, Steve Higgins, and Jeremy Midgley for enrichment on fire ecology over the years and Andrew Scott for opening up the exciting window on fire in deep time. Steve Pyne put it all together in the first place, and I have enjoyed his historian's exhilarating breadth and depth. My thanks to Tracey Nowell and Tristan Charles-Dominique for assistance with figures.

SJP: I would like to gratefully acknowledge the following people for their assistance, particularly with regard to illustrations: Johann Goldammer, Ray Lovett, Olle Zackrisson, Christian Kull, Jennifer Balch, Rich Gullette, Chris Elvidge, Mark Melvin, Zach Prusak, Cliff White, Randy Bomar, Brian van Wilgen, Jeremy Russell-Smith, Mary Huffman, Anders Granström, David Rönnblom, Peter Frost and Jerry Williams.

MEA: My good friends and fellow colleagues Miguel Cruz and Dave Thomas kindly provided detailed comments on all three chapters comprising Part Four. Miguel Cruz and graphic illustrator at large Wanda Lindquist were instrumental in the production or reproduction of many of the illustrations. Appreciation is extended to my long-time friends and fellow wildland fire behaviourists, Rick Lanoville and Dennis Quintilio, for undertaking a broad review of the manuscript. Other reviews of selected chapters were performed by Greg Baxter, Neil Burrows, Paulo Fernandes, Paul Keller, Ralph Nelson, Jim Steele and Wade Wahrenbrock. Several people have assisted me in various ways during the course of my 40-plus year journey in wildland fire. In addition to Miguel, Dave, Rick, Dennis, and Ralph, I would especially like to acknowledge the following individuals: Jack Barrows, Al Beaver, Phil Cheney, Jim Davis, Jack Dieterich, Dennis Dube, Murray Dudfield, Bill Furman, Dave Kiil, Wally Lancaster, Bruce Lawson, Murray Maffey, John Mason, Lachie McCaw, Peter Murphy, Bob Mutch, Grant Pearce, Dick Rothermel, Dave Sandberg, Jim Shell, Brian Stocks, Steve Taylor, Rob Thorburn, Chris Trevitt, Domingos Viegas, Terry Van Nest, Charlie Van Wagner, Dale Wade and Ron Wakimoto. Steve Longacre was instrumental in securing the photo in Figure 14.26. Finally, I am particularly indebted to Steve Pyne for allowing me the opportunity to contribute to this book. Part Four is a contribution in part of Joint Fire Science Program Project JFSP 09-S-03-1.

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About the Authors

Professor Andrew C. Scott is internationally recognized for his work in palaeobotany, palynology, coal geology, petrology and geochemistry and for his work on the geological history of wildfire. He is currently Professor of Applied Palaeobotany and a Distinguished Research Fellow in the Department of Earth Sciences at Royal Holloway University of London, England, where he has been since 1985. Professor Scott received his bachelor's degree in geology from Bedford College, University of London, England. He studied in the Botany Department of Birkbeck College, London where he received his PhD. He received a personal professorial chair in 1996. He was awarded a D.Sc. in 2002 by the University of London for his published work. Professor Scott is a Fellow of the Geological Societies of London, America, the Royal Society of Arts, and the Higher Education Academy. He received the Gilbert H. Cady award from the Geological Society of America in 2007.

Professor David M. J. S. Bowman holds a research chair in Environmental Change Biology in the School of Biological Sciences at the University of Tasmania. The primary motivation for his research is understanding the effects of global environmental change, natural climate variability and Aboriginal landscape burning on bushfire activity and landscape change across the Australian continent. He also studies the effect of bushfire smoke on human health. These research quests are truly transdisciplinary and involve numerous national and international collaborators and use a variety of techniques, including remote sensing and geographic information systems, epidemiology, historical ecology, palynology, dendrochronology, stable isotopes analyses, ecophysiology, mathematical modelling, biological survey, field experiments and molecular ecology. After completing his PhD in forest ecology and silviculture at the University of Tasmania in 1984, he spent two decades undertaking full time research in rainforest and savanna ecology throughout northern Australia. He received a DSc in 2002 from University of Tasmania, and has received travelling fellowships from the Australian Academy of Science, Harvard, Kyoto, Leeds and Arizona universities.

Professor William J. Bond holds the Harry Bolus Chair of Botany at the University of Cape Town. His interest in fire began while working for the Forestry Department of South Africa on understanding fynbos shrublands and how to manage them. From this beginning, he was able to forge links with researchers on fire ecology in the other Mediterranean-type ecosystems. In the 1990s, after he moved to UCT, he began working on the ecology of African savannas and the intriguing interactions of fire, large herbivores and physical forces in shaping these ecosystems. He has had the good fortune to work with colleagues in similar ecosystems elsewhere in the world helping to develop a global perspective. He has also made periodic excursions into the deep past to better understand the present. He is a Fellow of the Royal Society of South Africa and a foreign associate of the National Academy of the USA.

Professor Stephen J. Pyne is a historian and Regents Professor in the School of Life Sciences, Arizona State University, Tempe, Arizona, USA. He has written over a score of books, including fire histories of the U.S. (*Fire in America; Between Two Fires*), Canada (*Awful Splendour*), Australia (*Burning Bush*), Europe (*Vestal Fire*), and the world generally; two editions of a textbook, *Introduction to Wildland Fire*; and numerous articles about fire elsewhere in the world. Among his other interests is the history of exploration, to which he has contributed *The Ice: A Journey to Antarctica*, *How the Canyon Became Grand*, and *Voyager: Exploration, Space, and the Third Great Age of Discovery*. He spent 18 seasons in fire management with the National Park Service. He is a MacArthur Fellow, a member of the American Academy of Arts and Sciences, and twice a fellow at the National Humanities Center.

Dr. Martin E. Alexander, a forester by training, but began specializing in wildland fire with the 1972 and 1973 fire seasons when he worked as a U.S. Forest Service hotshot crew member. He obtained his B.Sc.F. (1974) and M.Sc.F. (1979) degrees from Colorado State University and Ph.D. degree in forestry from the Australian National University (1998). Marty retired in late 2010 as a Senior Fire Behaviour Research Officer with the Canadian Forest Service stationed at the Northern Forestry Centre in Edmonton, Alberta, after nearly 35 years of public service. He presently serves as an Adjunct Professor of wildland fire science and management at the University of Alberta and Utah State University. His research and technology transfer efforts have focused on practical applications of wildland fire behaviour knowledge, including firefighter and public safety. In 2003, Dr. Alexander received the International Wildland Fire Safety Award from the International Association of Wildland Fire and the Canadian Forestry Achievement Award from the Canadian Institute of Forestry in 2010. His work has taken him to all the provinces and territories of Canada, and to many parts of the world, including the continental USA and Alaska, Australia, New Zealand, Portugal, Greece, Italy, Turkey, and Fiji.

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/scott/fireonearth

The website includes:

- Powerpoints of all figures from the book for downloading
- PDFs of all tables from the book for downloading
- Links to key fire websites
- Links to videos and podcasts
- Additional teaching material

PART ONE

Fire in the Earth System

Photo

Recent research using satellite data has revolutionized our understanding on the distribution of fire on Earth. This image shows smoke plumes from Californian fires between Los Angeles and San Francisco in October 2007 billowing out over the Pacific Ocean. Red spots indicate active fires. (Image from Modis Rapid Response Project at NASA/GSFC, image 1163886).

Fire on Earth: An Introduction, First Edition. Andrew C. Scott, David M.J.S. Bowman, William J. Bond, Stephen J. Pyne and Martin E. Alexander.

Preface to part one

The first part of this book is an introduction to fire that not only considers fundamentals of fire as a physical/chemical process but also includes methods for the study of fire, an appreciation of the geological history of fire and its importance in the Earth System.

For some, fire is an every day part of life; for others, it is a remote phenomenon and is unimportant; for still others, it evades consciousness altogether. This may be said not only for individuals, but also for entire subject areas where fire has yet to be given its rightful place.

In this section, we discuss the nature and occurrence of fire and illustrate ways by which it can be recognized and studied. The past ten years has seen a revolution in our perception of fire, and news of major wildfires may now be instantly broadcast through a wide range of media. In addition, the increase in the ways we can observe fire through the use of satellites and the ability to view maps of the positions of active fires – even from our mobile phones –has brought a phenomenon unfamiliar to many to the forefront of current debate on human impact on the planet.

What is less well known or appreciated is the long geological history of fire on our planet and the role that fire has played in deep time in shaping our Earth. In this section, we demonstrate the methods we can use to unravel the history of fire – not just in terms of thousands of years, but in terms of hundreds of millions of years. In only the past few years, we have begun to unravel the relationship between fire and atmospheric change, especially with oxygen in the fossil record. This has led to a reassessment of the relationship between fire and vegetation, both from an ecological as well as from an evolutionary perspective. Part One sets up, therefore, the role of fire as an Earth System process and its special role in the evolution of life on land.

Chapter 1

What is fire?

This chapter serves as an introduction not only to Part One but also to the book as a whole. It considers many of the fundamentals of fire. We introduce here a number of concepts that are developed throughout the text and, where relevant, the chapter numbers or parts are given for reference. In addition, some areas are dealt with here because there is no space to develop them more fully within this book, as to do so would make it too long and unwieldy. Due to this, we have tried to provide a wide range of illustrative material here, as well as more extensive references for further reading.

1.1 How fire starts and initially spreads

Simply put, fire – generally called combustion – is a rapid chemical oxidative reaction that generates heat, light and produces a range of chemical products (Torero, 2013). However, in the context of vegetation fires, it is important to consider not only the range of materials that may be combusted, but also the conditions under which fire may occur and even be ignited.

It is obvious, therefore, that the basis of a fire is the nature of the fuel that will be combusted and the type of ignition source. The general principle for vegetation fires is that there is an initial high-temperature heat source. This may be produced by lightning, volcanic activity, a spark from a rock fall or, of course, by humans. Plants contain a range of organic compounds that include cellulose, a carbohydrate that is a linear polysaccharide polymer found in many cell walls. The high initial temperature causes a breakdown of the cellulose molecule and produces a range of gaseous components that include ammonia (NH_3), carbon dioxide (CO_2) and methane (CH_4). These gases mix with atmospheric oxygen and undergo a rapid exothermic reaction – combustion. This rapid increase in heat, together with the readily available oxygen, allows the reaction to continue and a fire is started (Cochrane and Ryan, 2009). These features may be characterized by the use of a fire triangle (Figure 1.1, Fire fundamentals).

Each element will be discussed in more detail below, but it is worth making a few general points at the outset.

- First, the fuel needs to be as dry as possible. This is because the initial heat may be dissipated by the need to evaporate water. If dry, then the heat can begin to break down the cellulose in the plant material. The moisture value of the fuel will depend on whether the plant is alive or dead. If alive, then the plant may contain moisture in the leaves, branches and trunk. If dead, the plant may be more prone to drying out.
- The second element is the fuel itself. For a fire to spread, it is necessary to have sufficient fuel to burn. Extreme build-up of litter that is dry would obviously be conducive to the spread of fire. However, how the fuel is arrayed and how quickly it is combusted is also important (Van Wagtendonk, 2006). There are also differences in the ways in which woody and non-woody vegetation burn, as well as other features such

Fire on Earth: An Introduction, First Edition. Andrew C. Scott, David M.J.S. Bowman, William J. Bond, Stephen J. Pyne and Martin E. Alexander.

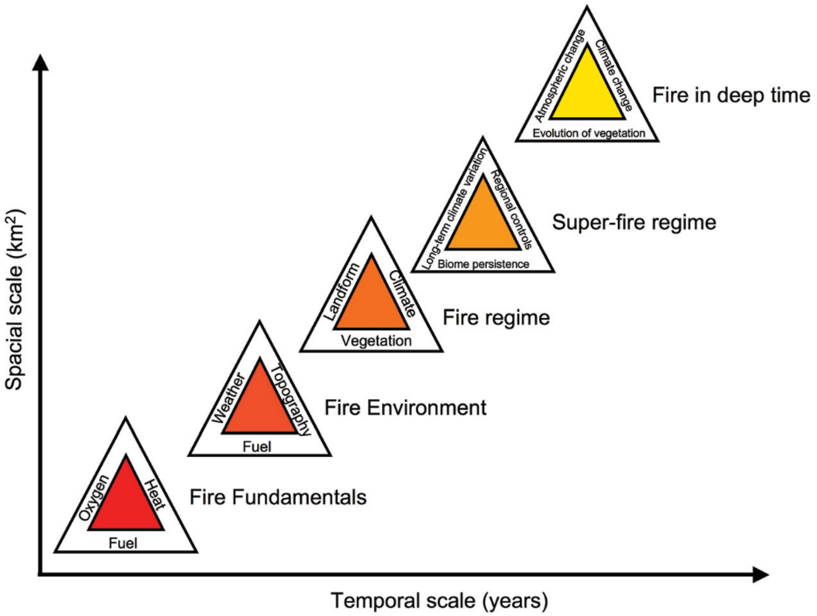

Figure 1.1 Fire triangles. The importance of different elements of fire is shown in relation to different scales, from the initial starting of a fire to the controls on fire in deep time. (This figure is compiled from a range of different authors' work including S. Pyne, M. Oritz, C. Whitlock, A. C. Scott).

as calorific value, the rate of fire spread and its intensity (see Chapter 14, Part Four).

- Third, a key element is readily available oxygen. In today's atmosphere, where the air contains 21% O_2, then combustion and fire spread is possible. For fire to be maintained, oxygen must continue to arrive at the burning point or the fire will be exhausted. This is why wind is so dangerous, as it not only drives the fire, but also replenishes the oxygen at a faster rate.

The implications of the above are also that to put a fire out, water may be added to the fuel to stop flame spread; or, in a confined space, oxygen may be excluded by smothering the fire by the use of inorganic materials such as sand or CO_2 to replace the oxygen-rich air.

1.2 Lightning and other ignition sources

Of all the natural ignition sources for a wildfire, lightning, volcanic eruptions and sparks from rock falls, it is lightning that is the most important. Human sources of ignition will be considered elsewhere in this book (see Part Three).

Lightning occurs when there is electrostatic discharge from the atmosphere. The most significant is sky-to-ground lightning (Figure 1.2). Here, a strong electrical charge is transferred from a cloud to the ground. Where the lightning hits the ground, there is a sudden increase in temperature, creating temperatures sometimes in excess of 30 000 °C. Lightning may or may not occur associated with rainfall.

Lightning may strike across many parts of the Earth's surface, but it is found concentrated in particular regions (see map, Figure 1.3). One problem with lightning maps, however, is that they show all lightning, including cloud-to-cloud lightning, not just cloud-to-ground lightning. It is significant that there may be as many as eight million lightning strikes every day.

When not associated with rain, the lightning may be referred to as 'dry lightning' and may occur in cumulonimbus clouds, which then may produce pyrocumulus clouds that create more lightning as a result of a warming ground surface from fire and is, therefore, a result of part of a positive feedback mechanism.

Not all lightning gives rise to a wildfire. In many cases, when trees are struck, this may result merely in scorching. However, if the tree is dead or dry because of drought, the great heat allows combustion to occur. This is equally the case with herbaceous vegetation,

Figure 1.2 Lightning strike. Dry lightning (not associated with rain) is one of the major ignition sources for fire (Courtesy valdezrl/Fotolia).

but sufficient fuel also needs to be available for a fire to spread.

The occurrence of fire may, therefore, be limited because of the amount or nature of the fuel (fuel limited) or because of moisture content of that fuel (moisture limited). In the tropics, this can lead to a single tree on fire, as it is unable to spread because of fuel moisture (Figure 1.4).

In regions of grassland, however, such as in savannas in Africa, fire may start just hours following a

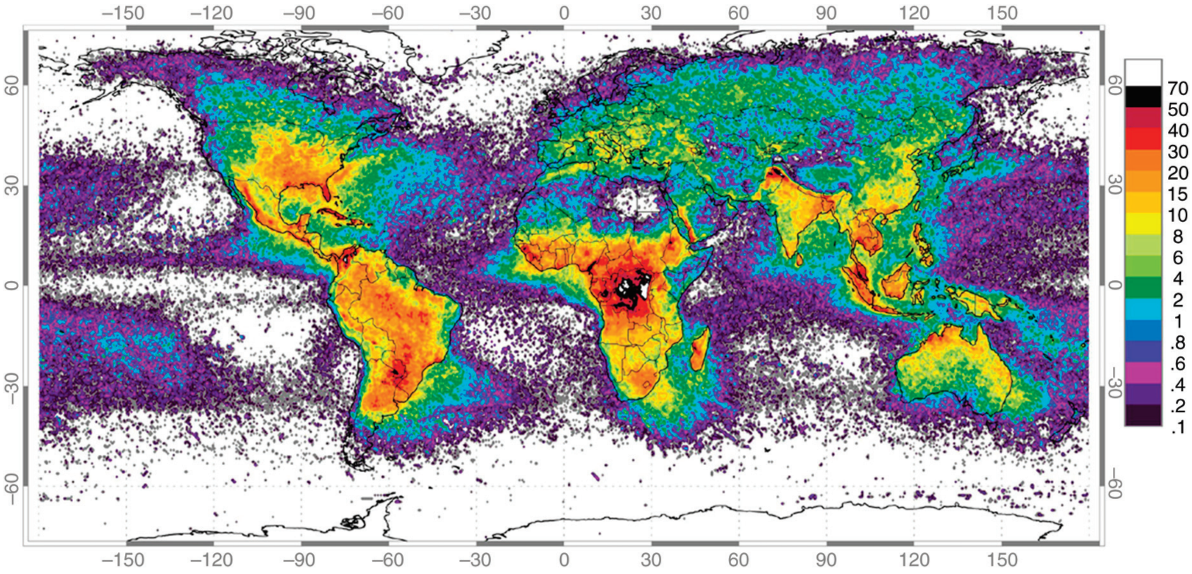

Figure 1.3 Global lightning activity (number of flashes/km^2 per year). Data available from Global Hydrology Resource Center (http://ghrc.msfc.nasa.gov). (From Bowman, 2005).

Figure 1.4 Fire burning a solitary tree in the Amazon rainforest. (Photo: M. Cochrane).

rainstorm, as the atmosphere is warm and dry, which allows the fine fuels to dry out very quickly. All of these facts are of particular significance to those producing fire potential maps (Figure 1.5).

1.3 The charring process

Most plant material comprises of a range of organic compounds, including a variety of macromolecules. For example, wood is composed of cellulose and lignin, but also includes hemicelluloses. Leaf coatings contain cutin, whereas spores and pollen are composed of the inert macromolecule sporopollenin. All of these compounds, including those from other organic sources (e.g. chitin from fungi), will break down upon heating. Of particular significance are aliphatic compounds such as cellulose, a carbohydrate, and lignin, which is an aromatic compound that is heavily cross-linked.

When heated in the absence of air this pyrolysis process results in the decomposition of the biomacromolecules to produce liquid and gaseous materials. The resultant residue is termed charcoal, and this is highly aromatic, with an increased

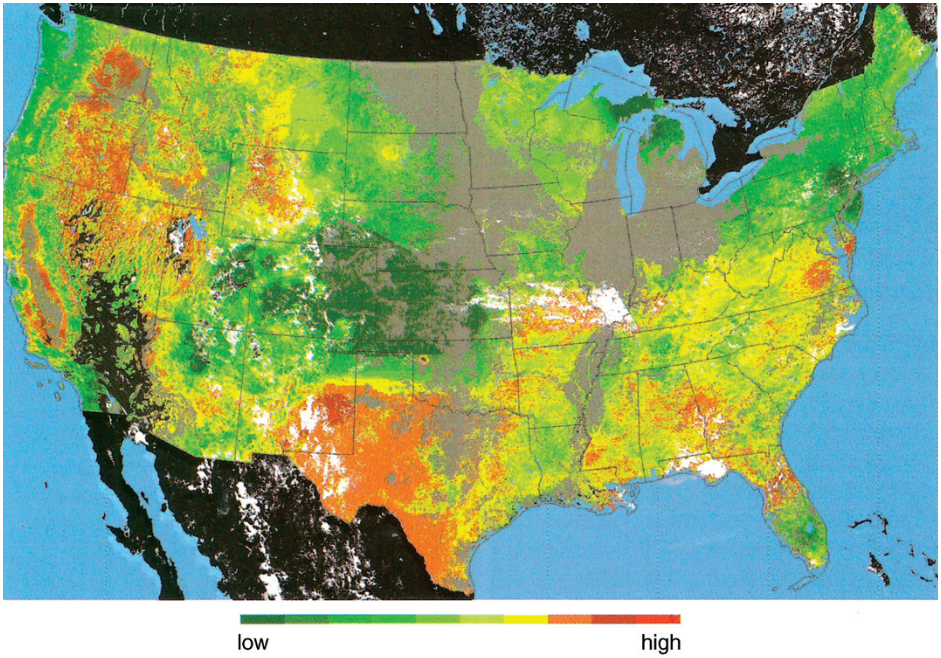

Figure 1.5 Fire potential index map of the United States for August 13, 1998. White areas are cloud cover; grey are agricultural lands (not rated). (From USGS factsheet 125–98, 1998).

proportion of carbon over the starting material. Some tar-like liquids may be produced, along with other volatile components and other gases. These materials may be mixed with oxygen in the air and combustion results, which, in turn, generates more heat for the process to continue.

The burning of plants is, therefore, a two-stage process in which:

1. pyrolysis occurs in the absence of oxygen, whereby the bio-macromolecules are charcoalified (Scott, 2010), releasing volatile components;
2. combustion then follows, representing an oxidative process whereby these components mix with oxygen in the air to allow burning.

Temperatures in the process are variable. For charcoalification to begin, the temperatures generally of 275 °C are required but higher temperatures will create a broad range of pyrolysis products that may be combusted.

1.4 Pyrolysis products

The result of the pyrolysis and combustion process leads to the production of a number of materials and compounds from charcoal: inorganic ash, volatile gases and compounds (aerosols), and soot (Santṓn *et al.*, 2012). Most fires generate this full range of material, and this may have a significant impact on the environment. Many of these products may be incorporated into the smoke plume of the fire and be transported considerable distances (Figure 1.6). Each of these products will be briefly examined in turn.

The products of a fire can be divided into two main groups: the material that remains in place after a fire

Figure 1.6 Smoke from fires.

A. White smoke columns from the Las Conchas Fire, New Mexico, USA, 2011 (see also Figure 1.42).
B. Grey smoke from the Norton Point Fire, Wyoming 2011.

(Photos from National Interagency Fire Center, https://picasaweb.google.com).

has passed (including mineral ash and charcoal); and the material that is transported away from a fire within a smoke plume. White or grey smoke (Figure 1.6) will depend on a range of factors, from fuel type to moisture content to temperature.

Usually the first visible evidence of a wildfire is its smoke plume. This may include water vapour which will be dependent on the water content of the fuel, small charcoal particles, usually less than 125 *m*m, but in some fires, significantly larger pieces may be lofted with the plume. Perhaps more important is the presence of soot, volatile components and aerosols (Artaxo *et al.*, 2009).

1.4.1 Soot

Soot, together with charcoal, is often referred to as black carbon. There is considerable disagreement among researchers on the nomenclature of these products. Some use the term 'black carbon' to mean only soot, whereas others include any combustion product that is recalcitrant in the biosphere (see Chapter 2 and Glasspool and Scott (2013)). Soot is formed by the recombination of vaporized organic molecules to form a new carbon material. Chemically, it is nearly pure carbon, and it is morphologically distinctive. Under the scanning electron microscope, it can be seen to have a range of morphologies, with a particle size less than 1 *m*m (see Figure 2.5g). Soot may also be produced by a range of other combustion processes (including petroleum), but that from vegetation fires may have this particular morphology.

Small cenospheres may also be produced from the burning of fossil fuels such as peat and coal. This soot may be widely dispersed into the atmosphere and may subsequently be deposited across the globe, even into deep-sea sediments (see Chapter 2). The soot may also be associated with micro-sized charcoal particles.

1.4.2 Volatile gases and compounds

A range of gases and aerosols may also be incorporated into the smoke plume. These include CO_2, carbon monoxide (CO), CH_4 and oxides of nitrogen (NO_x). Fire is therefore a significant producer of greenhouse gases. Most of the CO_2 is recaptured from the atmosphere by the re-growth of vegetation. If a fire results in the burning of peat, however, then this may become a significant issue for climate forcing.

Other important compounds include complex organic molecules such as pyrolitic polycyclic aromatic hydrocarbons (PAHs). These compounds may be produced in large quantities and their composition may depend of the type of vegetation being burned and the temperature involved. The higher the temperature, the larger the number of carbon rings found in the molecule. Table 1.1 shows a list of these compounds and their origin. The most common of these are cadanene and retene, but they also include phenanthracene, fluoromethene and chrysene, pyrene and coronene. Laevoglucosan derived from cellulose is widely used as a biomarker for vegetation fires. These compounds may also stay

Table 1.1 Major biomarker tracers in smoke from biomass burning. (From Simoneit, 2002).

Compound	Structure	Composition	Indicator for source
Anisic acid (p-methoxy-benzoic acid)	V	$C_8H_8O_3$	Gramineae lignin
Vanillic acid	II	$C_8H_8O_4$	Lignin
Syringic acid	IV	$C_9H_{10}O_5$	Angiosperm lignin
Matairesinol	VII, R = O	$C_{20}H_{22}O_6$	Conifer lignin[a]
Shonanin	VII, R = H_2	$C_{20}H_{24}O_5$	Conifer lignin[a]
Divanillyl	VIII	$C_{16}H_{18}O_4$	Lignin dimer
Divimillylmethane	IX	$C_{17}H_{20}O_4$	Lignin dimer
Divanillylelhane	X	$C_{18}H_{22}O_4$	Lignin dimer
Vanillylsyringyl	XI	$C_{17}H_{20}O_5$	Angiosperm lignin dimer
Disyringyl	XII	$C_{18}H_{22}O_6$	Angiospyrm lignin dimer
Dianisyl	XIII	$C_{16}H_{18}O_2$	Gramineae lignin dimer